SUBJECT: CONCRETE TECHNOLOGY

SUB CODE: 10CV42

Prepared by,

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UNIT – 1
INTRODUCTION

Definition:
Cement is defined in many ways as follows,
• Cement, any material that hardens and becomes strongly adhesive after application.
• Manufactured substance consisting of gypsum plaster, or Portland cement.
• Portland cement hardens and adheres after being mixed with water.

History of Cement:
• The term “Portland cement” was first used in 1824 by Joseph Aspdin, a British cement-maker, because of the resemblance between concrete made from his cement and Portland stone, which was commonly used in buildings in Britain.
• At that time cements were usually made in upright kilns where the raw materials were spread between layers of coke, which was then burnt.
• The first rotary kilns were introduced about 1880. Portland cement is now almost universally used for structural concrete.

Manufacturing Process:
• Main ingredients used in the manufacture of cement are:
  • Limestone
    – Calcium
  • Clay, shale
    – Silica/Alumina
  • Quarrying
    – Local resources necessary: no market
• Limestone (CaCO3) and Clay are two main raw materials used for manufacturing Portland cement clinker.
• Clays have various amount of SiO2 and Al2O3.
• In the manufacturing process of Portland cement, clinker consist essentially of
grinding the raw materials, mixing them in appropriate proportion, burning the raw material in a kiln at a temperature of 1400-1500°C until material partially fuses into balls known as **Clinker** and grinding cooled clinker together with a small amount of gypsum rock.

- The mixture of raw material is burned in a rotary kiln.

**THE KILN**

The heart of the cement plant

- Largest moving part of any machine.
- Inclined, rotates.
- Up to 50m long and 5m diam.
- Heated by fire jet
- The rotary kiln is along steel cylinder lined with refractory brick (length/diameter ~30). Modern kilns may reach 6m in diameter and over 180m in height with a production capacity exceeding 1000 tones a day.
- The kiln is inclined a few degrees from the horizontal (about 4 cm/m) and is rotated about its axis at a speed of about 60 to 150 revolution/hour.
- Pulverized coal or gas is used as the source of heat. The heat is supplied from the lower end of the kiln. The max. temperature near the lower end of the kiln is generally about 1400-1500 OC.
- The upper end of the kiln the temperature is around 150 OC.
- The mixture of the raw material is fed from the upper end of the kiln. This material move toward the lower end by effect of inclination and rotation of the kiln. Thus the materials are subjected to high temperature at lower end of the kiln.
- The materials that are introduced into the rotary kiln are subjected to several distinct process as they move downward.
- When the raw materials are fed into the kiln, drying of the material takes place, and any free water in the raw material is evaporated.
- Clay losses its water about 150 to 350 OC.
• Clay decompose at a range of 350 to 650 OC.
• Magnesite in raw material loss about 600 OC.
• The limestone losses its CO2 at about 900 OC.
• At 1250 to 1280 OC some liquid formation begins and compound formation start to takes place.
• Clinkering begins at about 1280OC. The liquid that forms during the burning process causes the charge to agglomerate into nodules of various size, usually 1 - 25 mm in diameter known as **Portland cement clinker**.
• All exhaust gases produced during the burning process of the materials leave the kiln through the stack

• The mixture of raw material is burned in a rotary kiln.

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Sketch of a rotary kiln for burning portland cement
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COOLING & GRINDING

• Rapid cool - glassy

• Grinding
  – Starts at golf ball size
  – ends about 2-80 microns, 300 m²/kg
  – depends on application

• Typical plant: 1 MT/y

• Portland cement is manufactured by inter grinding the portland cement clinker with some (3 to 6%) Gypsum rock.

QUANTITIES

• Worldwide: ~2 GT/y
  – China: 860 MT/y US: 100 MT/y
  – India: 200 MT/y UK: 12 MT/y

• CONCRETE: ~15 GT/y
  – cf. steel ~1 GT/y, wheat ~0.6 GT/y, rice ~0.4 GT/y
  – 2.5 T for each of us!
  – 2mm Earth surface

ECONOMIC IMPORTANCE

• Availability & price crucial to national development
  – Cement: 1-2% of total construction costs
  – Construction: 5-10% of GDP
  – Demand for cement is key economic indicator

APPLICATIONS

• Structural
  – Reinforced concrete

• Structuro-functional
  – bone/dental cements

• Functional
  – waste immobilisation, land remediation
• Sculptural
• Improbable

CONCRETE
Concrete is a mixture of Cement paste and aggregate
• Compression: up to 120 MPa
  – Comparable to Al
• Tension: <10 MPa
• Tension reinforcement
  – steel bars

Cement
(Chemical Composition and Hydration)
Oxide Composition of Portlant Cement
• Portland cement is composed of four major oxides: lime ( CaO ), silica ( SiO2 ),
alumina ( Al2O3 ), and iron ( Fe2O3 ).
• Also Portland cement contains small amount of magnesia ( MgO ), alkalies
(Na2O and K2O ), and sulfuric anhydrite ( SO3 ).

Bogue’s Compound Composition
• C3S = 4.07(CaO) - 7.6(SiO2) - 6.72(Al2O3) - 1.43(Fe2O3) - 2.85(SO3)
• C2S = 2.87(SiO2) - 0.75(3CaO.SiO2)
• C3A = 2.65(Al2O3) - 1.69(Fe2O3)
• C4AF = 3.04(Fe2O3)
Hydration of cement

- When Portland cement is mixed with water its chemical compound constituents undergo a series of chemical reactions that cause it to harden. This chemical reaction with water is called "hydration". Each one of these reactions occurs at a different time and rate. Together, the results of these reactions determine how Portland cement hardens and gains strength.

OPC hydration

- Hydration starts as soon as the cement and water are mixed.
- The rate of hydration and the heat liberated by the reaction of each compound is different.
- Each compound produces different products when it hydrates.
- Tricalcium silicate (C3S). Hydrates and hardens rapidly and is largely responsible for initial set and early strength. Portland cements with higher percentages of C3S will exhibit higher early strength.
- Tricalcium aluminate (C3A). Hydrates and hardens the quickest. Liberates a large amount of heat almost immediately and contributes somewhat to early strength. Gypsum is added to Portland cement to retard C3A hydration. Without gypsum, C3A hydration would cause Portland cement to set almost immediately after adding water.
- Dicalcium silicate (C2S). Hydrates and hardens slowly and is largely responsible for strength increases beyond one week.
- Tetracalcium aluminoferrite (C4AF). Hydrates rapidly but contributes very little to strength. Its use allows lower kiln temperatures in Portland cement manufacturing. Most Portland cement color effects are due to C4AF.

Reactions of Hydration

- \( 2\text{C3S} + 6\text{H} = \text{C3S2H3} + 3\text{Ca(OH)2} \)  
  \( (100 + 24 = 75 + 49) \)
- \( 2\text{C2S} + 4\text{H} = \text{C3S2H3} + \text{Ca(OH)2} \)  
  \( (100 + 21 = 99 + 22) \)
• \( C_3A + 6H = C_3AH_6 \)

\([C_3A + CaSO_4 \cdot 2H_2O = 3Cao. Al_2O_3. 3CaSO_4. 31H_2O]\)

Calcium Sulfoaluminate

**Heat of Hydration**

• The heat of hydration is the heat generated when water and Portland cement react. Heat of hydration is most influenced by the proportion of C3S and C3A in the cement, but is also influenced by water-cement ratio, fineness and curing temperature. As each one of these factors is increased, heat of hydration increases.

• For usual range of Portland cements, about one-half of the total heat is liberated between 1 and 3 days, about three-quarters in 7 days, and nearly 90 percent in 6 months.

• The heat of hydration depends on the chemical composition of cement

**Concrete The Extensively used material after water because of the following reasons**

_ Versatile
_ Pliable when mixed
_ Strong & Durable
_ Does not Rust or Rot
_ Does Not Need a Coating
_ Resists Fire
_ Almost Suitable for any Environmental Exposure Conditions
CEMENT

• Cement, any material that hardens and becomes strongly adhesive after application.

• Manufactured substance consisting of gypsum plaster, or Portland cement

• Portland cement hardens and adheres after being mixed with water.

HISTORY OF CEMENT:

• The term “Portland cement” was first used in 1824 by Joseph Aspdin, a British cement-maker, because of the resemblance between concrete made from his cement and Portland stone, which was commonly used in building in Britain.

• The first modern Portland cement, made from lime and clay materials heated until they formed clinkers was produced by Isaac Charles Johnson in Britain in 1845.

• At that time cements were usually made in upright kilns where the raw materials were spread between layers of coke, which was then burnt.

• The first rotary kilns were introduced about 1880. Portland cement is now almost universally used for structural concrete.
HOW IS IT MADE?

- Limestone for calcium and Clay or shale for Silica/Alumina is used as raw materials.
- The manufacturing process of Portland cement clinker consist essentially of grinding the raw materials, mixing them in appropriate proportion, burning the raw material in a kiln at a temperature of 1400-1500 °C until material partially fuses into balls known as clinker and grinding to cooled clinker together with a small amount of gypsum rock.
- The mixture of raw material is burned in a rotary kiln.

The Kiln:

- The heart of the cement plant
  - Largest moving part of any machine
  - Inclined, rotates
  - Up to 50m long and 5m diam. Heated by fire jet
- The rotary kiln is along steel cylinder lined with refractory brick (length/diameter ~30). Modern kilns may reach 6m in diameter and over 180m in height with a production capacity exceeding 1000 tones a day.
• The kiln is inclined a few degrees from the horizontal (about 4 cm/m) and is rotated about its axis at a speed of about 60 to 150 revolution/hour.
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• All exhaust gases produced during the burning process of the materials leave the kiln through the stack.

**Cooling & grinding**

• Rapid cool - glassy
• Grinding starts golf ball size. Ends about 2-80 microns, 300 m2/kg. Grinding
depends on application. Typical plant capacity is about: 1 MT/y
• Portland cement is manufactured by inter grinding the Portland cement clinker with some (3 to 6 %) gypsum rock.

CEMENT:

PHYSICAL, CHEMICAL PROPERTIES AND HYDRATION

Physical Properties
Portland cements are commonly characterized by their physical properties for quality control purposes. Their physical properties can be used to classify and compare Portland cements. The challenge in physical property characterization is to develop physical tests that can satisfactorily characterize key parameters. The physical properties of cement
• Fineness
• Soundness
• Setting Time
• Strength

Fineness
• Fineness or particle size of Portland cement affects Hydration rate and thus the rate of strength gain. The smaller the particle size, the greater the surface area-to-volume ratio, and thus, the more area available for water-cement interaction per unit volume. The effects of greater fineness on strength are generally seen during the first seven days.
• When the cement particles are coarser, hydration starts on the surface of the particles. So the coarser particles may not be completely hydrated. This causes low strength and low durability.
• For a rapid development of strength a high fineness is necessary.
**Soundness**

When referring to Portland cement, "soundness" refers to the ability of a hardened cement paste to retain its volume after setting without delayed expansion. This expansion is caused by excessive amounts of free lime (CaO) or magnesia (MgO). Most Portland cement specifications limit magnesia content and expansion.

**Setting Time**

- Cement paste setting time is affected by a number of items including: cement fineness, water-cement ratio, chemical content (especially gypsum content) and admixtures. Setting tests are used to characterize how a particular cement paste sets. For construction purposes, the initial set must not be too soon and the final set must not be too late. Normally, two setting times are defined:
  - Initial set. Occurs when the paste begins to stiffen considerably.
  - Final set. Occurs when the cement has hardened to the point at which it can sustain some load.
• Setting is mainly caused by C3A and C3S and results in temperature rise in the cement paste.
• False set: No heat is evolved in a false set and the concrete can be remixed without adding water.
• Occurs due to the conversion of unhydrous/semihydrous gypsum to hydrous gypsum (CaSO₄·2H₂O).
• Flash Set: is due to absence of Gypsum. Specifically used for under water repair.

**Strength**

• Cement paste strength is typically defined in three ways: compressive, tensile and flexural. These strengths can be affected by a number of items including: water-cement ratio, cement-fine aggregate ratio, type and grading of fine aggregate, curing conditions, size and shape of specimen, loading conditions and age.

**Duration of Testing**

Typically, Durations of testing are:
• 1 day (for high early strength cement)
• 3 days, 7 days, 28 days and 90 days (for monitoring strength progress)
• 28 days strength is recognised as a basis for control in most codes.
• When considering cement paste strength tests, there are two items to consider:
  • Cement mortar strength is not directly related to concrete strength. Cement paste strength is typically used as a quality control measure.
  • Strength tests are done on cement mortars (cement + water + sand) and not on cement pastes.
TESTS FOR CEMENT

The physical principal tests on cement are:
• Consistency, Setting time, Soundness, Compressive strength, Fineness

CEMENT

Chemical Composition

Oxide Composition of Portlant Cement
• Portland cement is composed of four major oxides: lime (CaO), silica (SiO2), alumina (Al2O3), and iron (Fe2O3).
• Also Portland cement contains small amount of magnesia (MgO), alkalies (Na2O and K2O), and sulfiric anhydrite (SO3).

Approximate Composition Limits of Oxides in Portland Cement

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Common Name</th>
<th>Content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>Lime</td>
<td>60-67</td>
</tr>
<tr>
<td>SiO2</td>
<td>Silica</td>
<td>17-25</td>
</tr>
<tr>
<td>Al2O3</td>
<td>Alumina</td>
<td>3-8</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>Iron</td>
<td>0,5-6</td>
</tr>
<tr>
<td>MgO</td>
<td>Magnesia</td>
<td>0,1-4</td>
</tr>
<tr>
<td>Na2O and K2O</td>
<td>Alkalies</td>
<td>0,2-1,3</td>
</tr>
<tr>
<td>SO3</td>
<td>anhydride</td>
<td>1-3</td>
</tr>
</tbody>
</table>
Oxide composition

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Mass Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement 1</td>
</tr>
<tr>
<td>CaO</td>
<td>66</td>
</tr>
<tr>
<td>SiO2</td>
<td>20</td>
</tr>
<tr>
<td>Al2O3</td>
<td>7</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>3</td>
</tr>
<tr>
<td>Others</td>
<td>4</td>
</tr>
</tbody>
</table>

Major Compounds of Portland Cement
(Bogue’s Compound Composition)

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical formula</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Tricalcium silicate</td>
<td>3CaO.SiO2</td>
<td>C3S</td>
</tr>
<tr>
<td>• Dicalcium silicate</td>
<td>2CaO.SiO2</td>
<td>C2S</td>
</tr>
<tr>
<td>• Tricalcium aluminate</td>
<td>3CaO.Al2O3</td>
<td>C3A</td>
</tr>
<tr>
<td>• Tetracalcium alumino</td>
<td>4CaO.Al2O3</td>
<td>C4AF</td>
</tr>
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Significance of Compound Composition

<table>
<thead>
<tr>
<th>Compound</th>
<th>Mass Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass Percentage</td>
</tr>
<tr>
<td></td>
<td>Cement 1</td>
</tr>
<tr>
<td>C₃S</td>
<td>65</td>
</tr>
<tr>
<td>C₂S</td>
<td>8</td>
</tr>
<tr>
<td>C₃A</td>
<td>14</td>
</tr>
<tr>
<td>C₄AF</td>
<td>4</td>
</tr>
</tbody>
</table>

Hydration

When Portland cement is mixed with water its chemical compound constituents undergo a series of chemical reactions that cause it to harden. This chemical reaction with water is called "hydration". Each one of these reactions occurs at a different time and rate. Together, the results of these reactions determine how Portland cement hardens and gains strength.
OPC hydration

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### Characteristics of Hydration of the Cement Compounds

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Reaction Rate</th>
<th>Amount of Liberated</th>
<th>Strength</th>
<th>Heat Liberation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3S</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>C2S</td>
<td>Slow</td>
<td>Low</td>
<td>Low initially, high later</td>
<td>Low</td>
</tr>
<tr>
<td>C3A</td>
<td>Fast</td>
<td>Very high</td>
<td>Low</td>
<td>Very high</td>
</tr>
<tr>
<td>C4AF</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

### Reactions of Hydration

- \(2\text{C}_3\text{S} + 6\text{H} = \text{C}_3\text{S}_2\text{H}_3 + 3\text{Ca(OH)}2\)  
  \((100 + 24 = 75 + 49)\)
- \(2 \text{C}_2\text{S} + 4\text{H} = \text{C}_3\text{S}_2\text{H}_3 + \text{Ca(OH)}2\)  
  \((100 + 21 = 99 + 22)\)
- \(\text{C}_3\text{A} + 6\text{H} = \text{C}_3\text{AH}_6\)  
  \([\text{C}_3\text{A} + \text{CaSO}_4. 2\text{H}_2\text{O} = 3\text{CaO. Al}_2\text{O}_3. 3\text{CaSO}_4. 31\text{H}_2\text{O}]\)

Calcium Sulfoaluminate
Heat of Hydration

The heat of hydration is the heat generated when water and Portland cement react. Heat of hydration is most influenced by the proportion of C3S and C3A in the cement, but is also influenced by water-cement ratio, fineness and curing temperature. As each one of these factors is increased, heat of hydration increases.

• For usual range of Portland cements, about one-half of the total heat is liberated between 1 and 3 days, about three-quarters in 7 days, and nearly 90 percent in 6 months.
• The heat of hydration depends on the chemical composition of cement.
STRENGTH, ELASTICITY & SHRINKAGE

The "strength" of hardened concrete is its ability to resist strain or rupture induced by external forces. The resistance of concrete to compressive, tensile and bending stresses is known as compressive strength, tensile strength, and bending (or flexural) strength, respectively. The resistance of concrete to repeated stresses is called its fatigue strength. Strength is expressed in terms of kgf/cm² or MPa.
The compressive strength of concrete is usually determined at an age of 28 days of the specimen. The 28-day compressive strength is the strength value used in concrete designs. Sometimes, the compressive strength at 7 days is also determined. The 7-day compressive strength is approximately 65-70% of its 28-day strength.

At least three specimens should be tested; the average of their compressive strengths is found for determining the compressive strength of a concrete sample on a particular testing day. The compressive strength values obtained for cylinder specimens and cube specimens prepared from the same concrete sample are not the same.

**Compressive Strength Test (Drilling Core Method)**

This test is conducted on cylindrical concrete core specimens removed from the hardened concrete by a drilling operation. A core drilling machine is used for cutting and removing the concrete samples. This machine is equipped with diamond cutters located on the end of a cylindrical (tube-like) cutting device. As the machine is operated, the cylinder shaped cutter rotates at a high speed.
The diameter of the concrete core specimen removed from the hardened concrete depends on the inner diameter of the cylindrical cutting device. Usually concrete cores having diameters of 10 cm or 15 cm are obtained. The removed core specimens may have different lengths depending on the thickness of the hardened concrete that they are cut from. If the core specimen is too long, it is shortened so that it will have a length/diameter ratio of 2.0. Core specimens which have a length/diameter ratio of less than 2.0 can also be used for compressive strength testing purposes, but a specimen having a length/diameter ratio of less than 1.0 should not be used.

If the ratio of the length to the diameter of the specimen is less than 2.0, allowance is made; the compressive strength found by the test should be multiplied with the correction factors shown in Table.

<table>
<thead>
<tr>
<th>L/d</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.75</td>
<td>0.98</td>
</tr>
<tr>
<td>1.50</td>
<td>0.96</td>
</tr>
<tr>
<td>1.25</td>
<td>0.93</td>
</tr>
<tr>
<td>1.00</td>
<td>0.87</td>
</tr>
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</table>
Determination of the compressive strength of concrete by testing core specimens is useful in finding the strength of concrete that is present in a structure. As is known, the strength of the concrete in the structure may be different from the strength found by the standard test method. The operations applied to the concrete in the structure such as placing, consolidation, and curing may lead to these differences in the strength. This method provides the possibility of finding the actual quality of the concrete in the structure.

**Factors Influencing Cube Compressive Strength**

- Platen effect
- Rate of loading
- Size of the specimen
- Moisture content
- Age of the specimen

**Modulus Elasticity**

Defining modulus of elasticity of concrete is difficult; because concrete is not a linearly elastic material. Since the slope of $\sigma$-$\varepsilon$ curve of concrete is not constant. We must first describe modulus of elasticity ($Ec$). In general; Modulus of elasticity defined for concrete is the instantaneous $Ec$. This is not influenced by the time effect (mean $Ec$ is function of many variables).

Instantaneous $Ec$ can be defined in 3 ways.

- Initial Modulus of Elasticity, $E$
- Secant modulus
- Tangent modulus
Modulus Elasticity

a) Initial modulus: tangent to curve at origin.
b) Secant modulus: slope at secant at a given stress usually 0.5fc.
c) Tangent modulus: tangent at a given stress; usually 40 to 50% of compressive strength.
d) Depending on the problem, these three can be used in design and research.

