Chapter one: concrete as a material

1.1 General introduction

Concrete is a material that literally forms the basis of our modern society. For example, we may live, work, study, or play in concrete structures to which we drive over concrete roads and bridges. **Figure 1** demonstrates some of these concrete structures.

Figure 1. Concrete structures

We take concrete for granted in our everyday activities and tend to be impressed by the more dramatic impacts of technology. However, it can be truly said that many of the achievements of the earlier civilization of Rome were made possible by the use of the forerunner of modern concrete. The word concrete comes from the Latin verb "concretus" which means to grow together.

1.2 The nature of concrete

Concrete is a composite material composed of coarse granular material (the coarse or filler) embedded in a hard matrix of material (the cement or binder) that fills the space between the aggregate particles and glues them together. Aggregates can be obtained from many different kinds of materials although we mostly make use of the materials of nature – common rocks. Similarly, cement is a generic term that can apply to all binders. Therefore, descriptors must be used to qualify this term referring to specific materials. A civil engineer may have a cause to use portland cement concrete, calcium aluminate cement concrete, or polymer concrete where the binders are portland cement, calcium aluminate cement, or a polymer resin, respectively. In concrete construction, the engineer will use portland cement concrete 95% of the time. **Table 1** shows a summary of some technical terms that we need to know.

Table 1. Definitions of concrete, mortar, and paste

Concrete	=	Aggregate (fine + coarse)	+	Portland cement /binder	water
Mortar	=	Fine aggregate	+	Portland cement /binder	water
Paste	=	NA	+	Portland cement /binder	water

NA = not applicable

Concrete

Mortar

Paste

Figure 2. Concrete, mortar, and paste

1.3 Advantages of concrete

Concrete is the predominant material used in construction. It competes directly with all other major construction materials – steel, timber, asphalt, stone, etc. It is estimated that the present consumption of concrete in the world is of the order of 11 billion metric tons every year. Concrete has advantages; **Table 2** summarized them. The disadvantages of concrete will be discussed in the following section.

Table 2. Advantages and disadvantages of concrete

Advantages
• Ability to be cast • Economical • Durable • Fire resistant • Energy efficient (this is debatable) • On-site fabrication • Aesthetic properties

Typical properties of concrete are given in **Table 3**.

Table 3. Typical engineering properties of structural concrete

Property	Approximate value
Compressive strength	35 MPa
Flexural strength	6 MPa
Tensile strength	3 MPa
Modulus of elasticity	28 GPa
Poisson's ratio	0.18
Tensile strain at failure	0.001
Ultimate shrinkage strain	0.05%-0.1%
Density =	=
• Normal weight	• 2300 kg/m^3
• lightweight	• 1800 kg/m^3

It should be remembered, however, that concrete property can vary significantly from the properties given in **Table 3**, depending on the choice of materials and proportions for a particular application.

1.4 Limitations of concrete

Concrete may have weaknesses that may limit its use in certain applications and they are listed as follows:

- Concrete is a brittle material with very low tensile strength. Therefore, concrete should not be loaded in tension. Excepts can include unreinforced slabs on grade with low bending stress. Consequently, reinforcing steel must be used to carry such loads.
- Low ductility. The low ductility of concrete means that concrete lacks impact strength and toughness compared to metals.
- Low-to-weight ratio. This means the load capacity of concrete requires comparatively large masses of concrete. However, since concrete is low in cost, this is economically possible.
- Volume instability. Concrete undergoes considerable irreversible shrinkage due to moisture loss at ambient temperature and also creeps significantly under an applied load even under conditions of normal service.

Awareness of these problems with concrete enables us to compensate for them, by using suitable designs and by controlling them, through a suitable choice of materials and construction practices. Substantial research has been done to ameliorate these problems. As a result, ready-mixed concrete can easily be made with compressive strength of 100 MPa. Also, new types of concrete have been developed such as shrinkage compensated concrete, fiber-reinforced concrete, ultra-high performance concrete.

Chapter 2: historical development of cement and concrete

2.1 General introduction

From very early times, builders have tried to find materials that could be used to cement stones or bricks together. Perhaps the oldest cementing material was simply mud, sometimes mixed straw, to bind dried bricks together, as used in ancient Egypt. The Babylonians and Assyrians used naturally occurring bitumen to bind stones or bricks together.

This chapter will follow the development of cements based on compounds of lime; in particular, we are going to focus on those cements that are capable of hardening underwater.

2.2 Nonhydraulic cement

The cements derived from the calcination of gypsum or calcium carbonates are nonhydraulic cement because their products of hydration are not resistant to water.

2.3 Hydraulic limes

Cements that not only hardened by reacting with water but also form a water-resistant products.

2.4 Development of portland cement

- James Parker in England took out a patent in 1796 on a natural hydraulic cement produced by calcining nodules of impure limestone containing clay.
- A similar process began in France six years later.
- In 1813, also in France, Vicat prepared artificial hydraulic lime calcining synthetic mixtures of limestone and clay.
- James Frost introduced the same approach in England 1822.
- Finally, in 1824, Joseph Aspdin, a Leeds builder, took out a patent on "Portland cement". The name portland was coined by Aspdin because of the real or fancied similarity of the hardened cement to a popular, naturally occurring limestone quarried at the Isle of Portland.

Chapter 3: cement

3.1 General introduction

There is a wide variety of cements that are used to some extent in the construction and building materials or to solve special engineering problems. The chemical compositions of cements can be quite diverse, but by far the greatest amount of concrete used today is made with portland cements. This chapter is going to focus on portland cement.

3.2 Manufacture of portland cement

In principle, the manufacture of portland cement is very simple and relies on the use of abundant raw materials. An intimate mixture, usually of limestone and clay, is heated in a kiln to 1400℃ to 1600℃, which is the temperature range in which the two materials interact chemically to form calcium silicates. **Figure** 3 illustrates the manufacturing process of portland cement.

3.3 Raw materials

- Limestone (the most common source of calcium oxide).
- Iron-bearing aluminosilicates (the primary source of silica).
- Clays or silts (they are preferred since they are already in a finely divided state).
- Quartz and iron oxide are quite commonly added (especially in the western United States) to make up for deficiencies of SiO_2 and Fe_2O_3 in the main mixture.

