2.1 Introduction

Concrete is used in constructing buildings, harbors, runways, water structures, power plants, pressure vessels. In order to use concrete satisfactorily, the designer, the site engineer, and the contractor need to be familiar with construction materials and their technologies.

There are two common structural materials used in construction: concrete and steel. They sometimes complement one another, and sometimes compete with one another.

The man on the site needs to know more about concrete than about steel. Steel is manufactured under controlled conditions in a sophisticated plant. On a concrete building site, the situation is totally different. While the quality of cement is guaranteed, transporting, placing, compacting and curing of concrete greatly influence the final product. It is the competence of the contractor and the supplier which controls the actual quality of concrete in the finished structure.
2.2 Concrete

Concrete for reinforced concrete consists of aggregate particles bound together by a paste made from Portland cement and water. The paste fills the voids between the aggregate particles, and after the fresh concrete is placed, it hardens as a result of exothermic chemical reactions between cement and water to form a solid and durable structural material.

Although there are several types of ordinary Portland cements, most concrete for buildings is made from Type I ordinary cement.

In recent years, there has been a substantial increase in the use of other chemical additives for cement dispersion, acceleration or retardation of initial set, and improvement of workability. The so called Super-plasticizers are being used in many applications where high strength concrete with substantial slump is desired.

Aggregates are particles that form about three-fourths of the volume of finished concrete. According to their particle size, aggregates are classified as fine or coarse. Coarse aggregates consist of gravel or crushed rock particles not less than 5 mm in size. Fine aggregates consist of sand or pulverized rock particles usually less than 5 mm in size. Aggregates alone exhibit a linear stress-strain relationship and so does the hydrated cement paste. On the other hand, concrete exhibits a non-linear relationship due to presence of interfaces and the development of micro cracking at the interfaces under load, as indicated in Figure 2.1.
Mixing water should be clean and free of organic materials that react with the cement or the reinforcing bars in case of reinforced concrete. The quantity of water relative to that of the cement, called water-cement ratio, is the most important item in determining concrete strength. An increase in this ratio leads to a reduction in the compressive strength of concrete as shown in Figure 2.2.

It is important that concrete has workability adequate to assure its consolidation in the forms without excessive voids. This property is usually indirectly measured in the field by the slump test. The necessary slump may be small when vibrators are used to consolidate the concrete.
Proper curing of concrete requires that the water in the mix is not to be allowed to evaporate from the concrete until the concrete has gained the desired strength.

Figure 2.2: Relation between compressive strength and water-cement ratio of concrete

2.3 Mechanical Properties of Concrete

In this section, mechanical properties of concrete, including compressive strength, tensile strength, modulus of elasticity, shrinkage and creep will be briefly covered.

2.3.1 Concrete Compressive Strength

The compressive strength of concrete $f'_c$ is mainly affected by the water-cement ratio, degree of compaction, age, and temperature. It is determined through testing standard cylinders 15 cm in diameter and 30 cm in length in uniaxial compression at 28 days (ASTM C470). Test cubes 10 cm $\times$ 10 cm
× 10 cm are also tested in uniaxial compression at 28 days (BS 1881), shown in Figure 2.3.

The ACI Code is based on the concrete compressive strength as measured by a standard test cylinder. Designers have to pay attention to make the necessary transformation when concrete compressive strength is based on the cube test. The concrete compressive strength as measured by the standard cylinder test can be approximated by Eq. (2.1)

\[ f'_{c, \text{Cylinder}} = 0.80 \times f'_{c, \text{Cube}} \] (2.1)

According to ACI code 1.1.1 for structural concert, \( f'_{c} \) shall not be less than 17 MPa, and no maximum value of \( f'_{c} \) shall apply unless restricted by a specific code provision.

![Figure 2.3: Cube and cylinder test specimens](image)

### 2.3.2 Concrete Tensile Strength

The strength of concrete in tension is low compared to its compressive strength. Tests have shown that the tensile strength ranges from 8 to 15 percent of the compressive strength \( f'_{c} \).

Generally, the ratio of tensile strength to compressive strength is lower, the higher is the compressive strength as indicated in Figure 2.4. There are several factors which affect the relationship between the two strengths, the main one is being the method of testing the concrete in tension, the size of the specimen, the shape, surface texture of coarse aggregate, and the moisture condition of the concrete. The large difference between the tensile
and compressive strengths of concrete is attributed to the formation of fine cracks throughout the concrete.

Tensile strength of concrete is important in structures where cracks are not permitted, such as in the design of liquid containers.

### 2.3.2.1 Standard Tension Tests:

Three main tests are used to measure the tensile strength of concrete.

**A. The Direct Tension Test**

Direct tension tests are rarely used because of the problem of gripping the specimen and due to the secondary stresses developing at the ends of the specimens.