However, secant modulus is mostly used and codes referred.

• Categorize the elastic behaviour of concrete in terms of the various type of elastic behaviour of engineering materials. The definition of pure elasticity is that strains appear and disappear immediately on application and removal of stress.
• The stress-strain curve of the figure illustrate two categories of pure elasticity.
  A) is linear and elastic
  B) is brittle materials, such as glass and most rocks are described as linear and non elastic
C) because separate linear curves exist for the loading and unloading branches of stress-strain diagram and permanent deformation exists after removal of load.

D) described as non linear and non elastic behaviour.

**E-aggregate-concrete**

The properties of aggregate also influence the modulus of elasticity although they don’t affect the compressive Strength. The relation between the modulus of elasticity of concrete and Strength depends also on age.

**Poisson’s ratio**

- The design and analysis of some type of structure require the knowledge of poisson’s ratio viz. The ratio of the lateral strain. The sign of the strains is ignored. We are usually interested in applied compression and therefore have axial contraction and lateral extension.

- Generally poisson ratio for normal weight and light weight lies in range of 0.15 to 0.20 when determined from strain measurements taken in the static modulus of elasticity tests.

- An alternative method of determining poisson’s ratio is by dynamic means.

**CREEP**

- Creep is the time-dependent flow of concrete caused by its being subjected to stress.

- This deformation, which occurs rapidly at first and then decreases with time, can be several times larger than the strains due to elastic shortening.

- Using more scientific approach; When load is applied to concrete at time to, a deformation occurs immediately which can be expressed as the elastic strain, $\epsilon$
If this applied load is left on concrete producing a constant stress, the instantaneous elastic strain $\varepsilon$ (to) begins to increase.

- The rate of increase is fast during the first 3 months, after which it begins to slow down.
- Whichever slowing rate, creep continues for years.
- Creep of Concrete resulting from the action of a sustained stress is a gradual increase in strain with time; it can be of the same order of magnitude as drying shrinkage.
- Creep does not include any immediate elastic strains caused by loading or any shrinkage or swelling caused by moisture changes.
- When a concrete structural element is dried under load the creep that occurs is one to two times as large as it would be under constant moisture conditions. Adding normal drying shrinkage to this and considering the fact that creep can be several times as large as the elastic strain on loading, it may be seen that these factors can cause considerable deflection and that they are of great importance in structural mechanics.
If a sustained load is removed, the strain decreases immediately by an amount equal to the elastic strain at the given age; this is generally lower than the elastic strain on loading since the elastic modulus has increased in the intervening period. This instantaneous recovery is followed by a gradual decrease in strain, called creep recovery. This recovery is not complete because creep is not simply a reversible phenomenon.
Factors effecting creep

- Creep has been found to depend on
  - the mix proportions (w/c ratio, aggregate type)
  - humidity, temperature
  - curing conditions,
  - maturity of the concrete when first loaded (time, age of concrete, stress level under sustain load) (Nilson, 1987).

- The deformation due to creep causes a shortening of the prestressing strands, which leads to a loss in stress in the strand.

Mix proportions.

- The major portion of creep is due to removal of water from between the sheets of a calcium silicate crystallite and to a possible rearrangement of bonds between the surfaces of the individual crystallites.

- When hydrated cement is completely dried, little or no creep occurs.

- Water/cement ratio is the main factor influencing the porosity and the strength of concrete so that lower water/cement ratio results in a higher strength. Now for a constant cement paste, the effect of a decrease in water/cement ratio is to decrease creep.

- In normal weight of aggregate concrete, the source of creep is hardened cement paste since the aggregate is not liable to creep at the level of stress existing in concrete. Because aggregate is stiffer than the cement paste then the main role of the aggregate is to restrain the creep in the cement paste, the effect depends on the elastic modulus of aggregate and its volumetric proportion.

- Concretes made with different aggregates exhibit creep of varying magnitudes. Hence, the stiffer aggregate, the lower creep.

- And higher volume of aggregate is the lower creep.
• In terms of cement paste content which is complementary to aggregate content by volume; in other words, if the aggregate content by volume is g per cent, the cement content is (100-g) percent

**Humidity, temperature**

• For a given concrete basically, the lower the relative humidity, the higher the creep; the lower the temperature, the lower the creep.
• Change of humidity and temperature has already negative affect on creep
• Experiments have shown that creep continues for a very long time; detectable changes have been found after as long as 30 years.
• The rate decreases continuously, however, and it is generally assumed that creep tends to a limiting value. It has been estimated that 75 per cent of 20-year creep occurs during the first year.

**Effects of Creep**

• Creep of plain concrete does not by itself affect strength, although under very high stresses creep hastens the approach of the limiting strain at which failure takes place.
• The influence of creep on the ultimate strength of a simply supported, reinforced concrete beam subjected to a sustained load is insignificant, but deflection increases considerably and may in many cases be a critical consideration in design.
• Another instance of the adverse effects of creep is its influence on the stability of the structure through increase in deformation and consequent transfer of load to other components.
• Thus, even when creep does not affect the ultimate strength of the component in which it takes place, its effect may be extremely serious as far as the performance of the structure as a whole is concerned.
• The loss of prestress due to creep is well known and accounted for the failure of all early attempts at prestressing. Only with the introduction of high tensile steel did prestressing become a successful operation.

• The effects of creep may thus be harmful. On the whole, however, creep unlike shrinkage is beneficial in relieving stress concentrations and has contributed to the success of concrete as a structural material.
UNIT-2

CHEMICAL ADMIXTURES

Introduction

The realization that properties of concrete, in both the fresh and gardened states, can be modified by adding certain materials to concrete mixtures is responsible for the large growth of the concrete admixtures industry during the last 40 years. Hundreds of products are being marketed today, and in some countries it is not uncommon that 70 to 80 percent of all the concrete produced contains one or more admixtures; therefore, it is quite important that civil engineers be familiar with the commonly used admixtures, together with their typical applications and limitations. Admixtures vary in composition from surfactants and soluble salts and polymers to insoluble minerals. The purposes for which they are generally used in concrete include improvement of workability, acceleration or retardation of setting time, control of strength development, and enhancement of resistance to frost action, thermal cracking, alkali-aggregate expansion, and acidic and sulfate solutions. Important classes of concrete admixtures, their physical-chemical characteristics, mechanism of action, applications and side effects are as follows.

DEFINITION

An admixture is defined as a material other than water, aggregate, hydraulic cements and fiber reinforcement, used as an ingredient of concrete or mortar and added to the batch immediately before or during mixing.

IS9103:1999 Specification for admixtures for concrete (first revision) quotes:
1. Admixtures should not impair durability of concrete nor combine with the constituent to form harmful compounds nor increase the risk of corrosion of
reinforcement.

2. The workability, compressive strength and the slump loss of concrete with and without the use of admixtures shall be established during the trial mixes before use of admixtures.

3. The relative density of liquid admixtures shall be checked for each drum containing admixtures and compared with the specified value before acceptance.

4. The chloride content of admixtures shall be independently tested for each batch before acceptance.

5. If two or more admixtures are used simultaneously in the same concrete mix, data should be obtained to assess their interaction and to ensure their compatibility.

CLASSIFICATION OF ADMIXTURES:
Admixtures are commonly classified by their function in concrete but often they exhibit some additional action.

The classification is as follows:

1. Plasticizers
2. Super plasticizers
3. Retarders and retarding plasticizers
4. Accelerators and Accelerating Plasticizers
5. Air-entraining Admixtures
6. Mineral Admixtures
7. New generation super plasticizers

PLASTICIZERS (Water Reducers)
Requirement of right workability is the essence of good Concrete. Concrete in different situations require different degree of workability. A high degree of workability is required in situations like deep beams, thin walls of water retaining structures with a high percentage of steel reinforcement, column and beam junctions, pumping of Concrete, hot weather Concreting. Today, we have plasticizers which can help in difficult conditions for obtaining higher workability without using excess of water. The organic substances or the combinations of organic and inorganic substances, which allow a high reduction in water content for the given workability or give a higher workability at the same water content, are termed as Plasticizing Admixtures.

**The basic products constituting plasticizers are:**

1. Anionic surfactants such as lignosulphonates and their modifications and derivatives, salts of sulphonates hydrocarbons.
2. Nonionic surfactants such as polyglycol esters, acid of hydroxylated carboxyl acids and their modifications and derivatives.
3. Other products, such as carbohydrates etc. Among these, calcium, sodium and ammonium lignosulphonates are the most used. Plasticizers are used in the amount of 0.1% to 0.4% by weight of cement. At these doses, at constant workability the reduction in mixing water is expected to be of the order of 5% to 15%. This naturally increases the strength. The increase in workability that can be expected, at the same w/c ratio, may be anything from 30 mm to 150 mm slump, depending on the dosage, initial slump of concrete, cement content and type.

**ACTION OF PLASTICIZERS**

The action of plasticizers is mainly to fluidify the mix and improve the workability of concrete, mortar or grout. The mechanisms that are involved could be explained in the following way:
Dispersion: Portland cement, being in fine state of division, will have a tendency of flocculate in wet concrete. These flocculation entraps certain amount of water used in the mix and thereby all the water is not freely available to fluidify the mix.

When plasticizers are used, they get adsorbed on the cement particles. The adsorption of charged polymer on the particles of cement creates particle-to-particle repulsive forces which overcome the attractive forces. This repulsive force is called Zeta Potential, which depends on the base, solid content, quantity of plasticizer used. The overall result is that the cement particles are deflocculated and dispersed. When cement particles are deflocculated, the water trapped inside the flocs gets released and now available to fluidify the mix.

When cement particles get flocculated there will be interparticles friction between particle to particle and floc to floc. But in the dispersed condition there is water in between the cement particle and hence the interparticle friction is reduced.

Retarding Effect: The plasticizer will get adsorbed on the surface of cement particles and form a thin sheath. This thin sheath inhibits the surface hydration reaction between water and cement as long as sufficient plasticizer molecules are available at the particle/solution interface. The quantity of available plasticizers will progressively decrease as the polymers become entrapped in hydration products.

Compressive strength, percent of control sample, minimum

1 day --
3 days 110
7 days 110
28 days 110
6 months 100
1 year 100
Flexural strength, percent control sample, minimum

3 days 100
7 days 100
28 days 100

Commercial plasticizers (water reducing admixtures) available in India

Emce Plast BV
Conplast 211
Conplast P509
Plastiment BV 40
Roff Plast 330

SUPERPLASTICIZERS (HIGH RANGE WATER REDUCERS)

Superplasticizers constitute a relatively new category and improved version of plasticizer, the use of which was developed in Japan and Germany during 1960 and 1970 respectively. They are chemically different from normal plasticizers. Use of superplasticizer permits the reduction of water to the extent upto 30 per cent without reducing workability in contrast to the possible reduction up to 15 per cent in case of plasticizers.

The use of superplasticizer is practiced for production of flowing, self leveling, and self compacting and for the production of high strength and high performance concrete. The mechanism of action of super plasticizers is more or less same in case of ordinary plasticizer. Only thing is that the super plasticizers are more powerful as dispersing agents and they are high range water reducers. They are called High Range Water Reducers in American literature.

It is the use of superplasticizer which has made it possible to use w/c as low as 0.25 or even lower and yet to make flowing concrete to obtain strength of the order 120 Mpa or more. It is the use of superplasticizer which has made it possible
to use fly ash, slag and particularly silica fume to make high performance concrete.

The use of superplasticizer in concrete is an important milestone in the advancement of concrete technology. Since their introduction in the early 1960 in Japan and in the early 1970 in Germany, it is widely used all over the world. India is catching up with the use of superplasticizer in the construction of high rise buildings, long span bridges and the recently become popular Ready Mixed Concrete industry. Common builders and Government departments are yet to take up the use of this useful material. Super plasticizers can produce:

- At the same w/c ratio much more workable concrete than the plain ones,
- For the same workability, it permits the use of lower w/c ratio,
- As a consequence of increased strength with lower w/c ratio, it also permits a reduction of cement content.

The super plasticizers also produce a homogeneous, cohesive concrete generally without any tendency for segregation and bleeding.

Classification of Superplasticizer: Following are a few polymers which are commonly used as base for super plasticizers.

- Sulphonated melamine-formaldehyde condensates (SMF)
- Sulphonated naphthalene-formaldehyde condensates (SNF)
- Modified lignosulphonates (MLS)

**EFFECTS OF SUPERPLASTICIZERS ON FRESH CONCRETE**

It is to be noted that dramatic improvement in workability is not showing up when plasticizers or super plasticizers are added to very stiff or what is called zero slump concrete at nominal dosages. A mix with an initial slump of about 2 to 3 cm can only be fluidized by plasticizers or super plasticizers at nominal dosages. A
high dosage is required to fluidify no slump concrete. An improvement in slump value can be obtained to the extent of 25 cm or more depending upon the initial slump of the mix, the dosage and cement content. It is often noticed that slump increases with increase in dosage. But there is no appreciable increase in slump beyond certain limit of dosage. As a matter of fact, the over dosage may sometime harm the concrete. A typical curve, showing the slump and dosage is shown in Fig.

**COMPATIBILITY OF SUPERPLASTICIZERS AND CEMENT**

It has been noticed that all super plasticizers are not showing the same extent of improvement in fluidity with all types of cements. Some super plasticizers may show higher fluidizing effect on some type of cement than other cement. There is nothing wrong with either the superplasticizer of that of cement. The fact is that they are just not compatible to show maximum fluidizing effect. Optimum fluidizing effect at lowest dosage is an economical consideration. Giving maximum fluidizing effect for a particular superplasticizer and cement is very complex involving many factors like composition of cement, fineness of cement etc.

Although compatibility problem looks to be very complex, it could be more or less solved by simple rough and ready field method. Incidentally this simple field test shows also the optimum dose of the superplasticizer to the cement. Following methods could be adopted.

- Marsh cone test
- Mini slump test
- Flow table test.

Out of the above, Marsh cone test gives better results. In the Marsh cone test, cement slurry is made and its flow ability is found out. In concrete, really come to think of it, it is the cement paste that influence, it is the paste that influences flow ability. Although, the quantity of aggregates, its shape and texture etc. will have some influence, it is the paste that will have greater influence. The presence of
aggregate will make the test more complex and often erratic. Whereas using grout alone will make the test simple, consistent and indicative of the fluidifying effect of superplasticizer with cement. The following procedure is adopted in Marsh cone test.

Marsh cone is a conical brass vessel, which has a smooth aperture at the bottom of diameter 5 mm. The profile of the apparatus is shown in Fig.

Take 2 kg cement, proposed to be used at the project. Take one liter of water (w/x =0.5) and say 0.1% of plasticizer. Mix them thoroughly in a mechanical mixer (Hobart mixer is preferable) for two minutes. Hand mixing does not give consistent results because of unavoidable lump formation which blocks the aperture. If hand mixing is done, the slurry should be sieved through 1.18 sieve to exclude lumps. Take one liter slurry and pour it into Marsh cone duly closing the aperture with a finger. Start a stop watch and simultaneously remove the finger. Find out the time taken in seconds, for complete flow out of the slurry. The time in seconds is called the “Marsh Cone Time”. Repeat the test with different dosages of plasticizer. A typical graph is shown in Fig.

The dose at which the Marsh cone time is lowest is called the saturation point. The dose is the optimum dose for that brand of cement and plasticizer or super plasticizer for that w/c ratio.

FACTORS AFFECTING WORKABILITY
1. Type of super plasticizers
2. dosage
3. mix composition
4. variability in cement composition and properties
5. mixing procedure
6. equipments
Type of super plasticizers

It is a well established fact that the average molecular weight of the plasticizer is of primary importance for its efficiency as plasticizer in concrete. The higher the molecular weight, the higher is the efficiency.

**Dosage**

The optimum dosage can be ascertained from Marsh cone test if brand of cement, plasticizer and water cement ratio is already fixed. A dosage more than 2.5% by weight of cement is rarely used.

**Mix composition**

The mix composition particularly the aggregate/cement ratio or richness of the mix, w/c ratio, and use of other supplementary cementing materials like fly ash or silica fume affects the workability.

**Variability in cement composition**

The variability in cement with respect to compound composition, in particular C3A content, C3S/C2S ratio, fineness of cement, alkali content and gypsum content re responsible for the lack of compatibility with a particular type of super plasticizer and their performance in concrete.

**Mixing procedure**

Plasticizer must be properly and intimately mixed in concrete to bring about proper dispersion with cement particles. Site problems in the use of super plasticizers Some of the practical site problems in the use of super plasticizers are listed below:

- slump of reference mix (i.e., concrete without plasticizer)
- inefficient laboratory mixer for trial
- sequence of addition of plasticizer
- problem with crusher dust
- problem with crusher sand
- importance of shape and grading of coarse aggregate
- compatibility with cement
• selection of plasticizer and super plasticizers
• determination of dosage
• slump loss
• casting of cubes
• compaction at site
• segregation and bleeding
• finishing
• removal of form work

**Effect of super plasticizers on the properties of hardened concrete**

Since plasticizers and super plasticizers improve the workability, compatibility and facilitate reduction on w/c ratio, and thereby increase the strength of concrete.

**PHYSICAL REQUIREMENTS ACCORDING TO IS 9103:1999**

- Water content, percent of control 80
- Slump not more than 15mm
- Time of setting, allowable deviation from control sample hours: max +4
- Compressive strength, percent of control sample, minimum
  - 1 day 140
  - 3 days 125
  - 7 days 125
  - 28 days 115
  - 6 months 100
  - 1 year 100
- Flexural strength, percent of control sample min 28 days 100

**RETARDERS**

A retarder is an admixture that slows down the chemical process of hydration so that concrete remains plastic and workable for a longer time than concrete without the retarder. Retarders are used to overcome the accelerating effect of high temperature on setting properties of concrete on hot weather concreting.
The retarders are used in casting and consolidating large number of pours without the formation of cold joints. They are also used in grouting oil wells. Oil wells are sometimes taken up to a depth of about 6000 meter deep where the temperature may be about 2000°C. The annular spacing between the steel tube and the wall of the well will have to be sealed with cement grout. Sometimes at that depth stratified or porous rock strata may also require to be grouted to prevent the entry of gas or oil into some other strata... for all these works cement grout is required to be in mobile condition for about 3 to 4 hours, even at that high temperature without getting set. Use of retarding agent is often used for such requirements.

Sometimes concrete may have to be placed in difficult conditions and delay may occur in transporting and placing. In ready mixed concrete practices, concrete is manufactured in central batching plant and transported over a long distance to the job sites which may take considerable time. In the above cases the setting of concrete will have to be retarded, so that concrete when finally placed and compacted is in perfect plastic state.

Retarding admixtures are sometimes used to obtain exposed aggregate look in concrete. The retarder sprayed to the surface of the formwork, prevents the hardening of matrix at the interface of concrete and formwork, whereas the rest of the concrete gets hardened. On removing the formwork after one day of so, the unhardened matrix can be just washed off by a jet of water which will expose the aggregates. The above are some of the instances where a retarding agent is used. Perhaps the most common known retarder is calcium sulphate.

It is interground to retard the setting of cement. The appropriate amount of gypsum to be used must be determined carefully for the given job. Use of gypsum for the purpose of retarding setting time is only recommended when adequate inspection and control is available, otherwise, addition of excess amount may
cause undesirable expansion and indefinite delay in the setting of concrete. In addition to gypsum there are number of other materials found to be suitable for this purpose. They are: starches, cellulose products, sugars, acids or salts of acids. These chemicals may have variable action on different types of cement when used in different quantities. Unless experience has been had with a retarder, its use as an admixture should not be attempted without technical advice. Any mistake made in this respect may have disastrous consequences.

Common sugar is one of the most effective retarding agents used as an admixture for delaying the setting time of concrete without detrimental effect on the ultimate strength. Addition of excessive amounts will cause indefinite delay in setting. At normal temperatures addition of sugar 0.05 to 0.10 percent have little effect on the rate of hydration, but if the quantity is increased to 0.2 percent, hydration can be retarded to such an extent that final set may not take place for 72 hours or more. Skimmed milk powder (casein) has a retarding effect mainly due to sugar content. Other admixtures which have been successfully used as retarding agents are Ligno sulphonic acids and their salts, hydroxylated carboxylic acids and their salts which in addition to the retarding effect also reduce the quantity of water requirement for a given workability.