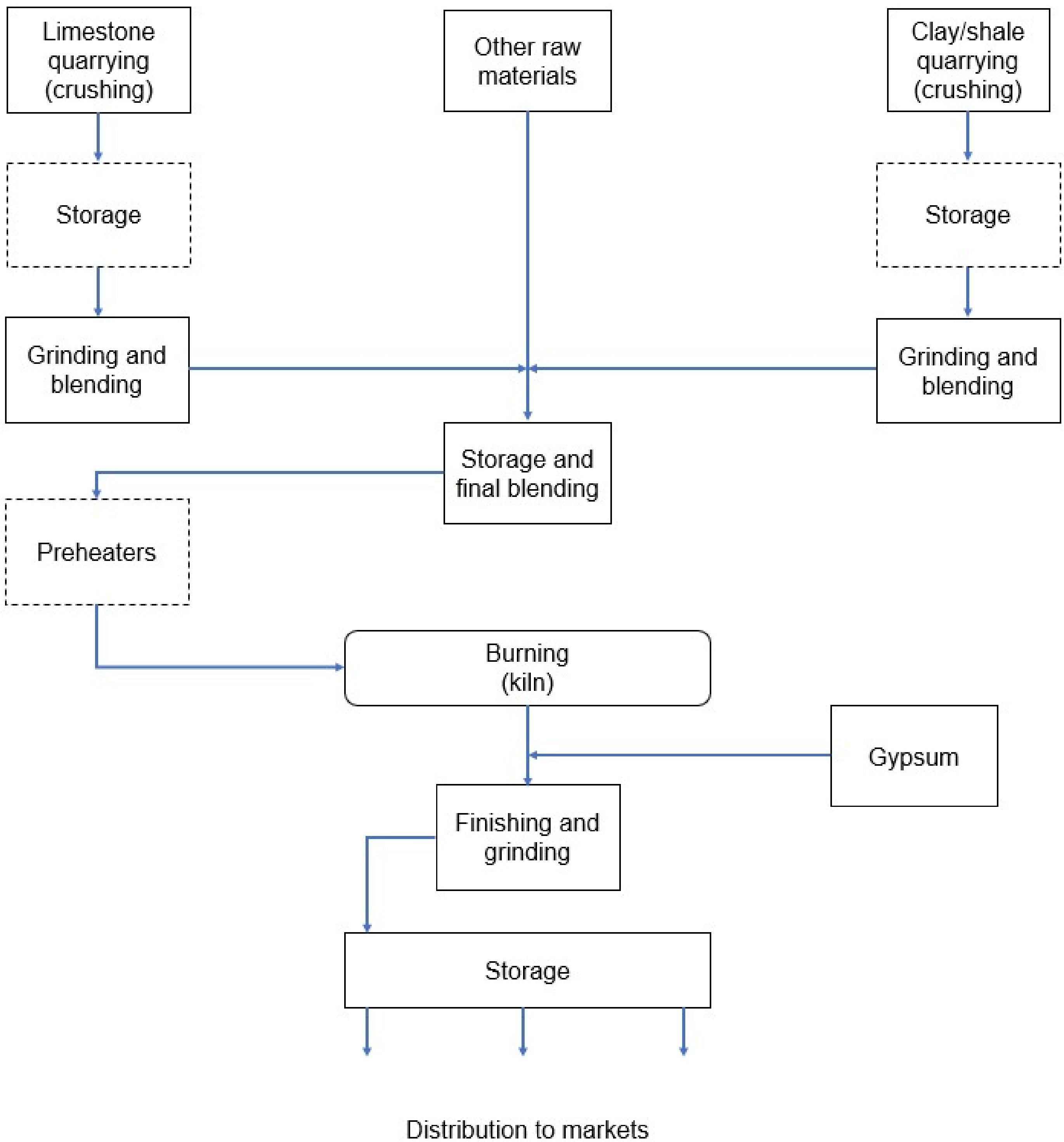


Figure 3. Cement production outline

3.4 Preparing of raw materials

- The objective of processing the raw materials is to ensure that the raw feed entering the kilns is of constant composition.
- Failure to do this would result in cement with variable composition and unpredictable properties.
- The exact sequence of operations at this stage may vary considerably from plant to plant depending on the raw materials, equipment, and plant design such as dry process, wet process, and semi-dry process.
    - *Dry process:* the raw materials are mixed, fined, and then fed into a kiln.
    - *Wet process:* the raw materials are crushed separately and then directly mixed in the correct proportion in the presence of water to make a fine thin paste known as Slurry.
    - *Semi-dry process:* the raw materials are prepared as in the dry process, however, 12% to 14% of water.

3.5 The burning process

Once the raw feed has been adequately ground and blended, it is ready to enter the kiln. This heat treatment is termed clinkering. The product of this process is called clinker. The required temperature to achieve this product is approximately 1450°C.

3.6 Final processing

The material that emerges from the kiln is known as clinker; further processing is still required. The clinker, in the form of dark-gray porous nodules (6 mm to 50 mm in diameter), is still hot and is further cooled by an air or water spray, typically on a moving grate. A small amount of gypsum is blended with the clinker. Therefore portland cement is clinker blended with gypsum; without gypsum, it is only ground clinker.

3.7 Composition of portland cement

The typical chemical composition of a general-purpose (ordinary) portland cement that can be purchased at a local building supply store is given in **Table 4**. It is noted that the quantities do not add up to 100%. The missing percentages are accounted for impurities.

Table 4. Cement chemistry

Chemical name	Chemical formula	Notation	Weight (%)
Tricalcium silicate	$3CaO.SiO_2$	C_3S	55
Dicalcium silicate	$2CaO.SiO_2$	C_2S	18
Tricalcium aluminate	$3CaO.\ Al_2O_3$	C_3A	10
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	8
Calcium sulfate dihydrate (gypsum)	$CaSO_4.\ 2H_2O$	CSH_2	6

The chemical formulas of these compounds are written traditionally in an oxide notation frequently used in the industry. The common notation is summarized in **Table 5**.

Table 5. Oxide analysis of portland cement (%)

Oxide	Notation	Common name	Weight percent
Cao	C	Lime	65.0
SiO_2	S	Silica	21.1
Al_2O_3	A	Alumina	6.2
Fe_2O_3	F	Ferric oxide	2.9
SO_3	$\bar{S}$	Sulfur trioxide	2.0
Rest			2.8

The *Bogue* equations for estimating the theoretical or the potential compound composition of portland cement are as follows:

$$\%C_3S = 4.071C - 7.600S - 6.718A - 1.430F - 2.850\bar{S}$$
$$\%C_2S = 2.8671C - 0.7544C_3S$$
$$\%C_3A = 2.650A - 1.692F$$
$$\%C_4AF = 3.043F$$

The equations apply to portland cement with an A/F ratio of 0.64 or higher; should the ratio be less than 0.64 another set of equations apply, which are included in ASTM C 150.

3.8 Hydration of cement

So far, we have discussed cement in powder form but the material of interest in practice is the set of cement paste; this is the product of the reaction of cement with water. In the presence of water, the silicates and aluminates (**Table 4**) of portland cement form products of hydration, which in time produce a firm and hard mass (the hardened cement paste). C_3S and C_2S are the main cementitious compounds in cement. The former hydrates much more rapidly than the latter. Both compounds produce calcium silicate hydrates (C-S-H) and calcium hydroxide (CH) in different amounts. The approximate hydration reactions are written as follows:

For C_3S:

$$2C_3S + 6H = C_3SH_3 + 3Cao(OH)_2$$

[100] [24] [75] [49]

For C_2S:

$$2C_2S + 4H = C_3SH_3 + 3Cao(OH)_2$$

[100] [21] [99] [22]

The amount of C_3A in most types of cement is comparatively small. The reaction of pure C_3A with water is very rapid and would lead to a flash set; which is prevented by the addition of gypsum to the cement clinker. On the other hand, C_4AF forms similar hydration products to C_3A, with or without gypsum. It may be convenient to summarize the pattern of formation and hydration of cement as shown in **Figure 4**.

Component elements: Si, Ca, Al, Fe

↓

Component oxides: Cao, SiO_2, Al_2O_3 & Fe_2O_3

↓

Cement compounds: C_3S, C_2S, C_3A & C_4AF

↓

portland cement: various types

↓

Hydration products: C-S-H and CH

Figure 4. schematic representation of the formation and hydration of portland cement

3.9 Heat of hydration

The hydration of cement compounds is exothermic and the quantity of heat evolved upon complete hydration at a given temperature is defined as the heat of hydration. The heat of hydration can be estimated using the following equations:

$$H_{(3-days)} = 240(C_3S) + 50(C_2S) + 880(C_3A) + 290(C_4AF)$$

$$H_{(1-year)} = 490(C_3S) + 225(C_2S) + 1160(C_3A) + 375(C_4AF)$$

The hydration characteristics of the cement compounds are summarized in **Table 6**.