**B. The Split Cylinder Test (ASTM 496)**

In this test, a standard compression test cylinder 15 cm in diameter and 30 cm in length is placed on its side and loaded in compression along a diameter until splitting occurs along the vertical diameter as shown in Figure 2.5.

The splitting tensile strength $f_{ct}$ is given by
\[ f_{ct} = \frac{2P}{\pi ld} \quad (2.2) \]

where

\( P \) = maximum applied load

\( l \) = length of the cylinder

\( d \) = diameter of the cylinder

\[ \lambda = \text{modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength.} \]

According to ACI 8.6.1, \( \lambda = 0.85 \) for sand-lightweight concrete and \( \lambda = 0.75 \) for all-lightweight concrete, Linear interpolation between 0.75 and

\[ f_{ct} = 1.78 \lambda \sqrt{f_c'} \quad (2.3) \]

where

\( f_{c'} \) is given in kg/cm\(^2\).

\( \lambda \) = modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength.
0.85 shall be permitted, on the basis of volumetric fractions, when a portion of the lightweight fine aggregate is replaced with normal weight fine aggregate.

Linear interpolation between 0.85 and 1.0 shall be permitted, on the basis of volumetric fractions, for concrete containing normal weight fine aggregate and a blend of lightweight and normal weight coarse aggregates. For normal weight concrete, $\lambda = 1.0$.

C. The Modulus of Rupture Test (ASTM C78)

In this test, a plain concrete beam 15 cm by 15 cm in cross section and 75 cm in length is loaded to failure in bending at the third points of a 60 cm span as shown in Figure 2.6.

The modulus of rupture is given by

$$f_r = \frac{6M}{bh^2} \quad (2.4)$$

where

- $M$ = maximum bending moment
- $b$ = width of specimen
- $h$ = depth of specimen.
$ACI$ 9.5.2.3 gives an approximate value for $f_r$

$$f_r = 2 \, \lambda \sqrt{f_c'}$$

(2.5)

where $f_c'$ is given in $kg/cm^2$.

### 2.3.3 Modulus of Elasticity

The modulus of elasticity of concrete $E_c$ is defined as the ratio of normal stress to corresponding strain for compression stresses below proportional limit. Since the stress-strain diagram for concrete is nonlinear as evident in Figure 2.7, the slope of the curve is variable, making the determination of such modulus a tough task. The secant method is usually used to determine $E_c$, being the slope of the line drawn from a compressive stress of zero to a compressive stress of 0.45 $f_c'$.

According to $ACI$ 8.5.1 and for normal weight concrete

$$E_c = 15100 \sqrt{f_c'}$$

(2.6)

where $f_c'$ is given in $kg/cm^2$. 
2.3.4 Creep

Creep is defined as the long-term deformation caused by the application of loads for long periods of time, usually years. The total deformation is divided into two parts; the first is called instantaneous deformation occurring right after the application of loads, and the second which is time dependent is called creep. Long-term deformation increases at a slowing rate for a period of two to three years with maximum value recorded at a period of five years.

ACI 9.5.2.5 states that additional long-term deflection resulting from creep and shrinkage of members under bending is determined by multiplying the immediate deflection caused by the sustained load by a factor $\lambda_\Delta$ given by

$$\lambda_\Delta = \frac{\xi}{1 + 50 \rho'}$$  \hspace{1cm} (2.7)

where

$$\rho' = \frac{A'}{bd} \text{ is ratio of } A' \text{ to } bd$$
$A' = \text{cross sectional area of compression reinforcement}$

$b = \text{width of cross section}$

$d = \text{effective depth of cross section}$

$\xi = \text{time-dependent factor for sustained load}$

$\lambda_A = \text{multiplier for additional deflection due to long-term effects}$

The time dependent factors $\xi$ are given at different periods of time:

- 3 months --------------1.00
- 6 months --------------1.20
- 12 months --------------1.40
- 60 months --------------2.00

Creep can be reduced through using high-strength concrete, good curing of concrete, and using reinforcement on the compression side of the cross section as evident in Eq. (2.7). Multipliers for long-term deflection are also given in Figure 2.8.

![Figure 2.8: Long-term deflection multipliers](image)
2.3.5 Shrinkage

Shrinkage of concrete is defined as the reduction in volume of concrete due to loss of moisture. If the concrete member is not restrained, no stresses will be produced. On the other hand, stresses will be developed in case of restraining the concrete member in any form. Once the allowable tensile stresses are exceeded, tension cracking will take place.

Shrinkage can be reduced through using a low water-cement ratio, good curing of concrete, nonporous aggregates, shrinkage reinforcement, and expansion joints.