This also increases 28 days compressive strength by 10 to 20 percent. Materials like mucic acid, calcium acetate and commercial products by name “Ray lig binder” are used for set retarding purposes. These days’ admixtures are manufactured to combine set retarding and water reducing properties. They are usually mixtures of conventional water reducing agents plus sugars or hydroxylated carboxylic acids or their salts. Both the setting time and the rate of strength build up are effected by these materials.
RETARDING ADMIXTURES
It is mentioned earlier that all the plasticizers and super plasticizers by themselves show certain extent of retardation. Many a time this extent of retardation of setting time offered by admixtures will not be sufficient. Instead of adding retarders separately, retarders are mixed with plasticizers or super plasticizers at the time of commercial production. Such commercial brand is known as retarding plasticizers or retarding super plasticizers.

PHYSICAL REQUIREMENTS ACCORDING TO IS 9103: 1999
Compressive strength, percent of control sample, min: 28 days 90
Flexural strength: 90

ACCELERATORS
Accelerating admixtures are added to concrete to increase the rate of early strength development in concrete to
• permit earlier removal of formwork;
• reduce the required period of curing;
• advance the time that a structure can be placed in service;
• partially compensate for the retarding effect of low temperature during cold weather concreting;
• in the emergency repair work.
In the past one of the commonly used materials as an accelerator was calcium chloride. But, now a days it is not used. Instead, some of the soluble carbonates, silicates fluosilicates and some of the organic compounds such as triethenolamine are used. Accelerators such as fluosilicates and triethenolamine are comparatively expensive. The recent studies have shown that calcium chloride is harmful for reinforced concrete and prestressed concrete.

It may be used or plain cement concrete in comparatively high dose. Some of the accelerators produced these days are so powerful that it is possible to make the
cement set into stone hard in a matter of five minutes are less. With the availability of such powerful accelerator, the under water concreting has become easy. Similarly, the repair work that would be carried out to the waterfront structures in the region of tidal variations has become easy. The use of such powerful accelerators have facilitated, the basement waterproofing operations. In the field of prefabrication also it has become an invaluable material. As these materials could be used up to -100C, they find an unquestionable use in cold weather concreting.

Some of the modern commercial accelerating materials are Mc-Schnell OC, Mc-Schnell SDS, Mc-Torkrethilfe BE, manufactured by Mc-Bauchemic (Ind) Pvt. Ltd. MC-Torkrethilfe BE is a material specially formulated to meet the demand for efficient and multifold properties desired for sprayed concrete and shotcreting operations. A field trial is essential to determine the dose for a given job and temperature conditions when the above materials are used.

**ACCELERATING PLASTICIZERS**

Certain ingredients are added to accelerate the strength development of concrete to plasticizers or super plasticizers. Such accelerating super plasticizers, when added to concrete result in faster development of strength. The accelerating materials added to plasticizers or super plasticizers are triethenolamine chlorides, calcium nitrite, nitrates and fluosilicates etc. The accelerating plasticizers or accelerating super plasticizers manufactured by well known companies are chloride free.

**PHYSICAL REQUIREMENTS ACCORDING TO IS9103:1999**

Compressive strength percent control sample minimum 28 days 100

Flexural strength percent of control sample minimum 28 days 100
AIR-ENTRAINING ADMIXTURE

Perhaps one of the important advancements made in concrete technology was the discovery of air entrained concrete. Since 1930 there has been an ever increasing use of air entrained concrete all over the world especially, in the United States and Canada. Due to the recognition of the merits of air entrained concrete, about 85 per cent of concrete manufactured in America contains one or the other type of air entraining agent. So much so that air entraining agents have almost come to be considered a necessary ‘fifth ingredient’ in concrete making. Air entrained concrete is made by mixing a small quantity of air entraining agent or by using air entraining cement. These air entraining agents incorporate millions of nocoalescing air bubbles, which will act as flexible ball bearings and will modify the properties of plastic concrete regarding workability, segregation, bleeding and finishing quality of concrete. It also modifies the properties of hardened concrete regarding its resistance to frost action and permeability.

The air voids present in concrete can be brought under two groups:
(a) Entrained air (b) Entrapped air.

Entrained air is intentionally incorporated, minute spherical bubbles of size ranging from 5 microns to 80 microns distributed evenly in the entire mass of concrete. The entrapped air is the void present in the concrete due to insufficient compaction. These entrapped air voids may be of any shape and size normally embracing the contour of aggregate surfaces. Their size may range from 10 to 1000 microns or more and they are not uniformly distributed throughout the concrete mass.
AIR ENTRAINING AGENTS

The following types of air entraining agents are used for making air entrained concrete.

(a) Natural wood resins
(b) Animal and vegetable fats and oils, such as tallow, olive oil and their fatty acids such as stearic and oleic acids.
(c) Various wetting agents such as alkali salts or sulphated and sulphonated organic compounds.
(d) Water soluble soaps of resin acids, and animal and vegetable fatty acids.
(e) Miscellaneous materials such as the sodium salts of petroleum sulphonic acids, hydrogen peroxide and aluminium powder, etc. There is a number of air entraining agents available in the market. The common air entraining agents in United States are Vinsol resin, Darex, N Tair, Airalon, Orvus, Teepol, Petrosan and Cheecol. Out of these the most important air entraining agents which at one time enjoyed world-wide market is Vinsol resin and Darex. In India, large scale use of air entrained concrete is not being practiced, primarily due to the fact that frost scaling of concrete is not a serious problem in our country so far. However, the advantages of the use of air entrained concrete have been realized for the construction of multi-purpose dams. Air entrained concrete has been used in the construction of Hirakud dam, Koyna dam, Rihand dam etc. In these dams, to start with, American air entraining agents such as Vinsol resin, Darex etc. were used. Later on in 1950’s certain indigenous air entraining agents were developed. They are Aerosin-HRS., Rihand A.E.A., Koynaea, Ritha powder, Hico, etc. Now modern admixture manufacturing companies are manufacturing a number of commercial air entraining agents. MC-Mischoel LP, MC-Michoel AEA, Complast AE 215, Roff AEA 330 are some of the commercial brands available in India.
FACTORS AFFECTING AMOUNT OF AIR ENTRAINMENT

The manufacture of air entrained concrete is complicated by the fact that the amount of air entainment in a mix is affected by many factors; the important ones are:

(a) The type and quantity of air entraining agent used.
(b) Water/cement ratio of the mix.
(c) Type and grading of aggregate.
(d) Mixing time.
(e) The temperature.
(f) Type of cement.
(g) Influence of compaction.
(h) Admixtures other than air entraining agent used.

Different air entraining agents produce different amounts of air entainment, depending upon the elasticity of the film of the bubble produced, and the extent to which the surface tension is reduced. Similarly, different quantities of air entraining agents will result in different amounts of air entainment. Water/cement ratio is one of the important factors affecting the quantity of air. At very low water/cement ratio, water films on the cement will be insufficient to produce adequate foaming action. At intermediate water/cement ratio (viz. 0.4 to 0.6) abundant air bubbles will be produced. But at a higher water/cement ratio although to start with, a large amount of air entainment is produced, a large proportion of the bubbles will be lost progressively with time. The grading of aggregate has shown good influence on the quantity of air entainment. It was established that the quantity of air increased from the lowest fineness modulus of sand to a peak at about F.M. of 2.5, and thereafter, decreased sharply. The sand fraction of 300 and 150 microns showed a significant effect on the quantity of air entainment. The higher quantity of these fractions resulted in more air entainment.
THE EFFECT OF AIR ENTRAINMENT ON THE PROPERTIES OF CONCRETE

Air entrainment will affect directly the following three properties of concrete
(a) Increased resistance to freezing and thawing.
(b) Improvement in workability.
(c) Reduction in strength.

Incidentally air entrainment will also affect the properties of concrete in the following ways:
(a) Reduces the tendencies of segregation.
(b) Reduces the bleeding and laitance.
(c) Decreases the permeability.
(d) Increases the resistance to chemical attack.
(e) Permits reduction in sand content.
(f) Improves placeability, and early finishing.
(g) Reduces the cement content, cost, and heat of hydration.
(h) Reduces the unit weight.
(i) Permits reduction in water content.
(j) Reduces the alkali-aggregate reaction.
(k) Reduces the modulus of elasticity.

RESISTANCE TO FREEZING AND THAWING
The greatest advantage derived from the use of air entrained concrete is the high resistance of hardened concrete to scaling due to freezing and thawing. It is found that when ordinary concrete is subjected to a temperature below freezing point, the water contained in the pore of the concrete freezes. It is well known that the volume of ice is about 10 per cent higher than the corresponding volume of water. Hence, the ice formed in the pores of hardened concrete exerts pressure.
The cumulative effect of this pressure becomes considerable, with the result that surface scaling and disruption of concrete at the weaker section takes place. Similarly, surface scaling and disruption also takes place in plain concrete when subjected to the action of salt used for deicing purpose. Similar pattern of failure of plain concrete is also noticed in concrete structures at the tidal zone and spray zone. It has been firmly established that air entrainment in concrete increases the resistance by about three to seven times in such situations.

**EFFECT ON WORKABILITY**

The entrainment of air in fresh concrete by means of air entraining agent improves workability. It was seen that the placeability of air entrained concrete having 7.5 cm slump is superior to that of non-air entrained concrete having 12.5 cm slump. This easier placeability of a lower slump should be recognized by the people concerned with concrete construction in difficult situations. Better placeability of air entrained concrete results in more homogeneous concrete with less segregation, bleeding and honeycombing. The concrete containing entrained air is more plastic and ‘fatty’ and can be more easily handled than ordinary concrete. The pump ability of the mix also increases enormously.

**EFFECT ON STRENGTH**

It can be generally stated that air entrainment in concrete reduces the compressive strength of concrete. But when the process is applied properly, taking advantage of the benefits accrued on account of air-entrainment, little or no loss of strength should take place and it is even possible that under certain circumstances a gain of strength may be possible. It is true that at a given water/cement ratio, an increase in air content results in loss of strength, but the air entrainment enables reduction of water/cement ratio and sand content, for the given workability, thereby regaining most of not all the lost strength.
EFFECT ON SEGREGATION, BLEEDING AND LAITANCE
Segregation and bleeding of concrete are different manifestations of loss of homogeneity. Segregation usually implies separation of coarse aggregate from mortar or separation of cement paste from aggregates. Bleeding is the autogenously flow of mixing water within or its emergence to the surface from freshly placed concrete, usually, as a result of sedimentation of the solids due to compaction and self weight of the solids. Bleeding results in the formation of this layer of neat cement particles is called laitance.

EFFECT ON PERMEABILITY
The entrainment of air does appear to have much effect on the permeability of concrete. Greater uniformity of concrete with entrained air due to its increased workability, modified pore-structure of the air entrained concrete, reduction of water channel due to reduction in bleeding, are some of the reasons for improving the permeability characteristics of air entrained concrete. Cement stored in silos built of air entrained concrete, has been found to show no caking of cement, whereas, cement stored in silos made of ordinary concrete revealed caking along the periphery of the silo. The minute disconnected air bubbles offer a better barrier to the passage of water. The reduced water/cement ratio also is one of the factors for reduced permeability.

EFFECT ON CHEMICAL RESISTANCE
In view of lower permeability and absorption, the air entrained concrete will have greater resistance for chemical attack than that of normal concrete. In the Road Research Laboratory, U.K., specimens of comparable mix of ordinary and air entrained concrete have been immersed in 5 percent solution of magnesium sulphate and the deterioration in quality has been assessed by measuring the decrease in the velocity of an ultrasonic wave through the specimen. It was found that air entrained concrete showed less deterioration than ordinary concrete.
EFFECT ON SAND, WATER AND CEMENT CONTENT
The minute spherical air bubbles act as fine aggregates and enable the reduction of fine aggregates. The reduction of fine aggregate further enables the reduction of water requirement without impairing the workability and slump. This will have to be considered in designing an air entrained mix. On the basis of a large number of experiments it is reported that sand content by weight of total aggregate may be reduced by one per cent for each per cent increase in air entrainment upto about 8 per cent, without any appreciable change in workability or slump. The water requirement of an average concrete mix is reduced approximately 3.5 kg/cu.m with rounded aggregate and 4.8 kg/cu.m with angular aggregates for each per cent air entraining. The reduction in water/cement ratio naturally affects the basic increase in strength and durability due to the non-availability of excess water for the formation of bleeding channels through the matrix of concrete.

ALKALI-AGGREGATE REACTION
There are evidences that air entrainment reduces the alkali-aggregate reaction. Use of air entraining agent has frequently been recommended as a means for controlling expansion due to alkali-aggregate reaction in mortar and concrete.

MODULUS OF ELASTICITY
Available data indicate that the modulus of elasticity of concrete mix having the same water/cement ratio and the same aggregate is reduced by 2 to 3 per cent for each per cent of air entrainment.

ABRASION RESISTANCE
Concrete containing less than 6 per cent air entrainment has about the same resistance to abrasion as normal concrete, when cement contents of the comparable concrete are constant. However, there is a progressive decrease in abrasion resistance with further increase in air content. When the air entrainment
is of the order of about 10 per cent, abrasion resistance is markedly low. Since concrete used in pavements is generally specified to have not more than 3 to 6 per cent of entrained air, the abrasion resistance should be satisfactory.

**OPTIMUM AIR CONTENT IN CONCRETE**

The recommended air content in a given concrete is a function of (a) the purpose for which the concrete is used and its location and climatic condition (b) the maximum size of aggregate (c) the richness of the mix. Usually, the desirable air content is ranging from 3 to 6 per cent.

**POZZOLANIC OR MINERAL ADMIXTURES**

The use of pozzolanic materials is as old as that of the art of concrete construction. It was recognized long time ago, that the suitable pozzolans used in appropriate amount, modify certain properties of fresh and hardened mortars and concretes. Ancient Greeks and Romans used certain finely divided siliceous materials which when mixed with lime produced strong cementing material having hydraulic properties and such cementing materials were employed in the construction of aqueducts, arch, bridges etc.

One such material was consolidated volcanic ash or tuff found near Pozzuoli (Italy) near Vesuvius. This came to be designated as Pozzuolana, a general term covering similar materials of volcanic origin found in other deposits in Italy, France and Spain. Later, the term pozzolan was employed throughout Europe to designate any materials irrespective of its origin which possessed similar properties. Specimens of concrete made by lime and volcanic ash from Mount Vesuvius were used in the construction of Caligula Wharf built in the time of Julius Caesar nearly 2000 years ago is now existing in a fairly good condition.

A number of structures stand today as evidence of the superiority of pozzolanic cement over lime. They also attest the fact that Greeks and Romans made real advance in the development of cementitious materials. After the development of
natural cement during the latter part of the 18th century, the Portland cement in the early 19th century, the practice of using pozzolans declined, but in more recent times, Pozzolans have been extensively used in Europe, USA and Japan, as an ingredient of Portland cement concrete particularly for marine and hydraulic structures. It has been amply demonstrated that the best pozzolans in optimum proportions mixed with Portland cement improves many qualities of concrete, such as:

(a) Lower the heat of hydration and thermal shrinkage;
(b) Increase the water tightness;
(c) Reduce the alkali-aggregate reaction;
(d) Improve resistance to attack by sulphonate soils and sea water;
(e) Improve extensibility;
(f) Lower susceptibility to dissolution and leaching;
(g) Improve workability;
(h) Lower costs.

In addition to these advantages, contrary to the general opinion, good pozzolans will not unduly increase water requirement or drying shrinkage.

FLY ASH:
Fly ash is finely divided residue resulting from the combustion of powdered coal and transported by the flue gases and collected by electrostatic precipitator. In U.K. it is referred as pulverized fuel ash (PFA). Fly ash is the most widely used pozzolanic material all over the world.

Fly ash was first used in large scale in the construction of Hungry Horse dam in America in the approximate amount of 30 per cent by weight of cement. Later on it was used in Canyon and Ferry dams etc. In India, Fly ash was used in Rihand dam construction replacing cement upto about 15 per cent.
In the recent time, the importance and use of fly ash in concrete has grown so much that it has almost become a common ingredient in concrete, particularly for making high strength and high performance concrete. Extensive research has been done all over the world on the benefits that could be accrued in the utilization of fly ash as a supplementary cementitious material. High volume fly ash concrete is a subject of current interest all over the world.

The use of fly ash as concrete admixture not only extends technical advantages to the properties of concrete but also contributes to the environmental pollution control. In India alone, we produce about 75 million tons of fly ash per year, the disposal of which has become a serious environmental problem. The effective utilization of fly ash in concrete making is, therefore, attracting serious considerations of concrete technologies and government departments.

There are two ways that the fly ash can be used: one way is to intergrind certain percentage of fly ash with cement clinker at the factory to produce Portland pozzolana cement (PPC) and the second way is to use the fly ash as an admixture at the time of making concrete at the site of work. The latter method gives freedom and flexibility to the user regarding the percentage addition of fly ash.

ASTM broadly classifies fly ash into two classes.

**Class F**: Fly ash normally produced by burning anthracite or bituminous coal, usually has less than 5% CaO. Class F fly ash has pozzolanic properties only.

**Class C**: Fly ash normally produced by burning lignite or sub-bituminous coal. Some class C fly ash may have CaO content in excess of 10%. In addition to pozzolanic properties, class C fly ash also possesses cementitious properties.

Fly ash, when tested in accordance with the methods of test specified in IS: 1727-1967.
EFFECT OF FLY ASH ON FRESH CONCRETE

Good fly ash with high fineness, low carbon content, highly reactive forms only a small fraction of total fly ash collected. The ESP fly ash collected in chambers I and II are generally very coarse, non spherical particles showing large ignition loss. They can be called coal ash rather than fly ash. Such fly ash (coal ash) is not suitable for use as pozzolan and they do not reduce the water demand. Use of right quality fly ash, results in reduction of water demand for desired slump. With the reduction of unit water content, bleeding and drying shrinkage will also be reduced. Since fly ash is not highly reactive, the heat of hydration can be reduced through replacement of part of the cement with fly ash.

EFFECTS OF FLY ASH ON HARDENED CONCRETE

Fly ash, when used in concrete, contributes to the strength of concrete due to its pozzolanic reactivity. However, since the pozzolanic reaction proceeds slowly, the initial strength of fly ash concrete tends to be lower than that of concrete without fly ash. Due to continued pozzolanic reactivity concrete develops greater strength at later age, which may exceed that of the concrete without fly ash. The pozzolanic reaction also contributes to making the texture of concrete dense, resulting in decrease of water permeability and gas permeability. It should be noted that since pozzolanic reaction can only proceed in the presence of water enough moisture should be available for long time. Therefore, fly ash concrete should be cured for longer period. In this sense, fly ash concrete used in under water structures such as dams will derive full benefits of attaining improved long term strength and water-tightness.
DURABILITY OF CONCRETE

Sufficiently curved concrete containing good quality fly ash shows dense structure which offers high resistivity to the infiltration of deleterious substances. A point for consideration is that the pozzolanic reactivity reduces the calcium hydroxide content, which results in reduction of passivity to the steel reinforcement and at the same time the additional secondary cementitious material formed makes the paste structure dense, and there by gives more resistance to the corrosion of reinforcement. Which one will have an overriding effect on the corrosion of reinforcement will be a point in question. Published data reports that concrete with fly ash shows similar depth of carbonation as that of concrete without fly ash, as long as the compressive strength level is same.

It is also recognized that the addition of fly ash contributes to the reduction of the expansion due to alkali-aggregate reaction. The dilution effect of alkali and reduction of the water permeability due to dense texture may be one of the factors for reduction of alkali-aggregate reaction. In conclusion it may be said that although fly ash is an industrial waste, its use in concrete significantly improve the long term strength and durability and reduce heat of hydration. In other words good fly ash will be an indispensable mineral admixture for high performance concrete.

SILICA FUME

Silica fume, also referred to as micro silica or condensed silica fume, is another material that is used as an artificial pozzolanic admixture. It is a product resulting from reduction of high purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy. Silica fume rises as an oxidized vapor. It cools, condenses and is collected on cloth bags. It is further processed to remove impurities and to control particle size. Condensed silica fume is essentially silicon dioxide in noncrystalline form. Since it is an airborne material like fly ash, it has spherical shape. It is extremely fine with particle size less than 1 micron and
with an average diameter of about 0.1 micron, about 100 times smaller than average cement particles. Silica fume has specific surface area of about 20000 m2/kg, as against 230 to 300 m2/kg that of cement. Since silica fume or micro silica is an important new material, let us see this material in some detail.

- Micro silica is initially produced as an ultra fine undensified powder
- At least 85% SiO2 content
- Mean particle size between 0.1 and 0.2 micron
- Minimum specific surface area is 15000 m2/kg
- Spherical particle shape.