Table 6. Characteristic of cement compound

Compounds	Reaction rate	Amount of heat liberated	Contribution to cement strength
C_3S	Moderate	Moderate	High
C_2S	slow	Low	Low initially (high later)
C_3A	Fast	Very high	Low

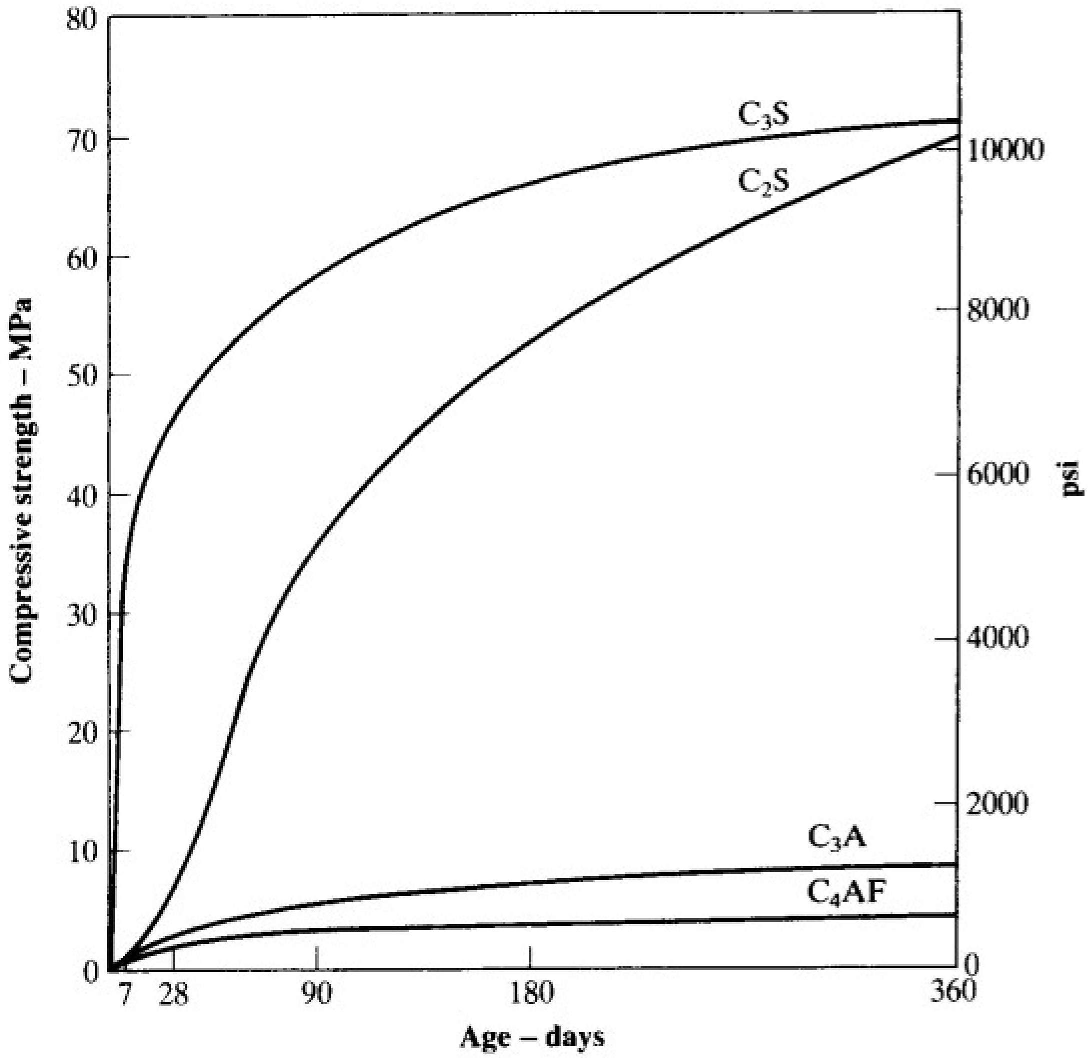


Figure 5. Development of strength of pure compounds

3.10 Classification of cement according to ASTM

ASTM C150 “Standard Specification for Portland Cement” covers the following types of portland cement. We will focus on the major types only.

- Type I: For general use, when the special properties specified for any other type are not required.
- Type II: For general use, more especially when moderate sulfate resistance is desired.
- Type III: For use when high early strength is desired.
- Type IV: For use when a low heat of hydration is desired.
- Type V: For use when high sulfate resistance is desired.

Table 7 shows a typical summary of the chemical composition and properties of these types of portland cement.

Table 7. Typical chemical composition and properties of portland cement according to ASM C150

Compound/Property	I	II	III	IV	V
C_3S	55	55	55	42	55
C_2S	18	19	17	32	22
C_3A	10	6	10	4	4
C_4AF	8	11	8	15	12
CSH_2	6	5	6	4	4
Fineness (Blaine m^2/kg)	365	375	550	340	380
Compressive strength (MPa – 1 day)	15	14	24	4	12
Heat of hydration (J/g – 7 days)	350	265	370	235	310

The above table will be discussed during the lecture in detail.

3.11 Special types of cement

There are different types of portland cement rather than the classification of ASTM C150. **Table 8** summarizes some of these types and their major uses. The next table can be found in the "Reference #2" on page 231.

I know it is a long table but it is very useful.

Table 8. Special cements and their uses

Classification and types	Composition	Major uses
Blended portland cements Portland blast-furnace slag cement (ASTM Type IS) Portland pozzolan cement (ASTM Type IP)	Consist essentially of an intimate and uniform blend of granulated blast-furnace slag or a pozzolan or both with portland cement, and often containing calcium sulfate. Industrial Type IS cements contain typically 30 to 40 percent slag, while Type IP cements contain 20 to 25 percent pozzolan. Compared to portland cement, both types are ground to finer particle size to partly compensate for the loss of early strength.	1. Low heat of hydration 2. Excellent durability when properly designed and cured 3. Energy-saving and resource- conserving, and generally less expensive than portland cement
Expansive cements Type K Type M Type S Type O	Consist essentially of portland cement with an expansive additive. Types K, M, and S cements, covered by ASTM C845, derive their expansion by ettringite formation from $C_4A_3\bar{S}$, CA, and C_3A, respectively. Hard-burnt CaO is the expansive agent in Type O cements.	1. Production of crack-resistant concrete by offsetting the tensile stress due to drying shrinkage 2. Production of chemically prestressed concrete elements 3. Demolition of old concrete without shattering
Rapid setting and hardening cements Regulated set cement (RSC) (or jet cement) Very high early strength cement (VHE) Rapid setting and hardending, High-iron cement (HIC) Ultra high early strength cement (UHE)	Most cements derive their rapid setting and hardening properties from compounds capable of forming a large amount of ettringite rapidly and C-S-H subsequently. For ettringite formation, the main source of aluminate ions is a calcium fluoroaluminate in RSC, while it is $C_4A_3\bar{S}$ in VHE and HIC. UHE is a high-C_3S portland cement containing ultra fine particles.	1. Emergency repairs, shotcreting 2. Fabrication of precast-prestressed concrete products without steam curing 3. Agglomeration of particulate matter in mining and metallurgical industries
Oil-well cements	Consist of portland cements with little or no C_3A; relatively coarser particles, and with or without a retarder present.	To allow time for placement of cement slurry, the thickening time at service temperature is retarded:
API Class A-C	Low-C_3A cements without any retarder; Class C is sulfate resistant	For well depths up to 6000 ft or 1830 m (80–170°F or 27–77°C)
API Class F	Low-C_3A cement with retarder	For well depths 10,000–16,000 ft or 3048–4877 m (230–320°F or 110–160°C)
API Class G, H	Essentially coarse-ground ASTM Types II and V portland cement, without retarder	For well temperatures (80–200°F or 27–93°C)
API Class J	Essentially βC_2S and pulverized silica sand	For well depths below 20,000 ft or 6100 m (>350°F or 177°C)
White and colored cements	Consist of portland cements with little or no iron present (Fss <1 percent). Colored cements are produced by adding suitable pigments to white cement.	Production of architectural concrete
Calcium aluminate cements	Consist essentially of pulverized clinker containing hydraulic calcium aluminates, such as $C_{12}A_7$, CA, and CA_2.	1. High-temperature concrete 2. Emergency repairs, especially in cold weather

3.12 Required tests for portland cement

There are chemical and physical test requirements for specifying portland cement. The chemical requirements of portland cement are given in ASTM C 150 **(see Table 3.9 on page 45 of Reference #1)**. Physical test requirements are more important to us as civil engineers. **Read these tests in detail using Reference #3 (pages 15 – 21).**

Table 9 summarized the common tests required of portland cement. For chemical requirements **see the table on page 229 of "Reference #2"**.