ACI 7.12.2.1 specifies that a minimum shrinkage and temperature reinforcement ratio of 0.0018 is to be used in one-way slabs perpendicular to the main reinforcement (for $f_y = 4200 \text{ kg/cm}^2$), 0.002 for $f_y = 2800 \text{ kg/cm}^2$, but not less than 0.0014.

2.4 Ultra-High Performance Concrete (UHPC)

Concrete with target strengths greater than 2000 kg/cm$^2$ has been developed for outstanding mechanical performance and shows a very promising future in construction applications. With the addition of fibers, UHPC shows very high compressive and tensile strength as well as high ductility when compared with conventional concrete and called Ultra High Performance Fiber Reinforced Concrete (UHPFRC).

In recent years; UHPFRC has been successfully applied to dam repair, bridge deck overlay, coupling beams in high-rise buildings and other specialized structures.

2.5 Light-Weight Concrete

Concrete lighter in weight than normal-weight concrete is used for thermal insulation and to reduce dead load. It is made using light-weight aggregates or foaming agents added to the mix.
2.6 Reinforcement

Steel and steel alloys are widely used as construction materials throughout the world. Steel is an iron-carbon alloy with the carbon content less than 2 %. Structural steel is an alloy with carbon content ranges from 0.80 % to 2 %. Cast iron contains more than 2 % of carbon, thus characterized by its hardness and brittleness. Steel has three main uses in construction; structural steel, forms, pans, and steel reinforcement.

The low tensile strength of plain concrete, a brittle material, results in limited structural applications since most structural elements carry loads that create tensile stresses of significant magnitude. The addition of high-strength ductile reinforcement that bonds strongly to concrete produces a tough ductile material capable of transmitting tension and suitable for constructing many types of structural elements, e.g., slabs, beams, and columns.

Most concrete members are reinforced with steel in the form of bars. Steel reinforcement imparts a great strength and toughness to concrete. Moreover, reinforcement reduces creep and minimizes the width of cracks.

2.6.1 Properties of Steel Reinforcement

Steel reinforcement in the form of longitudinal bars is used to resist tensile forces resulting from direct tension and/or flexure. Reinforcement is also used to resist stresses resulting from shear and/or torsion. In some cases, reinforcement is used to resist compressive stresses.

Reinforcement comes in two forms; round steel bars or welded wire fabric WWF. When bars have smooth surfaces, they are called plain, and when they have projections on their surfaces, they are called deformed. Round bars come in diameters ranging from 6 mm to 50 mm.

Reinforcement is to be free from mud, oil, or other nonmetallic coatings that decrease bond. Welded wire fabric is a prefabricated reinforcement
welded together to form rectangular or square mesh, usually used in slab or wall reinforcement.

Epoxy-coated reinforcing bars are used to minimize corrosion of reinforcement under severe environmental conditions, such as bridge decks and parking garages.

The most important mechanical property of steel reinforcement is the yield stress $f_y$. Mild steel has a well-defined yield stress on the stress-strain curve, while high strength steel does not have a well-defined yield stress as shown in Figure 2.9. For high strength steels, ACI 3.5.3.2 defines the yield stress as the stress corresponding to a strain of 0.0035. Grade 4200 kg/cm$^2$ (60 ksi) and 2800 kg/cm$^2$ (40 ksi) are the commonly used steel grades in our region. Currently Grade 5200 kg/cm$^2$ (75 ksi) is particularly used in high-rise buildings where it is used in combination with high strength concretes. Grade 4200 kg/cm$^2$ is the most commonly used main reinforcement since Grade 5200 kg/cm$^2$ is rather expensive. When crack widths are to be minimized through reducing reinforcement stresses, grade 2800 kg/cm$^2$ is to be preferred over grade 4200 kg/cm$^2$ and 5200 kg/cm$^2$.

The modulus of elasticity $E_s$ is defined as the slope of the stress-strain curve.

ACI 8.5.2 gives the modulus of elasticity for mild and high strength steels as

$$E_s = 2.0 \times 10^6$$  \hspace{1cm} (2.8)

where $E_s$ is given in kg/cm$^2$.

Table 2.1 shows weights and cross sectional areas of different bar sizes while Table 2.2 shows US bar sizes and their metric equivalence.
Figure 2.9: Stress-strain relation for steel reinforcement

Table 2.1: Properties of reinforcing bars

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<th>φ</th>
<th>Weight Kg/m</th>
<th>Cross – sectional area (cm²)</th>
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<tr>
<td></td>
<td></td>
<td>Number of bars</td>
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<td>mm</td>
<td>Kg/m</td>
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### Table 2.2: US bars and their metric equivalence

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<th>Metric Units</th>
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<td>Diameter (inch)</td>
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