Available forms
- Undensified forms with bulk density of 200-300 kg/cum
- Densified forms with bulk density of 500-600 kg/cum
- Micro-palletized forms with bulk density of 600-800 kg/cum
- Slurry forms with density 1400 kg/cum
- Slurry is produced by mixing undensified micro silica powder and water in equal proportions by weight. Slurry is the easiest and most practical way to introduce micro silica into the concrete mix
- Surface area 15-20 m2/g
- Standard grade slurry pH value 4.7

**POZZOLANIC ACTION**

Micro silica is much more reactive than fly ash or any other natural pozzolana. The reactivity of a pozzolana can be quantified by measuring the amount of calcium hydroxide in the cement paste at different times.

**INFLUENCE ON FRESH CONCRETE**

Water demand increases in proportion to the amount of microsilica added. The increase in water demand of concrete containing microsilica will be about 1% for every 1% of cement substituted.
INFLUENCE ON HARDENED CONCRETE

Concrete containing micro silica showed outstanding characteristics in the development of strength.

GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

Ground granulated blast-furnace slag is a non metallic product consisting essentially of silicates and aluminates of calcium and other bases. The molten slag is rapidly chilled by quenching in water ton form a glassy sand like granulated material. The granulated material when further ground to less than 45 micron will have specific surface of about 400-600m2/kg.

Chemical composition

- Calcium oxide 30-45%
- Silicon dioxide 30-38%
- Aluminium oxide 15-25%
- Ferrous oxide 0.5-2.0
- Specific gravity 2.9

In India, we produce about 7.8 million tons of blast furnace slag. All the blast furnace slags are granulated by quenching the molten slag by high power water jet, making 100% glassy slag granules of 0.4 mm size. The blast furnace slag is mainly used in India for manufacturing slag cement. There are two methods for making blast furnace slag cement. In the first method blast furnace slag is interground with cement clinker along with gypsum. In the second method blast furnace slag is separately ground and then mixed with the cement. Clinker is hydraulically more active than slag. It follows then that slag should be ground finer than clinker, in order to fully develop its hydraulic potential. However, since slag is much harder and difficult to grind compared to clinker, it is ground relatively coarser during the process of inter grinding. This leads to waste of hydraulic potential of slag. Not only that the inter-grinding seriously restricts the flexibility to optimize slag level for different uses. Just as fly ash is used as an
admixture in making concrete ground granulated blast furnace slag popularly called GGBS is used as an admixture in making concrete. In other countries it’s as an admixture is more common than its use as slag cement. Recently for marine outfall work at Bandra, Mumbai, GGBS has been used as an admixture to replace cement to the tune of 70%. Presently in India, with the growing popularity of RMC, the scope for using GGBS for customer’s tailor made requirements should also become popular.

PERFORMANCE OF GGBS IN CONCRETE

FRESH CONCRETE:
The replacement of cement with GGBS will reduce the unit water content necessary to obtain the same slump. This reduction of unit water content will be more pronounced with increase in slag content and also on the fineness of slag. This is because of the surface configuration and particle shape of being different than cement particle. In addition, water used for mixing is not immediately lost, as the surface hydration slag is slightly slower than that of cement. Reduction of bleeding is not significant with slag of 4000 sqcm/g fineness. But significant beneficial effect is observed with slag fineness of 6000 sqcm/g and above.

HARDENED CONCRETE:
Exclusive research works have shown that the use of slag leads to the enhancement of intrinsic properties of concrete in both fresh and hardened conditions. The major advantages recognized are

• Reduced heat of hydration
• Refinement of pore structures
• Reduced permeability to the external agencies
• increased resistance to chemical attack
UNIT - 3

CONCRETE MIX DESIGN

Introduction

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required, strength, durability, and workability as economically as possible, is termed the concrete mix design. The proportioning of ingredient of concrete is governed by the required performance of concrete in 2 states, namely the plastic and the hardened states. If the plastic concrete is not workable, it cannot be properly placed and compacted. The property of workability, therefore, becomes of vital importance. The compressive strength of hardened concrete which is generally considered to be an index of its other properties, depends upon many factors, e.g. quality and quantity of cement, water and aggregates; batching and mixing; placing, compaction and curing. The cost of concrete is made up of the cost of materials, plant and labour. The variations in the cost of materials arise from the fact that the cement is several times costly than the aggregate, thus the aim is to produce as lean a mix as possible. From technical point of view the rich mixes may lead to high shrinkage and cracking in the structural concrete, and to evolution of high heat of hydration in mass concrete which may cause cracking.

The actual cost of concrete is related to the cost of materials required for producing a minimum mean strength called characteristic strength that is specified by the designer of the structure. This depends on the quality control measures, but there is no doubt that the quality control adds to the cost of concrete. The extent of quality control is often an economic compromise, and depends on the size and type of job. The cost of labour depends on the workability of mix, e.g., a concrete mix of inadequate workability may result in a high cost of labour to obtain a degree of compaction with available equipment.

2. Requirements of concrete mix design
The requirements which form the basis of selection and proportioning of mix ingredients are:

a) The minimum compressive strength required from structural consideration
b) The adequate workability necessary for full compaction with the compacting equipment available.
c) Maximum water-cement ratio and/or maximum cement content to give adequate durability for the particular site conditions
d) Maximum cement content to avoid shrinkage cracking due to temperature cycle in mass concrete.

2.1 Types of Mixes

i. Nominal Mixes
In the past the specifications for concrete prescribed the proportions of cement, fine and coarse aggregates. These mixes of fixed cement-aggregate ratio which ensures adequate strength are termed nominal mixes. These offer simplicity and under normal circumstances, have a margin of strength above that specified. However, due to the variability of mix ingredients the nominal concrete for a given workability varies widely in strength.

ii. Standard mixes
The nominal mixes of fixed cement-aggregate ratio (by volume) vary widely in strength and may result in under- or over-rich mixes. For this reason, the minimum compressive strength has been included in many specifications. These mixes are termed standard mixes. IS 456-2000 has designated the concrete mixes into a number of grades as M10, M15, M20, M25, M30, M35 and M40. In this designation the letter M refers to the mix and the number to the specified 28 day cube strength of mix in N/mm². The mixes of grades M10, M15, M20 and M25 correspond approximately to the mix proportions (1:3:6), (1:2:4), (1:1.5:3) and (1:1:2) respectively.

iii. Designed Mixes
In these mixes the performance of the concrete is specified by the designer but the mix proportions are determined by the producer of concrete, except that the minimum cement content can be laid down. This is most rational approach to the selection of mix proportions with specific materials in mind possessing more or less unique characteristics. The approach results in the production of concrete with the appropriate properties most economically. However, the designed mix does not serve as a guide since this does not guarantee the correct mix proportions for the prescribed performance. For the concrete with undemanding performance nominal or standard mixes (prescribed in the codes by quantities of dry ingredients per cubic meter and by slump) may be used only for very small jobs, when the 28-day strength of concrete does not exceed 30 N/mm². No control testing is necessary reliance being placed on the masses of the ingredients.

3. Factors affecting the choice of mix proportions

The various factors affecting the mix design are:

3.1. Compressive strength

It is one of the most important properties of concrete and influences many other describable properties of the hardened concrete. The mean compressive strength required at a specific age, usually 28 days, determines the nominal water-cement ratio of the mix. The other factor affecting the strength of concrete at a given age and cured at a prescribed temperature is the degree of compaction. According to Abraham’s law the strength of fully compacted concrete is inversely proportional to the water-cement ratio.

3.2. Workability

The degree of workability required depends on three factors. These are the size of the section to be concreted, the amount of reinforcement, and the method of compaction to be used. For the narrow and complicated section with numerous corners or inaccessible parts, the concrete must have a high workability so that full compaction can be achieved with a reasonable amount of effort. This also applies to the embedded steel sections. The desired workability depends on the
3.3. Durability
The durability of concrete is its resistance to the aggressive environmental conditions. High strength concrete is generally more durable than low strength concrete. In the situations when the high strength is not necessary but the conditions of exposure are such that high durability is vital, the durability requirement will determine the water-cement ratio to be used.

3.4. Maximum nominal size of aggregate
In general, larger the maximum size of aggregate, smaller is the cement requirement for a particular water-cement ratio, because the workability of concrete increases with increase in maximum size of the aggregate. However, the compressive strength tends to increase with the decrease in size of aggregate. IS 456:2000 and IS 1343:1980 recommend that the nominal size of the aggregate should be as large as possible.

3.5. Grading and type of aggregate
The grading of aggregate influences the mix proportions for a specified workability and water-cement ratio. Coarser the grading leaner will be mix which can be used. Very lean mix is not desirable since it does not contain enough finer material to make the concrete cohesive. The type of aggregate influences strongly the aggregate-cement ratio for the desired workability and stipulated water cement ratio. An important feature of a satisfactory aggregate is the uniformity of the grading which can be achieved by mixing different size fractions.

3.6. Quality Control
The degree of control can be estimated statistically by the variations in test results. The variation in strength results from the variations in the properties of the mix ingredients and lack of control of accuracy in batching, mixing, placing, curing and testing. The lower the difference between the mean and minimum strengths of the mix lower will be the cement-content required. The factor controlling this difference is termed as quality control.
4 Mix Proportion designations

The common method of expressing the proportions of ingredients of a concrete mix is in the terms of parts or ratios of cement, fine and coarse aggregates. For e.g., a concrete mix of proportions 1:2:4 means that cement, fine and coarse aggregate are in the ratio 1:2:4 or the mix contains one part of cement, two parts of fine aggregate and four parts of coarse aggregate. The proportions are either by volume or by mass. The water-cement ratio is usually expressed in mass.

4.1 Factors to be considered for mix design

• The grade designation giving the characteristic strength requirement of concrete.
• The type of cement influences the rate of development of compressive strength of concrete.
• Maximum nominal size of aggregates to be used in concrete may be as large as possible within the limits prescribed by IS 456:2000.
• The cement content is to be limited from shrinkage, cracking and creep.
• The workability of concrete for satisfactory placing and compaction is related to the size and shape of section, quantity and spacing of reinforcement and technique used for transportation, placing and compaction.

5. Examples of concrete mix proportioning

1 Problems

1 - M40 pumpable concrete

A-1 Design stipulations for proportioning

a) Grade designation : M40
b) Type of cement : OPC 43 grade confirming to IS 8112
c) Maximum nominal size of aggregates : 20 mm
d) Minimum cement content : 320 kg/m3
e) Maximum water cement ratio : 0.45
f) Workability : 100 mm (slump)
g) Exposure condition : Severe (for reinforced concrete)
h) Method of concrete placing : Pumping  
i) Degree of supervision : Good  
j) Type of aggregate : Crushed angular aggregate  
k) Maximum cement content : 450 kg/m3  
l) Chemical admixture type : Superplasticiser  

A-2 TEST DATA FOR MATERIALS  
a) Cement used : OPC 43 grade confirming to IS 8112  
b) Specific gravity of cement : 3.15  
c) Chemical admixture : Superplasticiser conforming to IS 9103  
d) Specific gravity of  
Coarse aggregate : 2.74  
Fine aggregate : 2.74  
e) Water absorption  
Coarse aggregate : 0.5 percent  
Fine aggregate : 1.0 percent  
f) Free (surface) moisture  
Coarse aggregate : Nil (absorbed moisture also nil)  
Fine aggregate : Nil  
g) Sieve analysis  
Coarse aggregate : Conforming to Table 2 of IS: 383  
Fine aggregate : Conforming to Zone I of IS: 383  

A-3 TARGET STRENGTH FOR MIX PROPORTIONING  
f’ck = fck + 1.65 s  
Where  
f’ck = Target average compressive strength at 28 days,  
fck = Characteristic compressive strength at 28 days,  
s= Standard deviation  
From Table 1 standard deviation, s = 5 N/mm2  
Therefore target strength = 40 + 1.65 x 5 = 48.25 N/mm2
A-4 SELECTION OF WATER CEMENT RATIO
From Table 5 of IS:456-2000, maximum water cement ratio = 0.45
Based on experience adopt water cement ratio as 0.40
0.4 < 0.45, hence ok

A-5 SELECTION OF WATER CONTENT
From Table-2, maximum water content = 186 liters (for 25mm – 50mm slump range and for 20 mm aggregates)
Estimated water content for 100 mm slump = 186 + 6/100 x186 = 197 liters
As superplasticiser is used, the water content can be reduced up to 20 percent and above Based on trials with SP water content reduction of 29 percent has been achieved.
Hence the water content arrived = 19 x 0.71 =140 liters

A-6 CALCULATION OF CEMENT CONTENT
Water cement ratio = 0.40
Cement content = 140/0.40 = 350 kg/m3
From Table 5 of IS: 456, minimum cement content for severe exposure condition = 320 kg/m3
350 kg/m3 > 320 kg/m3, hence OK

A-7 PROPORTION OF VOLUME OF COARSE AGGREGATE AND FINE AGGREGATE CONTENT
From Table 3, volume of coarse aggregate corresponding to 20 mm size aggregate and fine aggregate (Zone I) for water-cement ratio of 0.50 =0.60
In the present case w/c= 0.40. The volume of coarse aggregate is required to be increased to decrease the fine aggregate content. As w/c ratio is lower by 0.10, increase the coarse aggregate volume by 0.02 (at the rate of +/- 0.01 for every +/- 0.05 change in water cement ratio). Therefore corrected volume of coarse aggregate for w/c of 0.40 =0.62
Note: In case the coarse aggregate is not angular, then also the volume of CA may be required to be increased suitably based on experience.

For pumpable concrete these values should be reduced by 10 percent
Therefore volume of coarse aggregate = 0.62 x 0.9 = 0.56
Volume of fine aggregate content = 1 - 0.56 = 0.44

A-8 MIX CALCULATIONS

The mix calculations per unit volume of concrete shall be as follows
a) Volume of concrete = 1 m³
b) Volume of cement = \[ \frac{350}{3.15} \times \frac{1}{1000} = 0.111 \text{ m}³ \]
c) Volume of water = \[ \frac{140}{1} \times \frac{1}{1000} = 0.140 \text{ m}³ \]
d) Volume of chemical admixture = \[ \frac{7}{1.145} \times \frac{1}{1000} = 0.006 \text{ m}³ \]
  (SP 2% by mass of cement)
e) Volume of all in aggregates (e) = a – (b + c + d)
  = 1 – (0.111 + 0.140 + 0.006) = 0.743 \text{ m}³
f) Volume of coarse aggregates = e x Volume of CA x specific gravity of CA
  = 0.743 x 0.56 x 2.74 x 1000 = 11140 kg
g) Volume of fine aggregates = e x Volume of FA x specific gravity of FA
  = 0.743 x 0.44 x 2.74 x 1000 = 896 kg

A-9 MIX PROPORTIONS FOR TRIAL NUMBER 1

Cement = 350 kg/m³
Water = 140 kg/m³
Fine aggregate = 896 kg/m³
Coarse aggregates = 1140 kg/m³
Chemical admixture = 7 kg/m³
Water cement ratio = 0.40

Aggregates are assumed to be in SSD. Otherwise corrections are to be applied while calculating the water content. Necessary corrections are also required to be made in mass of aggregates.
A-10 The slump shall be measured and the water content and dosages of admixture shall be adjusted for achieving the required slump based on trials, if required. The mix proportions shall be reworked for the actual water content and checked for durability requirements.

A-11 Two more trials having variation of ± 10 percent of water cement ratio in A-10 shall be carried out keeping water content constant, and a graph between three water cement ratios and their corresponding strengths shall be plotted to work out the mix proportions for the given target strength for field trials. However, durability requirements shall be met.

Problem 2
Illustrative examples on concrete mix proportioning [M40 pumpable concrete with fly ash]

A-1 Design stipulations for proportioning
m) Grade designation : M40
n) Type of cement : OPC 43 grade confirming to IS 8112
o) Type of mineral admixture : Fly ash confirming to IS 3812 (Part-1)
p) Maximum nominal size of aggregates : 20 mm
q) Minimum cement content : 320 kg/m3
r) Maximum water cement ratio : 0.45
s) Workability : 100 mm (slump)
t) Exposure condition : Severe (for reinforced concrete)
u) Method of concrete placing : Pumping
v) Degree of supervision : Good
w) Type of aggregate : Crushed angular aggregate
x) Maximum cement content : 450 kg/m3
y) Chemical admixture type : Superplasticiser

A-2 TEST DATA FOR MATERIALS
h) Cement used : OPC 43 grade confirming to IS 8112
i) Specific gravity of cement : 3.15
z) Fly ash used : Fly ash confirming to IS 3812 (Part-1)
j) Specific gravity of fly ash : 2.2
k) Chemical admixture : Superplasticiser conforming to IS 9103
l) Specific gravity of
Coarse aggregate : 2.74
Fine aggregate : 2.74
m) Water absorption
Coarse aggregate : 0.5 percent
Fine aggregate : 1.0 percent
n) Free (surface) moisture
Coarse aggregate : Nil (absorbed moisture also nil)
Fine aggregate : Nil
o) Sieve analysis
Coarse aggregate : Conforming to Table 2 of IS: 383
Fine aggregate : Conforming to Zone I of IS: 383

A-3 TARGET STRENGTH FOR MIX PROPORTIONING

\[ f'_c k = f_{ck} + 1.65 \, s \]

Where
\[ f'_c \] = Target average compressive strength at 28 days,  
\[ f_{ck} = \text{Characteristic compressive strength at 28 days,} \]
\[ s = \text{Standard deviation} \]

From Table 1 standard deviation, \( s = 5 \, \text{N/mm}^2 \)
Therefore target strength = \( 40 + 1.65 \times 5 = 48.25 \, \text{N/mm}^2 \)

A-4 SELECTION OF WATER CEMENT RATIO

From Table 5 of IS:456-2000, maximum water cement ratio = 0.45
Based on experience adopt water cement ratio as 0.40
0.4 < 0.45, hence ok

A-5 SELECTION OF WATER CONTENT
From Table-2, maximum water content = 186 liters (for 25mm – 50mm slump range and for 20 mm aggregates) Estimated water content for 100 mm slump = 186 + 6/100 x186 = 197 liters  As superplasticiser is used, the water content can be reduced up to 20 percent and above Based on trials with SP water content reduction of 29 percent has been achieved. Hence the water content arrived = 19 x 0.71 =140 liters

**A-6 CALCULATION OF CEMENT CONTENT**

Water cement ratio = 0.40
Cement content = 140/0.40 = 350 kg/m3

From Table 5 of IS: 456, minimum cement content for severe exposure condition = 320 kg/m3
350 kg/m3 > 320 kg/m3, hence OK

*For proportioning fly ash concrete, the suggested steps are; Decide the percentage of fly ash to be used based on [project requirement and quality of Materials In certain situations increase in cementitious material content may be warranted. The decision on increase in cementitious material content and its percentage may be based on experience and trial. The example is with increase of 10% of cementitious material content.*

Cementitious material content 1.1 x 350 = 385 kg/m3
Water content = 140 kg/m3
Water cement ratio = 140/385 = 0.364 _0.40

*Let us use fly as at 30 percent of cementitious material content in addition to cement Fly ash = 385 x 0.3 = 115 kg/m3
Cement =385-115=270 kg/m3
(Saving of cement compared to previous design = 350-279 = 80 kg/m3 and fly ash utilization = 115 kg/m3)*

**A-7 PROPORTION OF VOLUME OF COARSE AGGREGATE AND FINE AGGREGATE CONTENT**
From Table 3, volume of coarse aggregate corresponding to 20 mm size aggregate and fine aggregate (Zone I) for water-cement ratio of 0.50 =0.60 In the present case w/c= 0.40. The volume of coarse aggregate is required to be increased to decrease the fine aggregate content. As w/c ratio is lower by 0.10, increase the coarse aggregate volume by 0.02 (at the rate of +/- 0.01 for every +/- 0.05 change in water cement ratio). Therefore, corrected volume of coarse aggregate for w/c of 0.40 =0.62.

Note: In case the coarse aggregate is not angular, then also the volume of CA may be required to be increased suitably based on experience For pumpable concrete these values should be reduced by 10 percent.

Therefore volume of coarse aggregate = 0.62 x 0.9 = 0.56

Volume of fine aggregate content = 1 - 0.56 = 0.44

A-8 MIX CALCULATIONS

The mix calculations per unit volume of concrete shall be as follows

h) Volume of concrete = 1 m³

i) Volume of cement =

= [270/3.15] x [1/1000] = 0.086 m³

j) Volume of fly ash = [115/2.2] x [1/1000] = 0.052 m³

k) Volume of water = [140/1] x [1/1000] = 0.140 m³

l) Volume of chemical admixture = [7.7/1.145] x [1/1000] = 0.007 m³

( SP 2%by mass of cementitious material)

m) Volume of all in aggregates (e) =a – (b + c + d)

= 1 – (0.086 + 0.052 + 0.140 + 0.007) = 0.715 m³

n) Volume of coarse aggregates = e x Volume of CA x specific gravity of CA

= 0.715 x 0.56 x 2.74 x 1000 = 1097 kg

o) Volume of fine aggregates = e x Volume of FA x specific gravity of FA

= 0.715 x 0.44 x 2.74 x 1000 = 862 kg

A-9 MIX PROPORTIONS FOR TRIAL NUMBER 1

Cement = 270 kg/m³
Fly ash = 115 kg/m³
Water = 140 kg/m³
Fine aggregate = 862 kg/m³
Coarse aggregates = 1097 kg/m³
Chemical admixture = 7.7 kg/m³
Water cement ratio = 0.364

Aggregates are assumed to be in SSD. Otherwise corrections are to be applied while calculating the water content. Necessary corrections are also required to be made in mass of aggregates.