Table 9. Physical requirements of portland cement

Requirement specified by ASTM C 150	Type I	Type II	Type III	Type V	Method of test
Fineness: minimum (m^2/kg)	280	280	None	280	ASTM Method C 204 covers determination of fineness of cements using Blaine Air Permeability Apparatus. Fineness is expressed in terms of specific surface of the cement.
Soundness: maximum, autoclave expansion (%)	0.8	0.8	0.8	0.8	ASTM Method C 151 covers determination of soundness of cements by measuring expansion of neat cement paste prisms cured normally for 24 h and subsequently at 2 MPa (295 psi) steam pressure in an autoclave for 3 h.
Time of setting					ASTM Method C 191 covers determination of setting time of cement pastes by Vicat apparatus. Initial setting time is obtained when the 1-mm needle is able to penetrate the 35-mm depth of a 40-mm-thick pat of the cement paste. Final setting time is obtained when a hollowed-out 5-mm needle does not sink visibly into the paste.
Initial set minimum (min)	45	45	45	45	
Final set maximum (min)	375	375	375	375	
Compressive strength: minimum [MPa (psi)]					ASTM Method C 109 covers determination of compressive strength of mortar cubes composed of 1 part cement, 0.485 part water, and 2.75 parts graded standard sand by weight.
1 day moist air	None	None	12.4 (1800)	None	
1 day moist air +2 days water	12.4 (1800)	10.3* (1500)	24.1 (3500)	8.3 (1200)	
1 day moist air +6 days water	19.3 (2800)	17.2* (2500)	None	15.2 (2200)	
1 day moist air +27 days water	None†	None†	None	20.7 (3000)	

*The 3-day and the 7-day minimum compressive strength shall be 6.0 MPa (1000 psi) and 11.7 MPa (1700 psi), respectively, when the optional heat of hydration or the chemical limits on the sum of C_3S and C_3A are specified.

†When specifically requested, minimum 28-day strength values for Types I and II cements shall be 27.6 MPa (4000 psi).

3.13 The setting of cement paste

- Term setting is used to describe the stiffening of the cement paste
- Setting refers to a change from a fluid to a rigid state. On adding enough amount of water to cement, a paste is formed, which gradually becomes less plastic and finally becomes stiff and hard.
- When the paste has lost its plasticity and becomes rigid enough to resist a defined load, then the paste is said to have set, the setting period has been divided into two groups known as an initial set and final set.
- The initial set occurs when the paste begins to stiffen considerably.
- The final set occurs when the paste has hardened to the point at which it can sustain some load.
- The initial setting time must not be too soon and the final setting time must not be too late.

Chapter 4: aggregate

4.1 General introduction

Aggregate is relatively inexpensive and does not enter into complex chemical reactions with water; it has been customary, therefore, to treat it as an inert filler in concrete. However, due to increasing awareness of the role played by aggregates in determining many important properties of concrete, the traditional view of the aggregate as an inert filler is being seriously questioned. Aggregate characteristics that are significant for making concrete include porosity, grading or size distribution, moisture absorption, shape and surface texture, crushing strength, elastic modulus, and the type of deleterious substances present.

4.2 General classification

Classification of aggregates according to particle size, bulk density, or source has given rise to a special nomenclature, which should be clearly understood. For instance, the term *coarse aggregate* is used to describe particles larger than 4.75 mm (retained on No. 4 sieve), and the term *fine aggregate* is used for particles smaller than 4.75 mm.

Typically *fine aggregates* contain particles in the size range 75 µm (No. 200 sieve) to 4.75 mm, and *coarse aggregates* from 4.75 to about 50 mm, except for mass concrete that may contain particles up to 150 mm.

Most natural mineral aggregates, such as sand and gravel, have a bulk density of 1520 to 1680 kg/m^3 and produce normal-weight concrete with approximately 2400 kg/m^3 unit weight. For special needs, aggregates with lighter or heavier density can be used to make correspondingly lightweight and heavyweight concretes. Generally, the aggregates with bulk densities less than 1120 kg/m^3 are called lightweight and those weighing more than 2080 kg/m^3 are called heavyweight.

For the most part, concrete aggregates are comprised of sand, gravel, and crushed rock derived from natural sources.

4.3 Common aggregates for concrete

- Sand: it is typically used as a fine aggregate in the concrete industry. It is also called river sand.
- Gravel: coarse aggregate that occurs naturally.
- Crushed aggregates: it is obtained from the crushing of rocks such as mountains.
- Recycled concrete aggregate: it has been used frequently in the last decade in concrete production, especially in nonstructural concrete. It is obtained mainly from the construction and demolition of concrete wastes.

Figure 6. Types of aggregates

4.4 Classification of aggregate based on unit weight

- Normal weight aggregate: unit weight 1520 – 1680 kg/m^3. This type of aggregates is used to produce normal weight concrete.
- Lightweight aggregate: unit weight ≤ 1120 kg/m^3. This type of aggregates is used to produce lightweight concrete (decks of long-span bridges and construction of partition walls and panel walls in framed structures.
- Heavyweight aggregate: unit weight ≥ 2089 kg/m^3. This type of aggregates is used to produce heavyweight concrete (radiation shielding, safe rooms, blast resistance).

4.5 Shape and surface texture of aggregate

The shape of aggregate is an important characteristic, it affects the workability of concrete and the bond between cement paste and aggregates. The classification of particles based on shape is:

- Round shape
- Irregular shape
- Angular shape
- Flaky shape

The surface texture of aggregate particles can significantly affect the bond between cement paste and aggregate particles and consequently influence the strength of concrete.

Read pages 43 – 45 of reference #3 in detail.

4.6 Mechanical properties of aggregates

Mechanical properties of aggregate can affect the properties of concrete; therefore, it is important to have a look at some mechanical properties of aggregates. These mechanical properties include; bond, strength; toughness; hardness

Read pages 46 – 49 of reference #3 in detail

4.7 Physical properties of aggregates

The most important physical properties of aggregates are density, specific gravity, porosity, absorption, and moisture content. Specific gravity is a very important property that we are going to use in the mixture proportioning design.

Read pages 49 – 55 of reference #3 in detail.

4.8 Deleterious materials in aggregates

Aggregates should be free be from:

- Organic material such as vegetable matter.
- Clay and fine material.
- Unsound particles such as coal and wood.
- Salt and alkali reaction.

This material may interfere with the process of hydration and prevent the bonding of aggregate with cement paste.

4.9 Particle size distribution

The particle size distribution or grading of an aggregate supply is an important characteristic because it determines the requirements for workable concrete. well-graded aggregates will minimize the cement content in the mixture and therefore, reduce the cost of the concrete.

4.10 Sieve analysis

The grading of an aggregate supply is determined by a sieve analysis. The sieve sizes for coarse and fine aggregates are summarized in **Table 10**. The standard sieve designation is based on the nominal opening in millimeters and micrometers.