A-10 The slump shall be measured and the water content and dosages of admixture shall be adjusted for achieving the required slump based on trials, if required. The mix proportions shall be reworked for the actual water content and checked for durability requirements.

A-11 Two more trials having variation of ±10 percent of water cement ratio in A-10 shall be carried out keeping water content constant, and a graph between three water cement ratios and their corresponding strengths shall be plotted to work out the mix proportions for the given target strength for field trials. However, durability requirements shall be met.

**Problem 3**
Design of M20 concrete mix as per IS:10262-2009, Concrete mix proportioning-guidelines (First revision)

A-1 Design stipulations for proportioning
i. Grade designation: M20
ii. Type of cement: OPC 43 grade confirming to IS 8112
iii. Maximum nominal size of aggregates: 20 mm
iv. Minimum cement content: 320 kg/m³
v. Maximum water cement ratio: 0.55
vi. Workability: 75 mm (slump)
vii. Exposure condition : Mild
viii. Degree of supervision : Good
ix. Type of aggregate : Crushed angular aggregate
x. Maximum cement content : 450 kg/m³
xi. Chemical admixture : Not recommended

**A-2 TEST DATA FOR MATERIALS**

p) Cement used : OPC 43 grade confirming to IS 8112
q) Specific gravity of cement : 3.15
r) Specific gravity of
   Coarse aggregate : 2.68
   Fine aggregate : 2.65
s) Water absorption
   Coarse aggregate : 0.6 percent
   Fine aggregate : 1.0 percent
t) Free (surface) moisture
   Coarse aggregate : Nil (absorbed moisture full)
   Fine aggregate : Nil
u) Sieve analysis
   Coarse aggregate : Conforming to Table 2 of IS: 383
   Fine aggregate : Conforming to Zone I of IS: 383

**A-3 TARGET STRENGTH FOR MIX PROPORTIONING**

\[ f'_{ck} = fck + 1.65 \times s \]

Where

- \( f'_{ck} \) = Target average compressive strength at 28 days,
- \( fck \) = Characteristic compressive strength at 28 days,
- \( s \) = Standard deviation

From Table 1 standard deviation, \( s = 4 \) N/mm²

Therefore target strength = 20 + 1.65 \times 4 = 26.60 N/mm²

**A-4 SELECTION OF WATER CEMENT RATIO**
From Table 5 of IS:456-2000, maximum water cement ratio = 0.55 (Mild exposure) Based on experience adopt water cement ratio as 0.50 0.5 < 0.55, hence ok.

**A-5 SELECTION OF WATER CONTENT**

From Table-2, maximum water content = 186 liters (for 25mm – 50mm slump range and for 20 mm aggregates) Estimated water content for 75 mm slump = 186 + 3/100 x186 = 191.6 liters

**A-6 CALCULATION OF CEMENT CONTENT**

Water cement ratio = 0.50  
Cement content = 191.6/0.5 = 383 kg/m³ >320 kg/m³ (given)  
From Table 5 of IS: 456, minimum cement content for mild exposure condition = 300 kg/m³  
Hence OK

**A-7 PROPORTION OF VOLUME OF COARSE AGGREGATE AND FINE AGGREGATE CONTENT**

From Table 3, volume of coarse aggregate corresponding to 20 mm size aggregate and fine aggregate (Zone I) for water-cement ratio of 0.50 =0.60

**A-8 MIX CALCULATIONS**

The mix calculations per unit volume of concrete shall be as follows

a) Volume of concrete = 1 m³  
b) Volume of cement =  
= [383.16/3.15] x [1/1000] = 0.122 m³  
c) Volume of water = [192/1] x [1/1000] = 0.192 m³  
d) Volume of all in aggregates (e) =a – (b + c)  
= 1 – (0.122 + 0.192) = 0.686 m³  
e) Volume of coarse aggregates = e x Volume of CA x specific gravity of CA  
= 0.686 x 0.6 x 2.68 x 1000 = 1103 kg  
f) Volume of fine aggregates = e x Volume of FA x specific gravity of FA
= 0.686 x 0.4 x 2.65 x 1000 = 727 kg

A-9 MIX PROPORTIONS FOR TRIAL NUMBER 1

Cement = 383 kg/m3
Water = 191.6 kg/m3
Fine aggregate = 727 kg/m3
Coarse aggregates = 1103 kg/m3
Water cement ratio = 0.50
Yield = 2404.6 kg

Aggregates are assumed to be in SSD. Otherwise corrections are to be applied while calculating the water content. Necessary corrections are also required to be made in mass of aggregates. Trial mixes: Laboratory study.

Problem 4

Design of M30 concrete mix as per IS:10262-2009, Concrete mix proportioning- guidelines(First revision)

A-1 Design stipulations for proportioning

xii. Grade designation : M30
xiii. Type of cement : OPC 43 grade confirming to IS 8112
xiv. Maximum nominal size of aggregates : 20 mm
xv. Minimum cement content : 350 kg/m3
xvi. Maximum water cement ratio : 0.50
xvii. Workability : 25 - 50 mm (slump)
xviii. Exposure condition : Moderate
xix. Degree of supervision : Good
xx. Type of aggregate : Crushed angular aggregate
xxi. Maximum cement content : 450 kg/m3
xxii. Chemical admixture : Not recommended
A-2 TEST DATA FOR MATERIALS
v) Cement used : OPC 43 grade confirming to IS 8112
w) Specific gravity of cement : 3.15
x) Specific gravity of
   Coarse aggregate : 2.68
   Fine aggregate : 2.65
y) Water absorption
   Coarse aggregate : 0.6 percent
   Fine aggregate : 1.0 percent
z) Free (surface) moisture
   Coarse aggregate : Nil (absorbed moisture full)
   Fine aggregate : Nil
aa) Sieve analysis
   Coarse aggregate : Conforming to Table 2 of IS: 383
   Fine aggregate : Conforming to Zone I of IS: 383

A-3 TARGET STRENGTH FOR MIX PROPORTIONING
\[ f'_{ck} = f_{ck} + 1.65 s \]
Where
\[ f'_{ck} \] = Target average compressive strength at 28 days,
\[ f_{ck} \] = Characteristic compressive strength at 28 days,
\[ s \] = Standard deviation
From Table 1 standard deviation, \( s = 5 \text{ N/mm}^2 \)
Therefore target strength = \( 30 + 1.65 \times 5 = 38.25 \text{ N/mm}^2 \)

A-4 SELECTION OF WATER CEMENT RATIO
From Table 5 of IS:456-2000, maximum water cement ratio = 0.50 (Moderate exposure) Based on experience adopt water cement ratio as 0.45 as the cement is 53 grade 0.45 \(< or =0.5\), hence ok.
A-5 SELECTION OF WATER CONTENT
From Table-2, maximum water content = 186 liters (for 25mm – 50mm slump range and for 20 mm aggregates) Estimated water content for 25-50 mm slump = 186 liters

A-6 CALCULATION OF CEMENT CONTENT
Water cement ratio = 0.45
Cement content = 186/0.45 = 413 kg/m³ >350 kg/m³ (given)
From Table 5 of IS: 456, minimum cement content for moderate exposure condition = 300 kg/m³
Hence OK

A-7 PROPORTION OF VOLUME OF COARSE AGGREGATE AND FINE AGGREGATE CONTENT
From Table 3, volume of coarse aggregate corresponding to 20 mm size aggregate and fine aggregate (Zone I) for water-cement ratio of 0.50 =0.60. Modify this as w/c is 0.45. The new value is 0.61. Volume of fine aggregate is 0.39.

A-8 MIX CALCULATIONS
The mix calculations per unit volume of concrete shall be as follows

\[ g) \text{ Volume of concrete} = 1 \text{ m}^3 \]

h) Volume of cement
\[ = \frac{413}{3.15} \times \frac{1}{1000} = 0.131 \text{ m}^3 \]

i) Volume of water
\[ = \frac{186}{1} \times \frac{1}{1000} = 0.186 \text{ m}^3 \]

j) Volume of all in aggregates (e) = \( a - (b + c) \)
\[ = 1 - (0.131 + 0.186) = 0.683 \text{ m}^3 \]

k) Volume of coarse aggregates = \( e \times \text{Volume of CA} \times \text{specific gravity of CA} \)
\[ = 0.683 \times 0.61 \times 2.68 \times 1000 = 1117 \text{ kg} \]

l) Volume of fine aggregates = \( e \times \text{Volume of FA} \times \text{specific gravity of FA} \)
\[ = 0.683 \times 0.39 \times 2.65 \times 1000 = 706 \text{ kg} \]

A-9 MIX PROPORTIONS FOR TRIAL NUMBER 1
Cement = 413 kg/m³
Water = 186 kg/m³
Fine aggregate = 706 kg/m³
Coarse aggregates = 1117 kg/m³
Water cement ratio = 0.45
Yield = 2422 kg
UNIT - 4

DURABILITY OF CONCRETE STRUCTURES

Definition:
A long service life is considered synonymous with durability. Since durability under one set of conditions does not necessarily mean durability under another, it is customary to include a general reference to the environment when defining durability. According to ACI Committee 201, durability of Portland cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration; that is, durable concrete will retain its original form, quality, and serviceability when exposed to its environment. No material is inherently durable; as a result of environmental interactions the microstructure and, consequently, the properties of materials change with time. A material is assumed to reach the end of service life when its properties under given conditions of use have deteriorated to an extent that the continuing use of the material is ruled either unsafe or uneconomical.

Materials Related Failures

Concrete Deterioration can be caused by:
- The use of inappropriate materials.
- Poor construction practices.

Environmental Related Causes of Concrete Durability Problems
The inferior durability characteristics of concrete may be caused by the environment that the concrete is exposed to. The following environmental condition can affect the concrete durability:
- Temperature.
- Moisture.
- Physical factors.
- Chemical factors.
- Biological factors. These factors may be due to weathering conditions (temperature, and moisture changes), or to abrasion, attack by natural or industrial liquids and gases, or biological agents. Durability problems related to environmental causes include the following: steel corrosion, delamination, cracking, carbonation, sulfate attack, chemical attack, scaling, spalling, abrasion and cavitation.

**Dimensional Stability**

The influence of shrinkage and creep on concrete cracking: under restraining conditions in concrete, the interplay between the elastic tensile stresses induced by shrinkage strains and the stress relief due to the viscoelastic behavior is at the heart of the deformations and cracking in most structures. To understand the reason why a concrete element may not crack at all or may crack but not soon after exposure to the environment, we have to consider how concrete would respond to sustained stress or to sustained strain. The phenomenon of a gradual increase in strain with time under a given level of sustained stress is called creep.

The phenomenon of gradual decrease in stress with time under a given level of sustained strain is called stress relaxation. Both manifestations are typical of viscoelastic materials. When a concrete element is restrained, the viscoelasticity of concrete will manifest into a progressive decrease of stress with time (Fig. 4-1 curve b from Mehta textbook). Thus under the restraining conditions present is concrete, the interplay between elastic tensile stresses induced by shrinkage strains and stress relief due to viscoelastic behavior is at the heart of deformations and cracking in most structure.
THERMAL SHRINKAGE
In general, solids expand on heating and contract on cooling. The strain associated with change in temperature will depend on the coefficient of thermal expansion of the material and the magnitude of temperature drop or rise. Except under extreme climatic conditions, ordinary concrete structures suffer little or no distress from changes in ambient temperature. However, in massive structures, the combination of heat produced by cement hydration and relatively poor heat dissipation conditions results in a large rise in concrete temperature within a few days after placement. Subsequently, cooling to the ambient temperature often causes the concrete to crack.

Since the primary concern in the design and construction of mass concrete structures is that the completed structure remains a monolith, free of cracks, every effort to control the temperature rise is made through selection of proper materials, mix proportions, curing conditions, and construction practices.

With low tensile strength materials, such as concrete, it is the shrinkage strain from cooling that is more important than the expansion from heat generated by cement hydration. This is because, depending on the elastic modulus, the degree of restraint, and stress relaxation due to creep, the resulting tensile stresses can be
large enough to cause cracking. For instance, assuming that the coefficient of thermal expansion of concrete is $10 \times 10^{-6}$ per °C, and the temperature rise above the ambient from heat of hydration is 15 °C, then the thermal shrinkage caused by the 15 °C temperature drop will be $150 \times 10^{-6}$. The elastic modulus ($E$) of ordinary concrete may be assumed as $3 \times 10^6$ psi. If the concrete member is fully restrained ($Dr = 1$), the cooling would produce a tensile stress of 450 psi. Since the elastic tensile strength of ordinary concrete is usually less than 450 psi, it is likely to crack if there is no relief due to stress relaxation.

**Factors Affecting Thermal Stresses**

**Degree of restraint ($Kr$)**. A concrete element, if free to move, would have no stress development associated with thermal deformation on cooling. However, in practice, the concrete mass will be restrained either externally by the rock foundation or internally by differential deformations within different areas of concrete due to the presence of temperature gradients. For example, assuming a rigid foundation, there will be full restraint at the concrete-rock interface ($Kr = 1.0$), however, as the distance from the interface increases, the restraint will decrease, as shown in the following Figure.
Temperature change. The hydration of cement compounds involves exothermic reactions which generated heat, and increase the temperature of concrete mass. Heating causes expansion, and expansion under restraint results in compressive stress. However, at early ages, the elastic modulus of concrete is low and the stress relaxation is high, therefore, the compressive stress will be very small, even in areas of full restraint. In design, to be conservative, it is assumed that a condition of no initial compression exists.

THERMAL PROPERTIES OF CONCRETE

Coefficient of thermal expansion is defined as the change in unit length per degree of temperature change. Selecting an aggregate with a low coefficient of thermal expansion when it is economically feasible and technologically acceptable, may, under certain conditions, become a critical factor for crack prevention in mass concrete. This is because the thermal shrinkage strain is determined both by the magnitude of temperature drop and the linear coefficient of thermal expansion of concrete; the latter, in turn, is controlled primarily by the linear coefficient of thermal expansion of the aggregate which is the primary constituent of concrete.

The reported values of the linear coefficient of thermal expansion for saturated Portland cement pastes of varying water/cement ratios, for mortars containing 1:6
cement/natural silica sand, and for concrete mixtures of different aggregate types are approximately 18, 12, and 6 to 12 × 10⁻⁶ per °C, respectively. The coefficient of thermal expansion of commonly used rocks and minerals varies from about 5 × 10⁻⁶ per °C for limestones and gabbros to 11 to 12 × 10⁻⁶ per °C for sandstones, natural gravels, and quartzite. Since the coefficient of thermal expansion can be estimated from the weighted average of the components, assuming 70 to 80 percent aggregate in the concrete mixture, the calculated values of the coefficient for various rock types (both coarse and fine aggregate from the same rock) are shown in Fig. 4-24. The data in the figure are fairly close to the experimentally measured values of thermal coefficients reported in the published literature for concrete tested in moist condition, which is representative of the condition of typical mass concrete.

*Specific heat* is defined as the quantity of heat needed to raise the temperature of a unit mass of a material by one degree. The specific heat of normal weight concrete is not very much affected by the type of aggregate, temperature and other parameters. Typically the values of specific heat are in the range of 0.22 to 0.25 Btu/lb.F.

*Thermal conductivity* gives the flux transmitted through a unit area of a material under a unit temperature gradient. The thermal conductivity of concrete is influenced by the mineralogical characteristics of aggregate, and by the moisture content, density, and temperature of concrete. Typical values of thermal conductivity for concretes containing different aggregate types range between 23-25 25 Btu in/h.ft².F.
EXTENSIBILITY AND CRACKING
As stated earlier, the primary significance of deformations caused by applied stress and by thermal and moisture-related effects in concrete is whether or not their interaction would lead to cracking. Thus the magnitude of the shrinkage strain is only one of the factors governing the cracking of concrete. From 4-1 it is clear that the other factors are:

- **Modulus of elasticity.** The lower the modulus of elasticity, the lower will be the amount of the induced elastic tensile stress for a given magnitude of shrinkage.
- **Creep.** The higher the creep, the higher is the amount of stress relaxation and lower the net tensile stress.
- **Tensile strength.** The higher the tensile strength, the lower is the risk that the tensile stress will exceed the strength and crack the material.

The combination of factors that are desirable to reduce the advent of cracking in concrete can be described by a single term called **extensibility.** Concrete is said to have a high degree of extensibility when it can be subjected to large deformations without cracking. Obviously, for a minimum risk of cracking, the concrete should undergo not only less shrinkage but also should have a high degree of extensibility (i.e., low elastic modulus, high creep, and high tensile strength).

In general, high strength concretes are more prone to cracking because of greater shrinkage and lower creep; on the other hand, low strength concretes tend to crack less, probably because of lower shrinkage and higher creep.

ENVIRONMENTAL-RELATED CAUSES OF CONCRETE DURABILITY PROBLEMS
The inferior durability characteristics of concrete may be caused by the environment that the concrete is exposed to or by internal causes within the concrete.
The following environmental conditions can affect the concrete durability:

− Temperature
− Moisture
− Physical factors
− Chemical factors
− Biological factors

These factors may be due to weathering conditions (temperature and moisture changes), to abrasion, attack by natural or industrial liquids and gases, or biological agents. Durability problems related to environmental causes include the following: steel corrosion, delamination, cracking, carbonation, sulphate attack, chemical attack, scaling, spalling, abrasion and cavitation.

TEMPERATURE

Temperature variations will cause changes in the concrete volume. When temperature rises, the concrete slightly expands, and when temperature falls, the concrete contracts. If the concrete was unrestrained, these normal volume changes in concrete would have little consequences. Since concrete is usually restrained by foundations, subgrades, reinforcement, or connecting members, volume changes in concrete can produce significant stresses in the concrete. Tensile stresses can cause the concrete to crack.

Thermal expansion and contraction of concrete are influenced by its coefficient of thermal expansion. An average value for the coefficient of thermal expansion is about 10 millionths per degree Celsius or 0.000010/°C (5.5 millionths per degree Fahrenheit or 0.000055/°F), although values ranging from 3.2 millionths to 7.0 millionths per °F have been reported in the literature.
Temperatures greater than 95°C (203°F) can have significant effects on concrete. The total volume change in concrete is the sum of the volume changes of the cement paste and aggregates. At high temperatures, the cement paste will shrink due to dehydration of the calcium silicate hydrate (C-S-H), while the aggregate will expand. For normal aggregate concrete, there is a net expansion. Therefore, exposure to very high temperatures (i.e. fire) will result in concrete spalling, particularly when the concrete is exposed to high temperatures for a long time.

Several factors influence the behavior of concrete at high temperatures. These factors include concrete moisture content, aggregate type and stability, cement content, duration of concrete exposure, the rate that temperatures rise, the age of the concrete, and any restraint.

The Environmental-related Problems of Temperature

Environmental problems are ascribable to the daily and seasonal changes in temperature.

Daily Changes in Temperature

Daily changes in temperature can be up to 20°C (36°F) at the coast and somewhat higher inland. The limiting tensile strain for concrete is frequently quoted to be between 10^-4 and 2x10^-4. If the coefficient of thermal expansion of concrete is assumed to be 10 millionths per degree Celsius (5.5 millionths per degree Fahrenheit), a temperature change of 10°C to 20°C (18°F to 36°F) would be
sufficient to cause the restrained concrete to crack. Repeated tensile stresses cause the cracks to grow and lead to scaling, spalling, and delamination. If the cracks develop to the level of the reinforcing steel, ingress of salt and moisture will cause the steel to corrode.

**Seasonal Changes in Temperature**

Seasonal changes in temperature are considerably greater than the daily fluctuations. Seasonal changes in temperature range up to 50°C (90°F) between the summer and winter. Seasonal temperature changes cause higher stresses than daily temperature changes, and they result in more extensive cracking. In some cases, cracks developed at low temperatures may close when the concrete temperature increases in the summer. If dirt or debris enters the cracks when the openings are at their maximum, an increase in temperature will cause the compressive stresses to develop. In slabs on grade and sidewalks, if large compressive stresses are developed due to the expansion of the concrete, the slab may buckle upward and crack.