4.11 Maximum aggregate size

Per ASTM C 125, the maximum aggregate size of coarse aggregate is the smallest sieve size opening through which the entire sample passes. In practice, it is considered that of only a small amount of aggregate is retained on a sieve, it will not significantly affect the properties of concrete. Thus, it is usual to use a nominal maximum size, which is the smallest sieve opening through which the entire sample is permitted to pass, but need not do so. A percentage (5 – 10%)

of the sample weight may be retained on this sieve. ASTM grading requirements are based on nominal maximum size **(read pages 126 and 127 of reference #1).**

Table 10. Common sieve sizes used based on ASTM

Aggregate type	ASTM sieve designation	Alternative	Nominal size of sieve opening
Coarse aggregate	75 mm	3	3 in
	63 mm	$2\frac{1}{2}$	2.5 in
	50 mm	2	2 in
	37.5 mm	$1\frac{1}{2}$	1.5 in
	25 mm	1	1 in
	19 mm	$\frac{3}{4}$	0.75 in
	12.5 mm	$\frac{1}{2}$	0.5 in
	9.5 mm	$\frac{3}{8}$	0.375 in
	4.75 mm	No. 4	0.187 in
	2.36 mm	No. 8	0.0937 in
Fine aggregate	9.5 mm	$\frac{3}{8}$	0.375 in
	4.75 mm	No. 4	0.187 in
	2.36 mm	No. 8	0.0937 in
	1.18	No. 16	0.0469 in
	600 µm	No. 30	0.0234 in
	300 µm	No. 50	0.0124 in
	150 µm	No. 100	0.0059 in
	75 µm	No. 200	0.00295 in

Note: mm = millimeter; µm = micrometer; in = inches.

4.12 Grading requirements

ASTM C 33 specifies grading requirements for fine and coarse aggregates. **Table 11** shows the requirements for fine aggregate. Typically, these requirements are drawn using a reverse logarithmic scale. However, normal scale presentation also works perfectly fine. On the other hand, ASTM C 136 explains the method for performing the sieve analysis of the aggregate.

Table 11. Fine aggregate grading requirements

Sieve size	Percent passing
9.5 mm	100
4.75 mm	95 – 100
2.36 mm	80 – 100
1.18 mm	50 – 85
600 µm (0.6mm)	25 – 60
300 µm (0.3 mm)	5 – 30
150 µm (0.15 mm)	0 – 10
75 µm (0.075 mm)	0 – 3

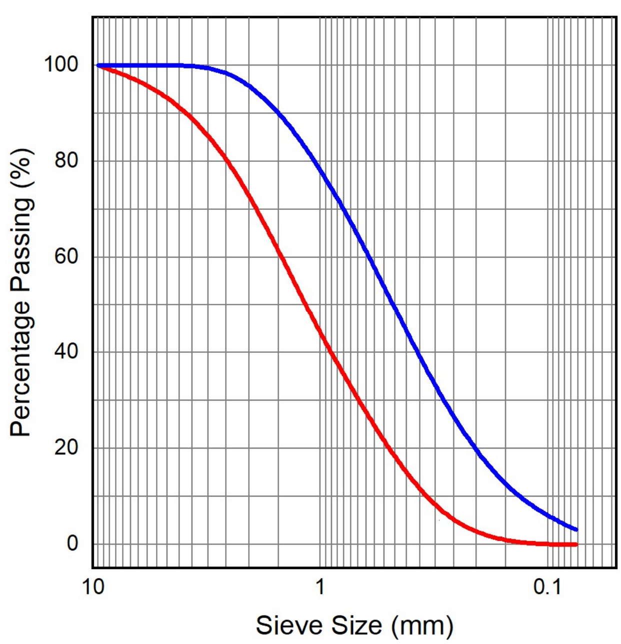


Figure 7. Fine aggregate requirements – ASTM C 33

In the case of coarse aggregates, the grading requirements depend on the nominal maximum aggregate size of aggregate **(see Table 3 of the ASTM C 33)**. Let us take an example from the mentioned table; consider the nominal size of coarse ranges from 9.5 mm – 25 mm as shown in **Table 12** below.

Table 12. Coarse aggregate grading requirements of 9.5 mm – 25 mm

Sieve size	Percent passing
37.5 mm	100
25 mm	90 – 100
19 mm	40 – 85
12.5 mm	10 – 40
9.5 mm	0 – 15
4.75 mm	0 – 5

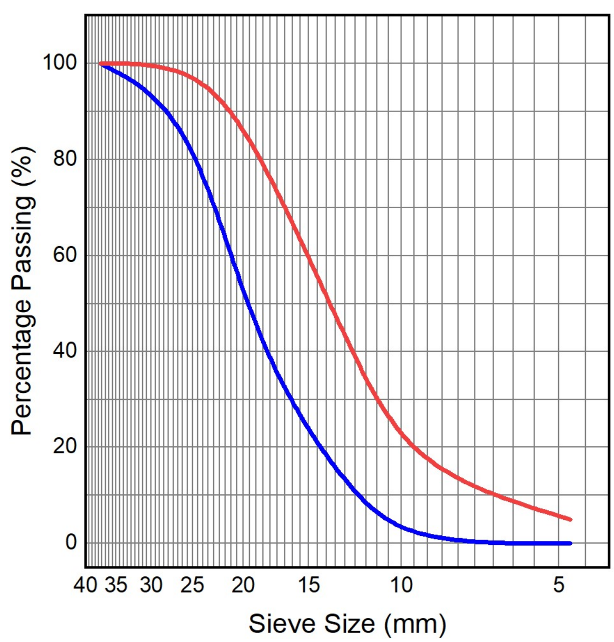


Figure 8. Coarse aggregate requirements – ASTM C 33

4.13 Fineness modulus (FM)

It is used to describe the grading curve of an aggregate. It is defined as:

$$FM = \frac{\sum(\text{cumulative percent retained on standard sieves})}{100}$$

Where the standard sieves are 150 µm (No. 100), 300 µm (No. 50), 600 µm (No. 30), 1.18 mm (No. 16), 2.36 mm (No. 8), 4.75 mm (No. 4), 9.5 mm, 19 mm, 37.5 mm, and larger, increasing in the size ratio 2 to 1.

The fineness modulus is usually calculated for the fine aggregate; however, it can be calculated for coarse aggregate as well, based on the assumption that 100% is retained on each of the sieves from 1.18 mm (No. 16) to 150 µm (No. 100). The fineness modulus of coarse aggregate then becomes:

$$FM = \frac{\sum\begin{pmatrix}\text{cumulative percent retained on standard sieves,}\\ \text{including 2.36 mm} + 400\end{pmatrix}}{100}$$

The fineness modulus of fine aggregate should lie between 2.3 and 3.1. A small number indicates a fine grading, while a larger number indicates a coarse material. The fineness modulus of fine aggregate is required for mixture proportioning as we can see later in the mix-design topic.

4.14 Grading of aggregate – example (calculation)

A grading analysis of fine and coarse aggregates was performed according to the ASTM C 136 and the following information was reported. Based on the given data, do the following.

- Calculate the fineness modulus of fine and coarse aggregates; total weights are 500 g and 1000 g, respectively for fine and coarse aggregates.
- Draw the grading curves for both fine and coarse aggregates.
- Find the maximum nominal size of coarse aggregate

- State whether the fine aggregate meets the requirements of ASTM C 33.
- D_{30} and D_{60}.
- Note: you can use ***Excel*** to simplify the calculations (you will see that during the lecture!)

Fine aggregate	
Sieve size	**Mass retained (g)**
4.75 mm	9
2.36 mm	46
1.18 mm	97
600 µm (0.6mm)	99
300 µm (0.3 mm)	120
150 µm (0.15 mm)	91
Sample weight	500

Coarse aggregate	
Sieve size	**Mass retained (g)**
75 mm	0
37.5 mm	42
19 mm	391
9.5 mm	350
4.75 mm	180
2.36 mm	20
Sample weight	1000

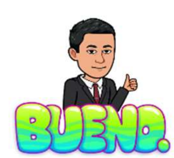
Solution

Fine aggregate Analysis					
Sieve size	**Mass retained (g)**	**Percent retained**	**Cumulative mass retained**	**Cumulative percent retained**	**Percent passing**
4.75 mm	9	2	9	2	98
2.36 mm	46	9	55	11	89
1.18 mm	97	19	152	30	70
600 μm (0.6mm)	99	20	251	50	50
300 μm (0.3 mm)	120	24	371	74	26
150 μm (0.15 mm)	91	18	462	92	8
Pan	38	8	500		
Sample weight	500				

$$\text{FM} = \frac{\sum(2+11+30+50+74+92)}{100} = 2.6$$

Coarse aggregate Analysis					
Sieve size	**Mass retained (g)**	**Percent retained**	**Cumulative mass retained**	**Cumulative percent retained**	**Percent passing**
75 mm	0	0	0	0	100
37.5 mm	42	4	42	4	96
19 mm	391	39	433	43	57
9.5 mm	350	35	783	78	22
4.75 mm	180	18	963	96	4
2.36 mm	20	2	983	98	2
Pan	17	2	1000		
Sample weight	1000				

$$\text{FM} = \frac{\sum(0+4+43+78+96+98+400)}{100} = 7.2$$



Nominal maximum size = __________ will find it during the lecture.

Checking the requirement of fine aggregate according to ASTM, D_{30}, and D_{60} will do it during the lecture as well, how does that sound to you?

Chapter 5: admixtures

5.1 General introduction

The recognition that properties of concrete, in both the fresh and hardened states, can be modified by adding certain materials to concrete mixtures has been responsible for the large growth of the concrete admixtures industry during the last 50 years. Hundreds of products are being marketed today. In some countries, it is not uncommon that 70 to 80 percent of all concrete produced contains one or more admixtures. Therefore, construction engineers should have some knowledge of the advantages and limitations of commonly used admixtures.

5.2 Significance

ASTM C 125 defines an admixture as a material other than water, aggregates, hydraulic cements, and fiber reinforcement that is used as an ingredient of concrete or mortar and added to the batch immediately before or during mixing. American Concrete Institute (ACI) Committee 212 lists 20 important purposes for which admixtures are used, for example, to increase the plasticity of concrete without increasing the water content, to reduce bleeding and segregation, to retard or accelerate the time of set, to accelerate the rates of strength development at early ages, to reduce the rate of heat evolution, and to increase the durability of concrete to specific exposure conditions.

Admixtures vary widely in chemical composition. Many perform more than one function, therefore, it is difficult to classify them according to their functions. In general, admixtures can be divided into major categories; chemical and mineral admixtures.

5.3 Chemical admixtures

ASTM C 494 covers materials for use as chemical admixtures to be added to hydraulic-cement concrete mixtures in the field for the purpose or purposes indicated for the eight types as follows:

- ***Type A: Water reducing admixtures*** – an admixture that reduces the quantity of mixing water required to produce concrete of a given consistency.

- ***Type B: Retarding admixtures*** – an admixture that retards the setting of concrete.
- ***Type C: Accelerators admixtures*** – an admixture that accelerates the setting and early strength development of concrete.
- ***Type D: Water reducer and retarding admixtures*** – an admixture that reduces the quantity of mixing water required to produce concrete of a given consistency and retards the setting of concrete
- ***Type E: Water-reducing and accelerating admixtures*** – an admixture that reduces the quantity of mixing water required to produce concrete of a given consistency and accelerates the setting and early strength development of concrete.
- ***Type F: Water-reducing, high range admixtures*** – an admixture that reduces the quantity of mixing water required to produce concrete of a given consistency.
- ***Type G: Water-reducing, high range, and retarding*** – an admixture that reduces the quantity of mixing water required to produce concrete of a given consistency and retards the setting of concrete admixtures.
- ***Type S: Specific performance admixtures*** – an admixture that provides the desired performance characteristic(s) other than reducing water content, or changing the time of setting of concrete, or both, without any adverse effects on fresh, hardened, and durability properties of concrete as specified herein, excluding admixtures that are used primarily in the manufacture of dry-cast concrete products.

Other specific performance characteristics include, but are not limited to, shrinkage reduction, mitigation of alkali-silica reaction, and viscosity modification. Admixtures used for the purposes of reducing water content or changing the time of setting of concrete are classified within the Type A through Type G grouping.

There is another type of chemical admixture called air-entraining. This type of admixture is discussed in the ASTM C 260.

The most important application of air-entraining admixtures is for concrete mixtures designed to resist freezing and thawing cycles. A side effect of entrained air is the improved workability of concrete mixtures, particularly those containing less cement and water, rough-textured aggregates, or lightweight aggregates. Air entrainment is, therefore, commonly used in making mass concrete and lightweight concrete mixtures. Note, because air-entraining surfactants render the cement particles hydrophobic, any overdose of the admixture would cause an excessive delay in cement hydration. Also, air-entrained mixtures depending on the amount of entrained air suffer a corresponding strength loss.

Famous companies that manufacture this type of admixtures are ***GCP*** and ***Sika***.

https://gcpat.com/en

5.4 Mineral admixtures

Mineral admixtures are finely divided siliceous materials that are added to concrete in relatively large amounts, generally, in the range of 20 to 70 percent by mass of the total cementitious material. Although natural pozzolans in the raw state or after thermal activation are still being used in some parts of the world, due to economic and environmental considerations many industrial by-products have become the primary source of mineral admixtures in concrete.

Power plants using coal as fuel, and metallurgical furnaces producing cast iron, silicon metal, and ferrosilicon alloys are the major sources of by-products being produced at the rate of millions of tons every year in many countries. Dumping of these by-products into landfills and streams amounts to a waste of the material and causes serious environmental pollution. Disposal as concrete aggregate or for road-base construction is a low-value use that does not utilize the pozzolanic and cementitious potential of these materials. With proper quality control, large amounts of many industrial by-products can be incorporated into concrete, either in the form of blended portland cement or as mineral admixtures. Whenever a pozzolanic and/or cementitious by-product can be used as a partial replacement for portland cement in concrete, it represents significant energy and cost savings.

5.5 Classification

Some mineral admixtures are pozzolanic (e.g., low-calcium fly ash), some are cementitious (e.g., granulated iron blast-furnace slag), whereas others are both cementitious and pozzolanic (e.g., high-calcium fly ash). Take a look at Table 8-6 on page 298 of reference #3.

For the purposes of a detailed description of the important mineral admixtures given below, the materials are divided into two groups:

- ***Natural materials.*** Those materials have been processed for the sole purpose of producing a pozzolan. Processing usually involves crushing, grinding, and size separation; in some cases, it may also involve thermal activation.

- ***By-product materials.*** Those materials are not the primary products of the industry producing them. Industrial by-products may or may not require any processing (e.g., drying and pulverization) before use as mineral admixtures.

5.6 Natural pozzolanic materials

Except diatomaceous earth, all natural pozzolans are derived from volcanic rocks and minerals. During an explosive volcanic eruption, quick cooling of the magma that is composed mainly of aluminosilicates results in the formation of glass or vitreous phases with a disordered structure.
It is difficult to classify natural pozzolans because the materials seldom contain only one reactive constituent. However, based on the principal reactive constituent present, a classification can be made into volcanic glasses, volcanic tuffs, calcined clays or shales, and diatomaceous earths.