**MOISTURE**

Changes in the moisture content in concrete will result in either concrete expansion or contraction. When concrete gains moisture, the concrete will slightly expand or swell. When concrete loses moisture, the concrete will contract or shrink. The effects of moisture gains and losses on the volume of concrete are illustrated in Figure 2.
Concrete will slightly expand if the concrete is kept continuously wet, however, concrete drying causes the concrete to shrink. Further, wetting and drying of the concrete can cause the concrete to alternately swell and shrink. As concrete drying occurs, the portion of concrete near the surface will dry and shrink faster than the inner portion of the concrete. This drying and shrinking of the concrete surface will cause the concrete surface to develop tensile stresses and possible cracks. If a section of the concrete is restrained, and if concrete joints are not provided, major random cracks may develop.

Shrinkage of reinforced concrete is less than the shrinkage of plain concrete. The difference depends on the amount of reinforcing steel used. Steel reinforcement restricts but does not prevent drying shrinkage. The concrete will crack if the shrinkage strain of the concrete exceeds the limiting tensile strain of the concrete.

**Environmental-related Problem of Moisture**

The three main problems with moisture and concrete are as follows:

- Carbonation
- The moisture cycle
- Contaminants

**Carbonation**

In addition to shrinkage upon drying, concrete undergoes shrinkage due to carbonation. Carbon dioxide (CO2) present in the atmosphere reacts in the presence of moisture with the hydrated cement minerals (i.e. the agent usually being the carbonic acid). Carbonation may lead to crazing. The extent of carbonation depends on the permeability of the concrete and on the concentration of carbon dioxide in the air. The penetration of carbon dioxide beyond the exposed surface of concrete is extremely slow. The alkaline conditions of hydrated cement paste are neutralized by carbonation. This neutralization, by dropping the pH from over 12 to about 9, affects the protection of reinforcing steel from corrosion. Thus,
if the entire concrete cover to steel were carbonated, corrosion of steel would occur in the presence of moisture and oxygen.

**Moisture Cycles**

Stresses caused by changes in moisture content of the concrete may be additive to stresses caused by temperature changes. Tensile stresses usually increase the tendency for cracking, scaling, spalling, and delamination. Rapidly fluctuating humidity (up to 70% in one day) can lead to moisture changes in the concrete. Condensation on concrete surfaces enters surface cracks and is absorbed into the concrete. Although the surface of the concrete may dry off rapidly, the water in the concrete and in the micro-cracks takes longer time to evaporate. If the moisture level at the reinforcing steel reaches 60% to 90% and sufficient chlorides are present, the steel will corrode. The influence of the relative humidity on steel corrosion is shown in Table.

**Table 1. Influence of Relative Humidity on the Corrosion of Steel in Concrete**

<table>
<thead>
<tr>
<th>Relative Humidity</th>
<th>Remarks</th>
<th>Corrosion Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete submerging in water</td>
<td>Capillaries filled with calcium hydroxide solution. Oxygen must diffuse through solution-filled capillaries to steel.</td>
<td>No-corrosion to small risk</td>
</tr>
<tr>
<td>90% to 95%</td>
<td>Pores filled with pore solution through which oxygen must diffuse.</td>
<td>Small to medium risk.</td>
</tr>
<tr>
<td>60% to 90%</td>
<td>Pores only partially filled. Water and oxygen reach steel easily.</td>
<td>Great risk.</td>
</tr>
<tr>
<td>below 60%</td>
<td>No or very little solution in pores.</td>
<td>No risk.</td>
</tr>
</tbody>
</table>
If the relative humidity is maintained at 80% and the temperature surrounding the reinforced concrete is increased, there will be a resulting increase in the rate of steel corrosion. Concrete that is subjected to moisture cycles may accumulate salts in the capillaries near the evaporating surface. This accumulation of salt may contribute to the chemical attack and/or salt scaling. Moisture movements in concrete may result in the concentrations of chlorides and sulphates in the concrete. Concentrations of chlorides in the concrete will cause the reinforcing steel to corrode and will also cause the concrete to crack and disintegrate.

**Contaminants**

Contaminants in the water that is absorbed into the concrete may cause staining, steel corrosion, or sulphate attack. Contaminants include: chloride and sulphate salts, carbonates, etc. Alternate cycles of wetting and drying allow the concentration of salts to increase and thereby increase the severity of their attack. An increase in the size of salt crystals in the capillaries near the evaporating surface causes cracking and scaling. If the salts are drawn to the surface and deposited at places where water evaporates, efflorescence will occur. The build-up of soluble salts depends on many factors, including the permeability of the concrete and the concentration of salts in the water that is being absorbed.

**PHYSICAL FACTORS**

Under many circumstances, concrete surfaces are subjected to wear. Concrete wear may be caused by the sliding, scraping or impact of objects that fall onto the concrete. In hydraulic structures, the action of the abrasive materials carried by flowing water generally leads to erosion of the concrete. Another cause of damage to concrete in flowing water is cavitation. Abrasion damage to concrete may be caused by the sliding or scraping of equipment across the concrete. Abrasion damage to concrete may also be caused by subjecting the concrete to abrasive materials (such as sand) that are carried by wind or water. Test results indicate the following facts;
− That abrasion resistance is clearly related to the compressive strength of the concrete.
− Strong concrete has more resistance than weak concrete.
− Since compressive strength depends on the water-cement ratio and adequate curing, a low water-cement ratio and proper curing of the concrete are necessary for abrasion resistance.
− Hard aggregates are more abrasion resistant than soft aggregates.
− Steel-trowelled surfaces resist abrasion more than a surface that is not trowelled.

Cavitation occurs when a high-velocity, flow of water (or any other fluid) suffers an abrupt change in direction or velocity. This change in direction or velocity in flowing water causes a zone of low pressure to occur at the surface of the concrete that is immediately downstream from the direction or velocity change. This low pressure zone may allow pockets (or cavities) of vapor to form. When leaving the low pressure zone, these pockets of vapor collapse. The collapse of these vapors causes a localized high-energy impact on the concrete surface. This localized high-energy impact leads to erosion of both the cement paste and aggregate.

Concrete that is affected by cavitation has an irregular, jagged, and pitted surface. In contrast, concrete that is eroded by water-borne solids has a smooth surface. Damage to the concrete surface does not progress steadily. After an initial period of small damage, rapid deterioration will occur. This rapid deterioration is followed by damage to the concrete at a slower rate.

Fire around concrete structures can weaken the superstructure and decrease the concrete strength tremendously. Damage by fire may include total or partial collapse of the structure, distortion, excessive deflection and expansion, buckling of the steel, spalling and shattering of the concrete, discoloration, and reduction of the physical properties of the steel and concrete.
Environmental-related Physical Problems

Concrete may be subjected to fire or other forms of physical contact, such as wear caused by sliding, scraping, impact, or cavitation. Physical contact with concrete surfaces may result in spalling, scaling; and disintegration.

Cavitation

Cavitation can be a problem in any open channel where the velocity of the flowing water is higher than 12 mls (39.4 ft/s). In a closed pipe or conduit, cavitation can occur at velocities as low as 7.5 mls (24.6 ft/s). Concrete damage that is due to cavitation can be minimized if irregularities in the flow of the water are eliminated or if the velocity of the flowing water is reduced. Concretes that have the best resistance to cavitation damage have a high strength, a low water-cement ratio, a small aggregate size that does not exceed 20 mm (3/4 inch), and a good paste-aggregate bond.

Fire

Human safety in the event of fire is one of the considerations in the design of residential, public, and industrial buildings. Concrete has a good service record in this respect. Unlike wood and plastics, concrete is incombustible and does not emit toxic fumes on exposure to thigh temperature.

Fire introduces high temperature gradients in the concrete. As a result of these high temperature gradients, hot surface layers tend to separate and spall from the cooler interior portions of the concrete body. Cracks; then; tend to form at joints, in poorly compacted parts of the concrete, or in planes of reinforcing steel bars. Once the reinforcement has become exposed, it conducts heat and accelerates the action of heat. The effect of increased temperatures on the strength of concrete is small and somewhat irregular below 250°C (482°F). A reduction in compressive strength begins soon after 100°C (212°F) has been reached. This loss increases with an increase in the concrete temperature. When heated above 600°C (1112°F), concrete has little residual strength. When mild steel or hot-rolled, high-yield
reinforcing steel is heated to about 200°C (392°F), there is a significant increase in strength. On further heating, the strength starts to decrease. At 400°C (752°F), the strength is approximately the same as the strength at normal temperatures. At 550°C (1022°F), the residual strength is only about 50% of the original. Above 550°C (1022°F), the strength drops rapidly.

Factors that tend to promote spalling include the high moisture content, restraint to expansion (e.g., panels within a frame), low porosity and low permeability, closely spaced reinforcement, and rapid temperature rise. Spalling can also result from differential expansion of the mix constituents. Another common cause of spalling is the rapid quenching of hot fires by fire hoses. Rapid quenching of fire can cause serious structural damage. Concrete that is made with various types of siliceous or limestone aggregate shows a change in color with temperature. These color changes are due to the presence of iron oxide in the concrete; however, these color changes are not always apparent.

The effects of the high temperatures caused by fires are shown in Table 2.

### Table 2. Impact of Fire Temperature on Concrete

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Effect on Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>100°C to 250°C (212°F to 482°F)</td>
<td>Normal color, slight loss in compressive strength</td>
</tr>
<tr>
<td>250°C to 300°C (482°F to 572°F)</td>
<td>Color changes to pink, strength loss increases</td>
</tr>
<tr>
<td>300°C to 600°C (572°F to 1112°F)</td>
<td>Color is pink to red, strength loss continues</td>
</tr>
<tr>
<td>Above 600°C (1112°F)</td>
<td>Color changes to black, gray; very little residual strength</td>
</tr>
<tr>
<td>About 900°C (1652°F)</td>
<td>Color changes to buff; total loss of strength</td>
</tr>
</tbody>
</table>
A key factor in the amount of damage that is caused to concrete is the duration of the fire. Because of the low thermal conductivity of concrete, it takes considerable time for the interior of concrete to reach damaging temperatures. For instance, damage commonly does not extend to more than about 10 to 30 mm (3/8 to 1 1/4 inches) below the surface of the concrete. Note that the interior of the concrete can never be more damaged from fire than its surfaces.

**BIOLOGICAL FACTORS**

Concrete may be damaged by live organisms such as plants, sponges, boring shells, or marine borers.

**Mosses** and **lichens**, which are plants of a higher order, cause insignificant damage to concrete. These plants produce weak acids in the fine hair roots. The roots enable mosses and lichens to adhere to the concrete. The acids that are produced from mosses and lichens will attack the cement paste and cause the concrete to disintegrate and scale. In some cases, carbonic acids are produced from plants, such as mosses and lichens, when substances from these plants decompose. The carbonic acid that is produced will attack the concrete.

Mosses on concrete.
Rotting seaweed has been known to produce sulfur. Sulfur can be easily converted to sulfuric acid. The presence of sulfuric acid on concrete leads to concrete disintegration. The growth of seaweed may also create a problem if the seaweed is exposed at low tide. When the seaweed is exposed at low tide, the seawater that is retained by the seaweed becomes more concentrated by evaporation. The effect of seawater on concrete increases as the concentration of seawater increases.

Rock boring mollusks and sponges, which are common in reefs or areas where the seabed is composed of limestone, may invade underwater concrete structures and piles containing limestone aggregate. The pattern of infestation greatly differs between organisms. When mollusks attack concrete, their pattern of infestation is widespread and relatively deep. The holes that the mollusks create tend to extend through both the aggregate and cement paste. Boreholes created by mollusks are located perpendicular to the outer surface of the concrete and can measure up to 10 mm (3/8 inch) in diameter. Although the depths of boreholes from mollusks vary, growth measurements indicate a rate of borehole penetration of about 10 mm (3/8 inch) per year. Boreholes serve solely as protective enclosures for the mollusks. The pattern of infestation created by boring sponges are shallow, closely spaced, with small diameter holes that average 1 mm (1/25 inch) in diameter. The
boreholes created by boring sponges are often interconnected. The attack of boring sponges on concrete is generally concentrated in small areas. As the degree of honeycomb in the concrete increases, the surface material of the concrete crumbles. Rock boring mollusks and sponges were discovered in the concrete piles of the Juaymah NGL Trestle in April 1982. This discovery took place about four years after the construction of the Juaymah NGL Trestle. The Juaymah NGL Trestle is approximately 10 kilometer (6.2 miles) long and is supported on 1500 precast, post-tensioned concrete cylinder piles. These concrete cylinder piles have outside diameters that range from 1.37 to 1.68 meters (4.5 to 5.5 feet). To stop the penetration of these mollusks and sponges, the concrete piles of the Juaymah NGL Trestle were encapsulated from about 1.2 meters (4 feet) to about 6 meters (20 feet) below the Indian Spring Low Water datum.

**Environmental-related Biological Problems**

Marine borers, such as mollusks and sponges, tend to form bore holes into underwater concrete structures. Marine borers reduce the concrete's load-carrying capacity as well as expose the concrete's outer reinforcing steel to the corrosive seawater. Boring sponges produce interconnected bore holes. As the degree of interconnection increases, the surface material of the concrete crumbles. Disintegration of the surface layer exposures a new substrate of the concrete to the boring sponges. Deterioration of concrete due to a boring sponge attack is relatively slow. Rock boring mollusks and sponges will also chemically bore holes into concrete containing calcareous substances.

**CHEMICAL FACTORS**

**Chemical Corrosion**

The resistance of concrete to deterioration processes triggered by chemical reactions involves generally, but not necessarily, chemical interactions between aggressive agents present in the external environment and the constituents of the cement paste. Among the exceptions are alkali-aggregate reactions which occur between the alkalies in cement paste and certain reactive materials when present in
aggregate, delayed hydration of crystalline CaO and MgO if present in excessive amounts in portland cement, and electrochemical corrosion of embedded steel in concrete. In a well-hydrated portland cement paste, the solid phase, which is composed primarily or relatively insoluble hydrates of calcium (such as C-S-H, CH, and C-A-SH), exists in a state of stable equilibrium with a high-pH pore fluid.

Large concentrations of Na+, K+, and OH− ions account for the high pH value, 12.5 to 13.5, of the pore fluid in Portland cement pastes. It is obvious that portland cement concrete would be in a state of chemical disequilibrium when it comes in contact with an acidic environment. Again, it needs to be emphasized that chemical reactions manifest into detrimental physical effects, such as increase in porosity and permeability, decrease in strength, and cracking and spalling. In practice, several chemical and physical processes of deterioration act at the same time and may even reinforce each other. For the purpose of developing a clear understanding, the chemical processes can be divided into three subgroups shown in Fig. 5-10, and discussed one at a time.

Special attention will be given to sulfate attack, alkali-aggregate attack, and corrosion of embedded steel, as these phenomena are responsible for deterioration of a large number of concrete structures. Finally, the last section of this chapter is devoted to durability of concrete in seawater, because coastal and offshore structures are exposed to a maze of interrelated chemical and physical processes of deteriorate which aptly demonstrate the complexities of concrete durability problems in practice.
Chemical corrosion results from the breaking down and dissolution of the cement paste and/or the chemical action of the aggressive agent. Combined physical and chemical corrosion may occur in cases where the aggressive agent combines with the cement or aggregate to form compounds that have a volume greater than the volume of the original constituents. This expansion may lead to a disruption in the concrete. The nature, concentration, and rate of replenishment of aggressive agents affect the rate of concrete deterioration that is caused by exposure to the aggressive agents. If an aggressive agent is carried by a flowing stream over the concrete surface of a pipe or canal, the replenishment of this aggressive agent will be maintained indefinitely. Indefinite replenishment of an aggressive agent will result in greater damage than would occur if the concrete were in contact with a limited quantity of the aggressive agent.

When the concrete is in direct contact with aggressive soils, the aggressive solution may be drawn into the concrete by capillary action. If evaporation at the surface of the concrete is possible, the concentration of salts in the capillaries may become dangerously high. A similar situation may occur when one surface of the concrete is exposed to an aggressive solution under hydrostatic pressure and the
other surface is dry. The solution is forced into the capillaries of the concrete and, if evaporation at the exposed face is possible, a heavy build up of salts may be expected in the pores of the concrete surface. Chemical corrosion in Saudi Aramco is manifested by steel corrosion, alkali aggregate reactivity, sulphate attack, and acid attack. Salt in the surrounding ground, ground water, or air diffuses into the concrete. Steel corrosion results in an increase in the volume of the corroded portion (i.e. surficial layer) of the reinforcing steel bar.

This increase in steel volume causes the concrete to crack and to disintegrate. The first evidence of steel corrosion may be the appearance of a brown stain on the concrete surface. The appearance of this brown stain is followed by the development of a fine crack running through the stain and roughly following the line of the steel. The increase in the volume of the steel corrosion products eventually bursts the concrete cover. Pieces of concrete are spalled off.

The spalling of concrete leaves the steel exposed. The pieces of concrete that are spalled are usually sound and show no evidence of concrete deterioration. Temperature and relative humidity play an important part in determining the rate of steel corrosion in concrete, as was explained in Table 1 under the topic of "Moisture".

**Chemical Attack**

Solid salts do not attack concrete, but when they are in the form of a solution, they can directly react with the hardened cement paste. Some soils contain alkali, magnesium and calcium sulphates. When these sulphates come into contact with groundwater, they form a sulphate solution. Seawater may also contain significant sulphate content. Attack of the hardened cement paste can occur when the sulphates react with the Ca(OH)2 and the calcium aluminate hydrates. This reaction is called **sulphate attack**. Due to the increase in volume, these expansive reactions can produce a sufficient pressure that disrupts the cement paste. This disruption of the cement paste results in concrete cracking and disintegration. Over
a period of time, excessive amounts of sulphates in soil or water can attack and destroy concrete that is not properly designed and protected.

The rate of a sulphate attack increases with an increase in the strength of the sulphate solution. The concentration of the sulphates is expressed as the number of parts of the weight of S04 per million parts of the solution (ppm). 1000 ppm is considered to be a moderately severe sulphate content. 2000ppm is considered to be a very severe sulphate content, especially if MgSO4 is the predominant constituent. The parallel values of soluble sulphates in the soil itself are 0.2 and 0.5 percent. The movement of the groundwater must be known in order to estimate the danger of a sulphate attack. A high rate of attack may occur because the sulphate that is removed by the reaction with the cement hydration products can be replenished. Likewise, alternating saturation and drying of the concrete can lead to rapid deterioration by sulphate attack.

Sulphate attack conditions are less severe when the concrete is completely buried and a channel for the groundwater does not exist. Concrete that is attacked by sulphates has a characteristicallly whitish appearance. Sulphate damage usually starts at the edges and corners of the concrete member and is followed by a progressive cracking and spalling of the concrete. Cracking and spalling of the concrete reduces the concrete to a friable or even soft state.

Some concrete structures may be subjected to chemical attack on one or more surfaces. Concrete can be attacked by water, acids, alkali, salt solutions, or a wide variety of organic chemicals. Damage may be limited to only surface discoloration or surface roughening. Damage could be as catastrophic as acid attack, with the resulting loss of structural integrity. The affected surfaces are generally covered with barrier materials. A barrier material separates the concrete surface from the environment. In damp conditions, SO2 CO2, SO3 and other acid forms that are present in the
atmosphere may attack concrete by dissolving in water and removing parts of the cement paste. These acids will leave a soft and mushy mass behind. This form of attack occurs in sewers, chimneys, and in/around sulfur pits. Almost all types of mineral acids will have a destructive effect on concrete. The rate of an acid attack is determined by some factors such as the amount and concentration of acid, the cement content, the type of aggregate used in respect to the aggregate's solubility in acids, and the permeability of the concrete. When the hydrated cement reacts with an acid, the lime in the cement tends to neutralize the acid. If the concrete is made with a siliceous aggregate, neutralization can only be affected by the breaking down of the cement binder. If a calcareous aggregate, such as limestone, is used in the concrete, the aggregate is also active in the neutralization of the acid.

The aggregate is referred to as a "sacrificial" aggregate. Even when the acid is constantly being replenished on concrete, the rate of deterioration by an acid attack can be considerably retarded through the use of limestone or dolomite aggregates in the concrete. The constant replenishment of acids on concrete can be observed in hydraulic structures, footings, or piles that are in direct contact with acid ground waters, cooling towers, and other structures that are exposed to acid atmospheres. In some environments (such as flash distillation chambers of desalination plants), the continuous exposure to mineral-free water will rapidly dissolve any available lime or other soluble compounds of the cement paste. When lime or other soluble compounds of the cement paste dissolve, concrete will deteriorate and eventually disintegrate. Environments, such as the flash distillation chambers of desalination plants, can cause concrete deterioration and disintegration because the concrete is constantly exposed to condensing water vapors or the resulting flow or dripping of distilled water.
ALKALI AGGREGATE REACTION IN CONCRETE (AAR)

INTRODUCTION

AAR is a chemical reaction of alkali in concrete and certain alkaline reactive minerals in aggregate producing a hygroscopic gel which, when moisture present, absorbs water and expand. Gel expansion causes cracking in the concrete.