5.7 By-product materials

Countries like China, India, the United States, Russia, Germany, South Africa, and the United Kingdom, are among the biggest producers of coal fly ash which, at the current rate of production, some 500 million tons a year, constitutes the largest industrial waste product in the world.
Norway is the principal producer of silica fume, while granulated blast-furnace slag is available in many countries. In addition to these materials, China, India, and other Asian countries have the potential for producing large amounts of rice husk ash. The production and properties of important by-product materials are described below:

- ***Fly ash (FA):*** there are two major types of fly ash; class C and class F. Fly ash are produced by coal-fired electric and steam generating plants.
- ***Iron blast-furnace slag:*** by-product from iron production in blast furnaces.
- ***Silica fume:*** also known by other names such as volatilized silica, microsilica, or condensed silica fume, is a by-product of the induction arc furnaces in the silicon metal and ferrosilicon alloy industries.
- ***Rice husk ash:*** also called rice hulls are the shells produced during the dehusking operation of paddy rice.

5.8 Applications

- ***Workability improvement:***
  - ✓ It is well known that the incorporation of finely divided particles generally improves workability by reducing the size and volume of voids.
  - ✓ Investigations have shown that by substituting 30 percent of the cement with fly ash, 7 percent less water was required than the control concrete mixture of equal workability.
  - ✓ On the other hand, the use of silica fume and rice husk increases the water requirement of a concrete mixture.
- ***Durability enhancement:***
  - ✓ Fly ash and slag reduce the heat of hydration and therefore they enhance the durability of concrete by minimizing the development of thermal cracks. This is because, under normal conditions, these admixtures do not react to a significant degree for several days. As a rule of thumb, the total heat of hydration produced by the pozzolanic reactions involving mineral admixtures is considered to be half as much as the average heat produced by the hydration of portland cement.
  - ✓ Mineral admixtures reduce the permeability of concrete by causing pores refinement.
  - ✓ Mineral admixtures are excellent for improving the durability of concrete to chemical attacks such as sulfates.
- ***Production of high-strength and high-performance concrete:***
  - ✓ Almost all high-strength concrete nowadays contains mineral admixtures, especially silica fume.
- ***Eco-friendly and cost-effective:***
  - ✓ Since most of the mineral admixtures are by-product materials, they tend to reduce the cost of concrete mixture and minimize the cement content.

Chapter 6: quality of water for mixing and curing

6.1 General introduction

Mixing water may contain impurities. These impurities may interfere with the setting of concrete, affect the strength, and may lead to the corrosion of the reinforcement. For these reasons, the suitability of water for *mixing* and *curing* should be considered.

6.2 Mixing water

In many cases, the quality of mixing water is covered by a clause saying that the water should be fit for drinking.

Such water very rarely contains dissolved solids over 2000 parts per million (ppm). The criterion of potability of water is not absolute; drinking water may be unsuitable as mixing water when the water has a high concentration of sodium or potassium and there is a danger of alkali-aggregate reaction.

While the use of potable water is generally safe, water not suitable for drinking may often also be satisfactorily used in making concrete. As a rule, any water with a pH (degree of acidity) of 6.0 to 8.0 which does not taste saline or brackish is suitable for use. On the other hand, dark color or smell do not necessarily mean that deleterious substances are present.

The presence of algae in mixing water results in air entrainment with a consequent loss of strength. On the other hand, the hardness of water does not affect the efficiency of air-entraining admixtures.

Sometimes it may be difficult to obtain sufficient quantities of fresh water and only brackish water is available, which contains chlorides and sulfates. ASTM C 1602 states the limits of such compounds based on the intended use of concrete. See **Table 13** for limits of these compounds.

Table 13. Optimal chemical limits for mixing water

	Limits
Chloride, ppm: • Prestress concrete, bridge decks, or otherwise designated. • Other reinforced concrete in moist environments or containing aluminum or dissimilar metals or with stay-in-place galvanized metal forms.	500
Sulfate ppm	3000
Alkaline as (Na_2O + 0.658 K_2O), ppm	600
Total solids by mass, ppm	50,000

Occasionally, the use of seawater as mixing water has to be considered. Seawater had typically a total salinity of about 3.5% (78% of the dissolved solids being NaCl and 15% $MgCl_2$and $MgSO_4$). Such water leads to a slightly higher early strength but lower long-term strength; the loss of strength is usually less than 15% and can be tolerated. Seawater or any water that contains large quantities of chlorides tends to cause persistent dampness and efflorescences. Such water should not be used where the appearance of the concrete is of importance or where a plaster finish is to be applied.

In the case of reinforced concrete, seawater increases the risk of corrosion of the reinforcement, especially in tropical countries. Corrosion has been observed in structures exposed to humid air when the cover of reinforcement is inadequate or the concrete is not sufficiently dense so that corrosive action of residual salts in the presence of moisture can take place. However, when the reinforced concrete is permanently in water, the use of seawater in mixing seems to have no ill effects. In practice, it is considered inadvisable to use seawater for mixing.

6.3 Curing water

Generally, water satisfactory for mixing is also suitable for curing purposes.

6.4 Testing of water

Potable water needs not be tested prior to its use in concrete. ASTM C 94 and the ACI Building Code require tests when the water is not potable or questionable.

- In both standards, water is evaluated based on its effect on the strength of mortar cubes. In addition, ASTM C 94 limits the effect on setting time to not more than one earlier nor more than one-and-half hours later than a control specimen made with potable water.
- Mortar specimens made with questionable water must produce a 7-day compressive strength equal to at least 90% of the strength obtained with control specimens made with potable water according to the ASTM C 94.
- ACI Building Code requires the mortar cubes made with questionable water to achieve compressive strength at least 90% of the strength obtained with control specimens made with potable water at 7 and 28 days.

Chapter 7: fresh concrete

7.1 General introduction

The properties of fresh concrete are important primarily because they affect the choice of equipment needed for handling and consolidation and because they may affect the properties of the hardened properties.

For hardened concrete to be of acceptable quality for a given job, the fresh concrete must be capable of satisfying the following requirements:

- It must be easily mixed and transported.
- It must be uniform throughout a given batch and between batches.
- It should have flow properties. It must have the ability to be compacted fully without an excessive amount of energy being applied.
- It must not segregate during placing and consolidation.
- It must be capable of being finished properly.

Figure 9. Fresh concrete

7.2 Workability

Workability is defined as the amount of useful internal work necessary to full compaction. The useful internal work is a physical property of concrete alone and is the work or energy to overcome the internal friction between the individual particles in the concrete. In practice, additional energy is required to overcome the surface friction between concrete the formwork, or the reinforcement. Thus in practice, it is difficult to measure the workability as defined.

Another term used to describe the state of fresh concrete is consistency, which is the firmness of form of a substance or the ease with which it will be flow.

Because the strength is of concrete is adversely affected by the presence of voids in the compacted mass, it is vital to achieving the maximum possible density. This requires sufficient workability for virtually full compaction to be possible using a reasonable amount of work under given conditions. **Figure 10** demonstrates the increase in compressive with an increase in density. It is obvious that the presence of voids in concrete reduces the density and greatly reduces strength; 5% of voids can lower the strength by as much as 30%.