The number of structures affected by AAR is relatively small comparing to the total number of concrete structure built, but the problem has been found in many countries around the world. In Hong Kong, occurrence of AAR have been identified for some structures [Stanley, 1992]. See photos in the Teaching Web Page for cases of AAR in Hong Kong and around the world. Most of the structures severely cracked by AAR are exposed to the whether or underground in contact with damp soil. This is because for significant expansion to occur sufficient presence of moisture is essential. Apart from the moisture, high content of alkali in the concrete is also essential. No case as been found where the alkali content, in terms of equivalent sodium oxide (Na2Oequi), is below 3-4 kg per cubic meter of concrete.

It is also found that, when there are sufficient moisture and alkali, maximum expansion of concrete due to AAR occurs when the content of reactive minerals in aggregate is within a sensitive region, some refer to this as "pessimum" content. Content of reactive minerals below or greater than the pessimum value, AAR expansion reduces. From the above, it can be seen that, for a damage AAR expansion to occur, it is necessary to have

- sufficient moisture supply,
- high content of alkali in concrete, and
- pessimum amount of reactive minerals in aggregate.
SOURCES OF ALKALIS IN CONCRETE

a. Cement
All ingredients of concrete may contribute to the total alkali content of the concrete, the major source of alkali is from cement. The chemical composition of cement is usually expressed in terms of oxides. In relation to AAR, alkali content in cement is determined from Na2O and K2O. Alkali content is described as total mass of "equivalent sodium oxide", Na2Oequ, which is determined from the following expression. Na2Oequ = Na2O + 0.658 K2O Alkali content of the cement commonly used in Hong Kong is, in terms of Na2Oequ, less than 1%. In some regions of China, e.g. in Tianjin and Beijing area, alkali content of local cement is relatively high, above 1.5%, owing to the raw material of cement.

b. Pozzolans
A pozzolan is a siliceous or siliceous and aluminous material which react with lime released from cement hydration forming a compound possessing cementitious properties. Pozzolanic materials are used as a cement replacement or as part of cementitious material to modify or improve properties of concrete, sometimes for economical consideration. Common pozzolanic material used in concrete include PFA (palverized fuel ash, or fly ash), silica fume, GGBS (ground granulated blastfurnace slag). Other pozzolans include volcanic ash (the original pozzolan), opaline shale and chert etc. PFA is the most common pozzolan used in concrete. The use of silica fume in concrete is on the rising. Pozzolan consumes alkali when react with lime. When considering pozzolan contribution of alkali to concrete, a reduction to the alkali content of the pozzolan should be allowed for.

c. Aggregate
Aggregate containing feldspars, some micas, glassy rock and glass may release alkali in concrete. Sea dredged sand, if not properly washed, may contain sodium chloride which can contribute significant alkali to concrete.
d. Admixtures

Admixture in the context of AAR in concrete means chemical agents added to concrete at the mixing stage. These include accelerators, water reducers (plasticizers), retarders, superplasticizers, air entraining, etc. Some of the chemicals contain sodium and potassium compounds which may contribute to the alkali content of concrete.

e. Water

Water may contain certain amount of alkali. PNAP 180 states that acid-soluble alkali content of water be determined in accordance with American Public Health Association (APHA) (17ed. 1989) Sections 3500-K and 3500-Na.

f. Alkalis from outside the concrete

In area of cold whether, de-icing salt containing sodium compounds may increase alkali content on the surface layer of concrete. Soils containing alkali may also increase alkali content on the surface of concrete.

ALKALI CONTENT AND AAR

Research show that when the total alkali content, in terms of equivalent sodium oxide, is less than 3 kg/m³, damage expansion due to AAR is unlikely to happen, provide that known highly alkali-reactive minerals, such as opal and glass, are not present in the concrete. Because of the above research findings, and also because no reliable universal testing method have been established for the determination of reactivity of an aggregate, limiting alkali content in concrete has become the most widely used approach for the control of AAR. In Hong Kong, PNAP 180 specifies that, in the absence of alternative approach for AAR control, the alkali content of concrete expressed as the equivalent sodium oxide shall not exceed 3.0 kg per cubic meter of concrete.
REACTIVE AGGREGATE

General types of AAR

There are mainly three types of AAR found in concrete. These are

- alkali-silica reaction
- alkali-silicate reaction and
- alkali-carbonate reaction

Alkali-silica reaction is a reaction between alkali hydroxides and free silica in aggregate form a alkali-silica gel.

\[
\text{SiO}_2 + 2\text{NaOH} + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{SiO}_3 \times 2\text{H}_2\text{O}
\]

Silica Alkali Water Alkali-silica gel Alkali-silicate reaction is the same as alkali-silica reaction except that in this case the reactive constituent is not free silica present in the combined form of phyllosilicates. Alkali-carbonate reaction occurs in concrete when alkalis react with certain dolomitic lime stones containing clay. Reaction causes cracks allowing water to enter which causes the clay to swell and disrupt the aggregate. Majority of the structures affected by AAR is found due to alkali-silica reaction. Alkalisilicate and alkali-carbonate reaction is relatively rear.

Tests for aggregate reactivity

Many test methods have been proposed by researchers for identifying potential reactivity of aggregate all over the world. These may be classified into three types.

- Petrographic examinations
- Chemical tests
- Expansion tests

Petrographic examination is the process of identifying the types of minerals in aggregate or concrete section by observation using microscope or other aids. This method can identify types of minerals in the aggregate and give suggestions as for whether the aggregate is potentially reactive or not. Because the uncertainties involved in the test, the method is generally used as a screening test as a part of an investigation. Many proposed test methods using chemical analyses to identify potential reactivity of aggregate. ASTM C389-87 chemical test (ASTM 1987a),
for example, evaluates aggregate reactivity by measuring the amount of dissolved silica and the reduction of alkalinity in the reaction alkali solution. In an expansion tests, mortar bars or concrete prisms are made using the aggregate to be investigated. There specimens are then put in to a specified condition and the expansion of the specimens are measured. Since at normal climate conditions the reaction will take a few years or even longer to complete, measures to accelerate the reaction sometimes adopted for such tests.

One of such measures is to place the specimens at 38°C or 40°C and 100% relative humidity. In such a condition the AAR and its expansion complete within a few months time. In another such test using mortar bar as specimens, the mortar bars are immersed in a NaOH solution at 80°C. This method is also referred to as Accelerated Mortar Bar Test.

It should be noted that the methods that have been proposed so far have their limitations. Some succeeds in identifying reactivity for certain aggregates whereas fails for others. Therefore it is difficult to ascertain an aggregate is absolutely non-reactive using the currently available testing methods.
Concrete in Seawater

For several reasons, effect of seawater on concrete deserves special attention. First, coastal and offshore sea structures are exposed to the simultaneous action of a number of physical and chemical deterioration processes, which provide an excellent opportunity to understand the complexity of concrete durability problems in practice. Second, oceans make up 80 percent of the surface of the earth; therefore, a large number of structures are exposed to seawater either directly or indirectly (e.g., winds can carry seawater spray up to a few miles inland from the coast). Concrete piers, decks, breakwater, and retaining walls are widely used in the construction of harbors and docks.

To relieve land from pressures of urban congestion and pollution, floating offshore platforms made of concrete are being considered for location of new airports, power plants, and waste disposal facilities. The use of concrete offshore drilling platforms and oil storage tanks is already on the increase. Most seawaters are fairly uniform in chemical composition, which is characterized by the presence of about 3.5 percent soluble salts by weight. The ionic concentrations of Na+ and Cl− are the highest, typically 11,000 and 20,000 mg/liter, respectively. However, from the standpoint of aggressive action to cement hydration products, sufficient amounts of Mg2+ and SO2− 4 are present, typically 1400 and 2700 mg/liter, respectively.

The pH of seawater varies between 7.5 and 8.4, the average value in equilibrium with the atmospheric CO2 being 8.2. Under exceptional conditions (i.e., in sheltered bays and estuaries) pH values lower than 7.5 may be encountered; these are usually due to a higher concentration of dissolved CO2, which would make the seawater more aggressive to Portland cement concrete.
The following Table shows the concentration of major ions in some of the world seas.

<table>
<thead>
<tr>
<th>Major Ion</th>
<th>Black Sea</th>
<th>Marmara Sea</th>
<th>Mediterranean Sea</th>
<th>North Sea</th>
<th>Atlantic Ocean</th>
<th>Baltic Sea</th>
<th>Arabian Gulf</th>
<th>BRE Exposure</th>
<th>Red Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>4,900</td>
<td>8,100</td>
<td>12,400</td>
<td>12,200</td>
<td>2,190</td>
<td>20,700</td>
<td>9,740</td>
<td>11,350</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>640</td>
<td>1,035</td>
<td>1,500</td>
<td>1,110</td>
<td>1,210</td>
<td>2,300</td>
<td>1,200</td>
<td>1,867</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>9,500</td>
<td>14,390</td>
<td>21,270</td>
<td>16,550</td>
<td>3,960</td>
<td>36,900</td>
<td>18,200</td>
<td>22,660</td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>1,362</td>
<td>2,034</td>
<td>2,596</td>
<td>2,220</td>
<td>2,180</td>
<td>580</td>
<td>5,120</td>
<td>2,600</td>
<td>3,050</td>
</tr>
<tr>
<td>TDS</td>
<td>17,085</td>
<td>26,409</td>
<td>38,795</td>
<td>33,060</td>
<td>35,370</td>
<td>7,110</td>
<td>66,650</td>
<td>32,540</td>
<td>40,960</td>
</tr>
<tr>
<td>TDS Ratio*</td>
<td>3.90</td>
<td>2.52</td>
<td>1.72</td>
<td>2.02</td>
<td>1.88</td>
<td>9.37</td>
<td>1.00</td>
<td>2.05</td>
<td>1.63</td>
</tr>
</tbody>
</table>

Concrete exposed to marine environment may deteriorate as a result of combined effects of chemical action of seawater constituents on cement hydration products, alkaliaggregate expansion (when reactive aggregates are present), crystallization pressure of salts within concrete if one face of the structure is subject to wetting and others to drying conditions, frost action in cold climates, corrosion of embedded steel in reinforced or prestressed members, and physical erosion due to wave action and floating objects. Attack on concrete due to any one of these causes tends to increase the permeability; not only would this make the material progressively more susceptible to further action by the same destructive agent but also to other types of attack. Thus a maze of interwoven chemical as well as physical causes of deterioration are found at work when a concrete structure exposed to seawater is in an advanced stage of degradation. The theoretical aspects, selected case histories of concrete deteriorated by seawater, and recommendations for construction of concrete structures in marine environment are discussed next.
Theoretical Aspects

From the standpoint of chemical attack on hydrated Portland cement in unreinforced concrete, when alkali reactive aggregates are not present, one might anticipate that sulfate and magnesium are the harmful constituents in seawater. It may be recalled that with groundwaters, sulfate attack is classified as severe when the sulfate ion concentration is higher than 1500 mg/liter; similarly, Portland cement paste can deteriorate by cation exchange reactions when magnesium ion concentration exceeds, for instance, 500 mg/liter.

Interestingly, in spite of the undesirably high sulfate content of seawater, it is a common observation that even when a high C3A Portland cement has been used and large amounts of ettringite are present as a result of sulfate attack on the cement paste, the deterioration of concrete is not characterized by expansion; instead, it mostly takes the form of erosion or loss of the solid constituents from the mass. It is proposed that ettringite expansion is suppressed in environments where (OH)− ions have essentially been replaced by Cl− ions. Incidentally, this view is consistent with the hypothesis that an alkaline environment is necessary for swelling of ettringite by water adsorption.

Irrespective of the mechanism by which the sulfate expansion associated with ettringite is suppressed in high C3A Portland cement concretes exposed to seawater, the influence of chloride on the system demonstrates the error too often made in modeling the behavior of materials when, for the sake of simplicity, the effect of an individual factor on a phenomenon is predicted without sufficient regard to the other factors present, which may modify the effect significantly.

It may be noted that according to ACI Building Code 318-83, sulfate exposure to seawater is classified as moderate, for which the use of ASTM Type II Portland cement (maximum 8 percent C3A) with a 0.50 maximum water/cement ratio in normal-weight concrete is permitted. In fact, it is stated in the ACI 318R-21...
Building Code Commentary that cements with C3A up to 10 percent may be used if the maximum water/cement ratio is further reduced to 0.40. The fact that the presence of uncombined calcium hydroxide in concrete can cause deterioration by an exchange reaction involving magnesium ions was known as early as 1818 from investigations on disintegration of lime-pozzolan concretes by Vicat, who undoubtedly is regarded as one of the founders of the technology of modern cement and concrete.

Vicat made the profound observation:
On being submitted to examination, the deteriorated parts exhibit much less lime than the others; what is deficient then, has been dissolved and carried off; it was in excess in the compound. Nature, we see, labors to arrive at exact proportions, and to attain them, corrects the errors of the hand which has adjusted the doses. Thus the effects which we have just described, and in the case alluded to, become the more marked, the further we deviate from these exact proportions. Several state-of-the-art reviews on the performance of structures in marine environments confirm that Vicat’s observation is equally valid for Portland cement concrete.

From long-term studies of Portland cement mortars and concretes exposed to seawater, the evidence of magnesium ion attack is well established by the presence of white deposits of Mg(OH)2, also called brucite, and magnesium silicate hydrate. In seawater, well-cured concretes containing large amounts of slag or pozzolan in cement usually outperform reference concrete containing only Portland cement, partly because the former contain less uncombined calcium hydroxide after curing. The implication of loss of lime by cement paste, whether by magnesium ion attack or by CO2 attack, is obvious from Figure.

Since seawater analyses seldom include the dissolved CO2 content, the potential for loss of concrete mass by leaching away of calcium from hydrated cement paste
due to carbonic acid attack is often overlooked. According to Feld, in 1955, after 21 years of use, the concrete piles and caps of the trestle bends of the James River Bridge at Newport News, Virginia, required a $1.4 million repair and replacement job which involved 70 percent of the 2500 piles. Similarly, 750 precast concrete piles driven in 1932 near Ocean City, New Jersey had to be repaired in 1957 after 25 years of service; some of the piles had been reduced from the original 550 mm diameter to 300 mm. In both cases, the loss of material was associated with higher than normal concentrations of dissolved CO2 present in the seawater.

It should be noted that in permeable concrete the normal amount of CO2 present in seawater is sufficient to decompose the cementitious products eventually. The presence of thaumasite (calcium silicocarbonate), hydrocalumite (calcium carboaluminate hydrate), and aragonite (calcium carbonate) have been reported in cement pastes derived from deteriorated concretes exposed to seawater for long periods.

![Figure 1. Strength loss in permeable concrete due to lime leaching](image_url)

Figure 1. Strength loss in permeable concrete due to lime leaching
Unit - 5

READY MIX CONCRETE

- RMC industry is about 12 years old in India, while it was introduced in other countries much earlier
  - PATENTED IN GERMANY
  - 1913- FIRST DELIVERY OF RMC (BALTIMORE)
  - 1926- BIRTH OF TRANSIT MIXER
  - 1931- ERECTION OF FIRST COMMERCIAL PLANT IN LONDON
  - 1950-1974 REMARKABLE GROWTH OF RMC – 31 MILLION CUBIC METRE OF CONCRETE PER YEAR

Factors Delaying Entry of RMC in India

- RMC is highly mechanized activity and entails initial high cost. Especially due to import of basic equipment and machinery.
- Smaller size of construction in unorganized sector highly competitive and cost conscious.
- Availability of abundant cheap labour for making and transporting concrete.
- Differential taxation between RMC and SMC. Especially before 1997 when excise duty @16% also existed.

Factors that Prompted Introduction of RMC

- Increasing stakes in the reliability and durability of construction of emerging users.
- Decreasing share of construction cost in overall cost of the facility.
- Increasing awareness on environmental factors and convenience.
- Globalization – adoption of best practices across the globe.
- Bigger size of projects and Time is recognised as a cost factor.
Table – 1 Growth projections of cement and concrete

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Year</th>
<th>Cement demand million tons</th>
<th>Total concrete requirement million m$^3$</th>
<th>Concrete requirement on major projects million m$^3$</th>
<th>Concrete requirement in rural areas million m$^3$</th>
<th>Concrete requirement within domain of RMC million m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2006-2007</td>
<td>145</td>
<td>282</td>
<td>55</td>
<td>96</td>
<td>131</td>
</tr>
<tr>
<td>2</td>
<td>2007-2008</td>
<td>158</td>
<td>308</td>
<td>60</td>
<td>104</td>
<td>144</td>
</tr>
<tr>
<td>3</td>
<td>2008-2009</td>
<td>172</td>
<td>335</td>
<td>66</td>
<td>113</td>
<td>156</td>
</tr>
<tr>
<td>4</td>
<td>2009-2010</td>
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## STATUS OF RMC IN INDIA

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A TYPICAL ‘RMC READY MIX’ PLANT
RMC- MAJOR ADVANTAGES
• Assured And Uniform Quality Of Concrete
• Speedier Construction Through Mechanised Operations
• Need For Ordering And Storing Cement, Aggregates And Sand On Site Totally Eliminated
• Lower Labour And Supervisory Costs
• Minimisation of cement wastage through bulk handling and storage
• Cleaner working environment
• -Eco-friendly product

COMMON QUALITY PROBLEMS: Quality problems of various natures which may get reported are listed below:
• Delay in setting of concrete beyond 24 hours.
• Development of cracks when the concrete is still in fresh state.
• Development of cracks in hardened concrete.
• Non-compliance of concrete cube strength (cast at site) to specifications at 7-days.
• Non-compliance of concrete cube strength (cast at site) to specifications at 28-days.
• Concrete supplied to site either has more slump than specified or has become stiff making it difficult to pump. Reasons for above problems to occur at construction site are many. It is necessary to understand the behaviour of each and every constituent of concrete and construction techniques adopted at site before arriving at any conclusion regarding quality problems of RMC.

In many cases, information regarding Concrete Mix Design adopted for the type of material available in the plant may not be available. Properties of the constituents may not be available due to lack of testing facilities at RMC plant.
1. Delay in setting of concrete beyond 24 hours:
Delay in setting of concrete is mainly due to excess dosage of set retarding admixture used to retain pumpable slump for longer durations. These admixtures are used to prolong the plasticity of concrete. Useful to counter the effects of high temperature, eliminate cold joints, and reduce cracking associated with form deflections. Basically, retarding admixtures increase dormant stage in the C3S hydration process. Too large a dose of admixture than specified by the manufacturer will cause the hydration reaction never to proceed resulting in cement that will never set. Remedies: It is important to carry out extensive trials while using set retarding admixture to arrive at optimum dosage without delaying setting of concrete than required. This also establishes the compatibility between cement and admixture. It is important to note that when a particular brand of cement is found to be compatible with a particular admixture, results may not be reproducible when cement is from a factory at a different location even though brand of cement is same. It is necessary to have a good quality control practices as properties of constituent materials vary to a large extent.

2. Development of cracks when the concrete is still in fresh state:
Cracks which appear when the concrete is still in fresh state are called plastic shrinkage cracks. These are caused by rapidly evaporating surface moisture. While some evaporation occurs all the time, its rate is increased by high ambient air temperature, elevated fresh concrete temperature, low humidity and strong winds. All four factors are in full force on warm summer days. Evaporation may be so strong; it actually pulls moisture from the concrete. Cracks are also caused by plastic settlement. Horizontal reinforcing bars may put restraint to overall settlement of concrete. Due to this thin plastic settlement cracks can occur. Vertical cracks form along line of the bars, penetrating from surface to bars.
Remedies: It is essential to keep the concrete surface moist always to prevent cracks being developed when the concrete is still in fresh state. Adoption of good curing techniques that stops moisture loss from surface as soon as after placing of concrete. Use of curing compounds can be a good solution wherever it is not possible to monitor effective curing of concrete.

3. Development of cracks in hardened concrete:
Early-age thermal cracking is caused by restraint to contraction on cooling from a temperature peak, which is associated with the release of the heat of hydration of the binders. Early-age thermal cracking occurs within few days in thin sections, but it may take several weeks to develop in massive sections. Because of fast track constructions taking place to meet demands of infrastructure development, the trend towards large continuous pours of concrete with the requirements of high early strength and shorter striking times and problems of heat of hydration are mainly responsible for early-age cracking in hardened concrete. This type of cracks occurs when the restrained thermal contraction strain exceeds tensile strain capacity of concrete. The concrete temperature rise depends on number factors such as cement and addition type and content, type of aggregate, as well as ambient temperature, formwork used and section thickness.