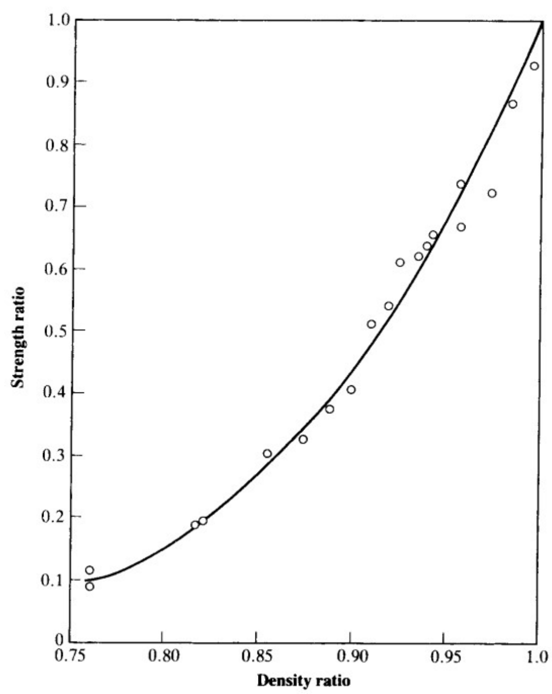


Figure 10. Relation between strength ratio and density ratio

7.3 Factors affecting workability

The workability of concrete is affected by a number of factors. The factors are listed below.

- ***Water content of the mixture***

  The most important factor governing the workability of concrete is the water content. Increasing the amount of water will increase the ease with which concrete flows and can be compacted. However, increasing the water reduces the strength and may lead to segregation and bleeding. In general, any collection of particles requires a certain amount of water to achieve plasticity so that it can be worked. First, it must be enough water to absorb on the particle surfaces. Then, water must fill the spaces between particles. Finer particles, which have a higher specific surface area, require more water. On the other hand, without some minimum quantity of fine materials, the concrete cannot exhibit plasticity. Thus the water content cannot be considered in isolation from the aggregate grading. Before discussing other factors, we need to learn about the term called water to cement ratio (***w/c***).

  w/c: the ratio of the weight of water to the weight of cement used in a concrete mixture. It affects the strength and overall performance of concrete.

- ***Influence of aggregates***

  When considering the effect of aggregates on workability, two factors are important; the amount of aggregate and the relative proportions of fine and coarse aggregates. For a constant *w/c*, an increase in the aggregate/cement ratio will decrease the workability. Also, more cement is needed when finer aggregate is used. A rather high ratio of volumes of coarse aggregate to fine aggregate can result in segregation low workability so that the mixture is harsh and not easily finished.

  The shape and texture of aggregate particles can also affect workability. As a general role, the more spherical the particles, the more workable is the resulting concrete will be. The porosity of the aggregate may affect the workability since it affects the amount of water that is absorbed by the aggregates. Therefore, the aggregate needs to achieve the surface dry condition (SSD) before being used in concrete or the additional water needs to be counted.

SSD: All pores filled with water, but no film of water on the surface.

- ***Time and temperature***

There is considerable evidence that as the ambient temperature increases, the workability decreases as shown in **Figure 11**.

Freshly mixed concrete stiffens with time. Some of the mixing water is absorbed by the aggregate, some is lost by the evaporation (particularly if the concrete is exposed to the sun and wind, and some is taken by the initial chemical reactions. The stiffening of concrete is effectively measured by a loss of workability with time which is known as slump loss.

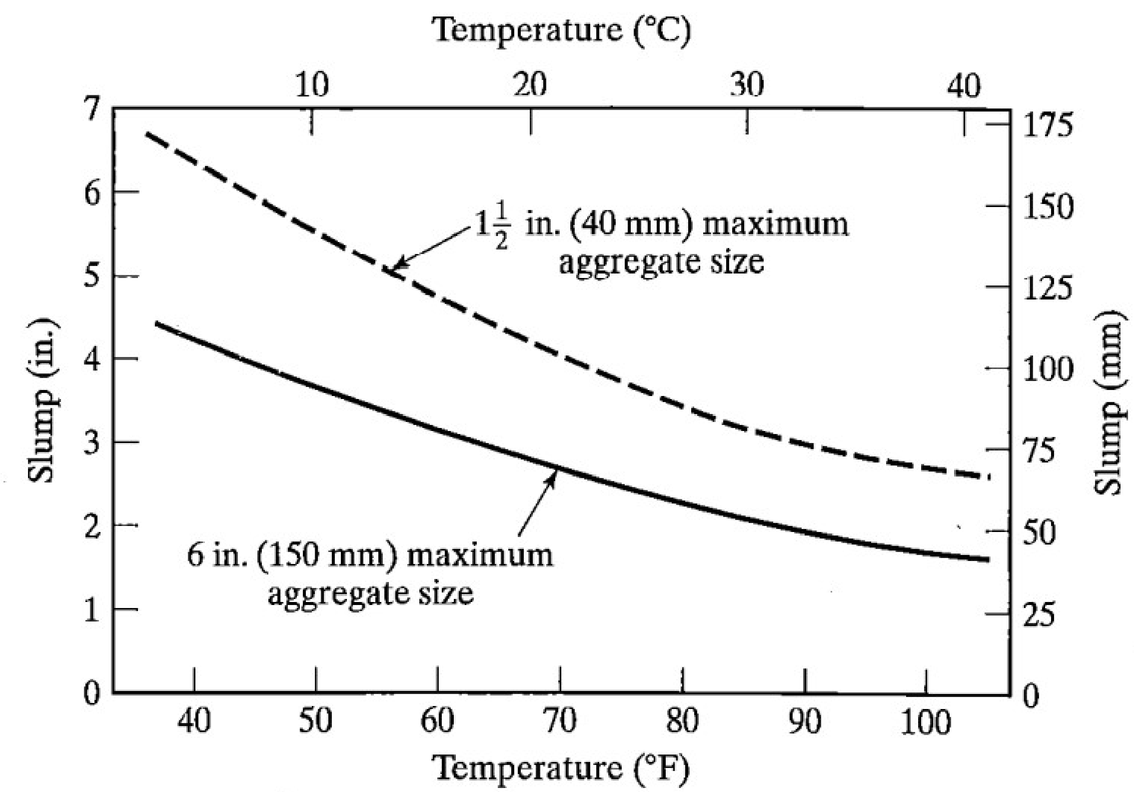


Figure 11. Relationship between slump and temperature of concrete

- ***Cement characteristics***

  The cement characteristics are much less important in determining workability than are the aggregate properties. However, the increased fineness of Type III (high early strength) reduces workability at a given w/c ratio due to the high surface area of this type of cement.

- ***Admixtures***

  The type of admixtures can affect the workability of concrete. for example, mineral admixtures such as fly ash improve the workability of the concrete. Air-entraining, water-reducing, and retarding admixtures improve the workability of concrete as well.

7.4 Segregation and bleeding

Segregation refers to a separation of the components of fresh concrete, resulting in a non-uniform mixture. In general, this means some separation of the coarse aggregate from the mortar. This separation can be of two types:

I. The setting of heavy particles to the bottom of the fresh concrete.

II. The separation of the coarse aggregates from the body of the concrete is due to improper placing or vibration.

The factors that contribute to increased segregation have been listed as follows:

I. Large maximum particles (> 25 mm).

II. A high specific gravity of the coarse aggregate compared to that of fine aggregate.

III. A decreased amount of fines (sand or cement).

IV. Mixtures that are either too dry or too wet.

Finely graded mineral admixtures and air-entering agents can reduce the segregation of fresh concrete.

Bleeding may be defined as the upward movement of water after the concrete has been consolidated, but before it has set. Bleeding can be reduced in a number of ways:

I. Increasing cement fineness or using mineral admixtures as a partial replacement of cement.

II. Increasing the rate of hydration. **How can we do that guys????** 

III. Reducing the water content if this can be done while maintaining acceptable workability.

IV. Through air entrainment admixtures, which is very effective. Entraining air will improve the mutual adhesion between cement and aggregate thus reducing segregation, further the air voids do not allow the heavier particles to settle down thus reducing bleeding considerably.