Restraint is a function of the construction sequence and the constraint of neighbouring elements. Non-compliance of concrete cube strength (cast at site) to specifications at 7-days: Concrete cubes are cast both at plant and at site to determine compressive strength of concrete at various ages viz. at 7-day and 28 day. Even though specifications do not exist for 7-day strength in IS 456-2000, concrete cubes are tested at 7-day to check progressive development of strength. Normally expected strength at 7-days is about 2/3 of the 28-day compressive strength for a particular grade of concrete. Getting 80%-90% of 28-day compressive strength can easily be achieved when 53- Grade OPC is used.
However with addition of flyash as a partial replacement to cement, strength at 7-day may not reach a value of 2/3 of the compressive strength at 28-days. In such cases, concrete cubes are certain to reach the required value at 28-days provided mix design is in order and standard procedure of cube curing and testing are followed. Non-compliance of concrete cube strength (cast at site) to specifications at 28-days When concrete cubes cast at site do not comply with specifications of 28-day compressive strength, then it becomes necessary to resort to non-destructive testing methods.

Of all the non-destructive testing methods determination of in-situ strength of concrete using concrete core extraction is most relied upon method. Reasons for failure of concrete cubes at 28-day can be many. Concrete supplied to site either has more slump than specified or has become stiff making it difficult to pump: Doubts will always be raised if the concrete supplied at site has more slump than specified. Addition of water during transit can be suspected which is bound to affect the quality of concrete. On the other hand it could be due to defects in carrying out trial mixes to assess the slump retaining characteristics of concrete using a particular admixture. Concrete losing workability making it difficult to pump is another area of concern. In such cases, water added to make concrete pumpable which again affects quality of concrete. Re-dosing of admixture, if adopted, has to be done under technical supervision following recommendation of manufacturer of admixture. Otherwise it may lead to delayed setting of concrete.
SAMPLING AND TESTING OF READY-MIXED CONCRETE (As per IS 4926-2003):

For the assessment of compliance of ready-mixed concrete, the point and the time of sampling shall be at the discharge from the producer’s delivery vehicle or from the mixer to the site or when delivered into the purchaser’s vehicle.

**Time in Transport:**

The general requirement is that concrete shall be discharged from the truck mixer within 2 hours of the time of loading. However, longer period may be permitted if retarding admixtures are used or in cool humid weather or when chilled concrete is produced.

**Workability:**

Workability is measured in terms of slump of concrete using the standard procedure laid down in IS 1199: 1959- Methods of sampling and analysis of concrete.

**Acceptance criteria for workability:**

The workability shall be within the following limit on the specified value as appropriate: Slump: ±25 mm or ±1/3 of the specified value whichever is less.

Sampling of concrete for assessment of compliance to strength: Unless otherwise agreed between the parties involved, the minimum testing frequency to be applied by the producer in the absence of a recognized ready-mixed concrete industry method of production control, should be one sample for every 50 m3 production or every 50 batches, whichever is the greater frequency.

Three test specimens shall be made up for each sample for testing at 28 days. The purchaser shall inform the producer if his requirements for sampling and testing are higher than one sample every 50 m3 or 50 batches, whichever is the greater frequency Acceptance criteria as per IS 456-2000: The test results of the sample shall be average of the strength of the three specimens. The individual variation should not be more than ±15% of the average.
Self Compacting Concrete

Normal Concrete

Traditionally Concrete is made by mixing:

- CEMENT
- WATER
- COARSE AND FINE AGGREGATES

The four main properties of concrete are:

- WORKABILITY
- COHESIVENESS
- STRENGTH and
- DURABILITY

Workability means how easy it is to:

- PLACE
- HANDLE
- COMPACT and
- FINISH a concrete mix

Never try to make a mixture more workable by just adding more water because this lowers the strength and durability of concrete.

Compressive Strength is governed by Abram’s law

- Proper compaction results in concrete with an increased density which is stronger and more durable.

So,

- By adding more water
- In fresh state- leads to segregation & bleeding
• In hardened state- leads to durability problems

So, what is Normal Concrete?
• Cement: 300-450Kg /m3
• Max. W/C ratio: 0.55
• Grade of Concrete: M20 - M40
• Permits the use of :
  o Mineral Admixtures (Fly Ash, Silica Fume, GGBS, Rice Husk Ash, Metakaoline)
  o Chemical Admixtures

Problems persist…….
• Lack of adequate compaction in normal concrete
• Compaction requires the use of heavy, noisy, expensive, energy-consuming vibrators – sometimes non available
• More advanced complex RC design - high density of reinforcing bars, complex shapes - shortage of skilled labour for supervision

There is a quest amongst concrete engineers for a still higher strength/ higher performance/ higher ductility concrete
• The answer could be …… SCC

Self-Compacting Concrete (SCC)
Defined by researchers as: “concrete that is able to flow and consolidate under its own weight, completely fill the formwork of any shape, even in the presence of dense reinforcement, while maintaining homogeneity and without the need for any additional compaction.

MATERIALS
SELF-COMPACTING CONCRETE
• SCC has more powder content and less coarse aggregate
• Fillers used can be flyash, ground granulated blast furnace slag, condensed silica fume, rice husk ash, lime powder, chalk powder & quarry dust.
• SCC incorporates high range water reducers (HRWR, Superplasticizers) & frequently, viscosity modifying agent in small amount.

From traditional concrete to SCC

Potential Benefits of SCC
Contractor
- Reduced labor requirement & cost
- Reduced plant requirement
- Reduced remedial work
- Reduced noise, improved site health & safety
- No vibrating equipment required, reduces placing costs

Designer / client
- Use in more complex design & heavy reinforcement
- Improved aesthetics & durability
- Quicker construction time
- Less variation in the production of concrete & more homogeneous concrete
- Better surface finish

**FRESH SCC REQUIREMENTS**

![Diagram showing Filling ability, Stability, and Passing ability]

Fresh SCC Properties
“The ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight.”

Passing ability

“The ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking.”

Fresh SCC Properties
Segregation resistance
“The ability of SCC to remain homogeneous in composition during transport and placing.”

CHARACTERISTICS OF SCC
• If SCC should not segregate- it must have mortar rich in fines & is also able to transport the coarse aggregate & keep them in viscous suspension
• Cement cannot be the only finer/filler material
• Mineral admixtures are used to enhance the deformability & stability of concrete
• Chemical admixtures are a must for achieving excellent flow at low water content. VMA reduces bleeding & improves the stability of the concrete mixture

Compared to Conventional Concrete, SCC has
• Higher powder content in the order of 450-600 Kg/m³
• Lower water/cement ratio. Typical range of water is 160 to 185 kg/ m³ & water/binder ratio, by volume in the range of 0.7 to 1.25. Volume of paste 0.36 to 0.43
• Lower coarse/fine aggregate ratio
• Use of superplasticizers & VMA compatible with cement in small percentages.

TEST METHODS FOR DETERMINING FRESH SCC PROPERTIES

_ FILLING ABILITY
• Slump flow & T
50CM slump flow
• V- Funnel

_ PASSING ABILITY
• L-Box
• U-box
• J-ring
• Fill Box
SEGREGATION RESISTANCE

- V-Funnel at T5 Minutes
- GTM Screen stability test

Slump flow (spread)

- Most popular method
- Assess the horizontal free flow of concrete in the absence of obstruction
- Measures the filling ability
- Normal range of flow recommended
  - 650 mm to 800 mm

TEST METHODS

Slump flow (spread)

- Secondary measurement of T50 cm can be made
- Represents time taken in seconds to reach horizontal diameter of 500 mm
- Recommended limits are 2 sec to 5 sec

V-Funnel Test

- To assess the flowability of fresh concrete
- The time taken for concrete to flow through the narrow end is measured
- Measures viscosity of concrete
• Recommended value for V-funnel flow
• < 12 sec

TEST METHODS

L-Box Test

• Passing ability of fresh concrete.
• T 20 cm and T 40 cm marks of horizontal section of L – box are the indications of ease of flow of concrete.
• Height of the concrete at the end of the horizontal section is expressed as a proportion of that of remaining in the vertical section (H2/H1).
• Recommended value for blocking ratio:
  o Blocking ratio H2/H1 ≥ 0.80.

_U-Box Test_
• Also called as ‘Box-shaped’
• Measures the filling ability of concrete.
• The difference in height of two sections is measured.
• Recommended value:
  o difference in the height of the limbs < 30 mm

_J-Ring Test_
• Measures passing ability of concrete
• Can be used in conjunction with Slump flow test, combination can test filling ability & passing ability
• The difference in height, in between the concrete inside and that just outside the J-ring is measured
• Difference in height of maximum of 10 mm is considered appropriate

• Bars can be of different diameters and also varied spacing:
  o Preferably three times the maximum aggregate size
• Used in conjunction with slump flow test V5min flow time
• This is secondary parameter of the V-funnel test
• Measures time of flow of concrete after time gap of 5min
• Indicates the tendency for segregation
• Recommended value is:
  o < +3 sec of time at zero hours
Unit -7
FIBER REINFORCED CONCRETE-
BEHAVIOUR PROPERTIES AND
APPLICATION

Introduction
The weak matrix in concrete, when reinforced with steel fibres, uniformly distributed across its entire mass, gets strengthened enormously, thereby rendering the matrix to behave as a composite material with properties significantly different from conventional concrete. Because of the vast improvements achieved by the addition of fibers to concrete, there are several applications where Fibers Reinforced Concrete (FRC) can be intelligently and beneficially used. These fibers have already been used in many large projects involving the construction of industrial floors, pavements, highway-overlays, etc. in India. The principal fibers in common commercial use for Civil Engineering applications include steel (SFRC/SFRS), glass, carbon and aramid. These fibers are also used in the production of continuous fibers and are used as a replacement to reinforcing steel. High percentages of steel fibers are used extensively in pavements and in tunnelling. This invention uses Slurry Infiltrated Fiber Concrete (SIFCON).

Fibers in the form of mat are also being used in the development of high performance structural composite. Continuous fiber-mat high performance fiber reinforced concrete (HPFRCs) called Slurry Infiltrated Mat Concrete (SIMCON) is used in the production of High performance concrete. Use of basalt fibers are picking up in western countries. Steel fibers are also used in the production new generation concretes such as Reactive Powder Concrete (RPC), Ductal and Compact Reinforcing Concrete (CRC). Properties and applications of SFRC and some of these new generation fiber concrete materials are discussed.
1. **Steel Fibre Reinforced Concrete (SFRC)**

Concrete is the most widely used structural material in the world with an annual production of over seven billion tons. For a variety of reasons, much of this concrete is cracked. The reason for concrete to suffer cracking may be attributed to structural, environmental or economic factors, but most of the cracks are formed due to the inherent weakness of the material to resist tensile forces. Again, concrete shrinks and will again crack, when it is restrained. It is now well established that steel fibre reinforcement offers a solution to the problem of cracking by making concrete tougher and more ductile. It has also been proved by extensive research and field trials carried out over the past three decades, that addition of steel fibres to conventional plain or reinforced and prestressed concrete members at the time of mixing/production imparts improvements to several properties of concrete, particularly those related to strength, performance and durability.

The weak matrix in concrete, when reinforced with steel fibres, uniformly distributed across its entire mass, gets strengthened enormously, thereby rendering the matrix to behave as a composite material with properties significantly different from conventional concrete.

The randomly-oriented steel fibres assist in controlling the propagation of micro-cracks present in the matrix, first by improving the overall cracking resistance of matrix itself, and later by bridging across even smaller cracks formed after the application of load on the member, thereby preventing their widening into major cracks (Fig. 1).
The idea that concrete can be strengthened by fibre inclusion was first put forward by Porter in 1910, but little progress was made in its development till 1963, when Roumaldi and Batson carried out extensive laboratory investigations and published their classical paper on the subject. Since then, there has been a great wave of interest in and applications of SFRC in many parts of the world. While steel fibres improve the compressive strength of concrete only marginally by about 10 to 30%, significant improvement is achieved in several other properties of concrete as listed in Table. Some popular shapes of fibres are given in Fig.2.
In general, SFRC is very ductile and particularly well suited for structures which are required to exhibit:

- Resistance to impact, blast and shock loads and high fatigue
- Shrinkage control of concrete (fissuration)
- Very high flexural, shear and tensile strength
- Resistance to splitting/spalling, erosion and abrasion
- High thermal/temperature resistance
- Resistance to seismic hazards.

The degree of improvement gained in any specific property exhibited by SFRC is dependent on a number of factors that include:

- Concrete mix and its age
- Steel fibre content
- Fibre shape, its aspect ratio (length to diameter ratio) and bond characteristics.

The efficiency of steel fibres as concrete macro-reinforcement is in proportion to increasing fibre content, fibre strength, aspect ratio and bonding efficiency of the fibres in the concrete matrix. The efficiency is further improved by deforming the fibres and by resorting to advanced production techniques. Any improvement in the mechanical bond ensures that the failure of a SFRC specimen is due mainly to fibres reaching their ultimate strength, and not due to their pull-out.

1.1 Mix Design for SFRC

Just as different types of fibres have different characteristics, concrete made with steel fibres will also have different properties. When developing an SFRC mix design, the fibre type and the application of the concrete must be considered. There must be sufficient quantity of mortar fraction in the concrete to adhere to the fibres and allow them to flow without tangling together, a phenomenon called ‘balling of fibres’. Cement content is, therefore, usually higher for SFRC than conventional mixes. Aggregate shape and content is critical. Coarse aggregates of sizes ranging from 10 mm to 20 mm are commonly used with SFRC. Larger aggregate sizes usually require less volume of fibres per cubic meter. SFRC with
10 mm maximum size aggregates typically uses 50 to 75 kg of fibres per cubic meter, while the one with 20 mm size uses 40 to 60 kg. It has been demonstrated that the coarse aggregate shape has a significant effect on workability and material properties. Crushed coarse aggregates result in higher strength and tensile strain capacity. Fine aggregates in SFRC mixes typically constitute about 45 to 55 percent of the total aggregate content. Typical mix proportions for SFRC will be: cement 325 to 560 kg; water-cement ratio 0.4-0.6; ratio of fine aggregate to total aggregate 0.5-1.0; maximum aggregate size 10mm; air content 6-9%; fibre content 0.5-2.5% by volume of concrete. An appropriate pozzolan may be used as a replacement for a portion of the Portland cement to improve workability further, and reduce heat of hydration and production cost.

The use of steel fibres in concrete generally reduces the slump by about 50 mm. To overcome this and to improve workability, it is highly recommended that a super plasticizer be included in the mix. This is especially true for SFRC used for highperformance applications. Generally, the ACI Committee Report No. ACI 554 ‘Guide for Specifying, Mixing, Placing and Finishing Steel Fibre Reinforced Concrete’ is followed for the design of SFRC mixes appropriate to specific applications.

1.2 Factors Controlling SFRC

- Aspect ratio, l/d
- Volume fraction, vf
- Fiber reinforcing index, RI=l/d x vf
- Critical length, lmin
- Balling of fibers
- Good mix design: more matrix, small aggregate, workable
- Type of fibers-size, shape, strength, modulus
Workability

• We know that it is usually wrong to add water to concrete for workability.
• The main problem with workability of steel fiber reinforced concrete is in getting proper distribution of the fibers so that they don't ball up.
• This difficulty is usually overcome by slow, continuous and uniform feeding of the fibers into the wet or dry mix by means of vibratory feeders.
• Sometimes the fibers are passed through screens as they are introduced. Proper feeding can virtually eliminate the problem of balling. On the other hand, addition of water to improve workability can reduce the flexural strength significantly, a critical matter when one considers that one of the main reasons for using steel fibers is to improve the flexural strength.
• In such cases use of suitable admixture probably would improve the workability to certain extent and may not to the extent that you require

Test for workability

• Slump test- subsidence in mm
• Inverted slump test-time in seconds
• Compacting factor test-degree of compaction
• VB test-time in seconds. The relationship among the different workability parameters are shown in Fig. 3. The effect of volume fraction and aspect ratio on VB time is shown in Fig.
Fig. 4. VB time vs percentage of fibers

VB time vs percentage of fibers
Mechanical properties and strength of SFRC

The various properties of SFRC and other FRCs can be seen in the following figures. Relative strength and toughness of the fiber reinforced mortar and concrete can be seen in Fig. As the percentage of fibers increases, the strength and toughness of fiber concrete increases. The increase in toughness and the effect of aspect ratio can be seen in Fig. . The effect of different types of fibers on the uniaxial tensile strength is presented in Fig. . The variation of compressive strength and the strain is shown in Fig. 8. The strain of SFRC corresponding to peak compressive strength increases as the volume fraction of fibers increases. As aspect ratio increases, the compressive strength of SFRC also increases marginally. The load vs deflection of SFRC beam subjected to bending is presented in Figs 9 and 10. As the load increases, the deflection also increases. However, the area under the load – deflection curve also increases substantially depending the type and amount of fibers added.

![Graph showing relative strength vs percentage of aligned fibers](image)

Relative strength vs percentage of aligned fibers
Toughness and strength in relation to plain concrete

Uniaxial tensile strength vs strain for different FRCs
Fibre Shotcreting

“Shotcreting” using steel fibres is being successfully employed in the construction of domes, ground level storage tanks, tunnel linings, rock slope stabilization and repair and retrofitting of deteriorated surfaces and concrete. Steel fibre reinforced shotcrete is substantially superior in toughness index and impact strength compared to plain concrete or mesh reinforced shotcrete. In Scandinavian countries, shotcreting is done by the wet process and as much as 60% of ground support structures (tanks and domes) in Norway are constructed using steel fibres. In many countries including India, steel fibre shotcrete has been successfully used in the construction of several railway and penstock tunnels.

1.4 Applications of SFRC

The applications of SFRC depend on the ingenuity of the designer and builder in taking advantage of its much enhanced and superior static and dynamic tensile strength, ductility, energy-absorbing characteristics, abrasion resistance and fatigue strength. Growing experience and confidence by engineers, designers and contractors has led to many new areas of use particularly in precast, cast in-situ, and shotcrete applications. Traditional application where SFRC was initially used as pavements, has now gained wide acceptance in the construction of a number of airport runways, heavy-duty and container yard floors in several parts of the world due to savings in cost and superior performance during service.

The advantages of SFRC have now been recognised and utilised in precast application where designers are looking for thinner sections and more complex shapes. Applications include building panels, sea-defence walls and blocks, piles, blast-resistant storage cabins, coffins, pipes, highway kerbs, prefabricated storage tanks, composite panels and ducts. Precast fibre reinforced concrete manhole covers and frames are being widely used in India, Europe and USA. Cast in-situ application includes bank vaults, bridges, nosing joints and water slides. “Sprayed-in” ground swimming pools is a new and growing area of shotcrete application.
in Australia.

SFRC has become a standard building material in Scandinavia. Applications of SFRC to bio-logical shielding in atomic reactors and also to waterfront marine structures which have to resist deterioration at the air-water interface and impact loadings have also been successfully made. The latter category includes jetty armor, floating pontoons, and caissons. Easiness with which fibre concrete can be moulded to compound curves makes it attractive for ship hull construction either alone or in conjunction with ferrocement.

SFRC shotcrete has recently been used for sealing the recesses at the anchorages of post stressing cables in oil platform concrete structures. Recent developments in fibre types and their geometry and also in concrete technology and equipment for mixing, placing and compaction of SFRC and mechanized methods for shotcreting have placed Scandinavian and German consultants and contractors in a front position in fibreshotcreting operations world wide.

Laboratory investigations have indicated that steel fibres can be used in lieu of stirrups in RCC frames, beams, and flat slabs and also as supplementary shear reinforcement in precast, thin-webbed beams. Steel fibre reinforcement can also be added to critical end zones of precast prestressed concrete beams and columns and in cast-in-place concrete to eliminate much of the secondary reinforcement. SFRC may also be an improved means of providing ductility to blast-resistant and seismic-resistant structures especially at their joints, owing to the ability of the fibres to resist deformation and undergo large rotations by permitting the development of plastic hinges under over-load conditions.
General Application of Steel Fibres

Steel Fiber Reinforced Concrete or Shotcrete (SFRC/SFRS) have been used in various applications throughout the world. In India their use is picking up slowly.

The principal advantages of SFRC versus plain or mesh/bar reinforced concretes are:

- Cost savings of 10% - 30% over conventional concrete flooring systems.
- Reinforcement throughout the section in all directions versus one plane of reinforcement (sometimes in the sub-grade) in only two directions.
- Increased ultimate flexural strength of the concrete composite and thus thinner sections.
- Increased flexural fatigue endurance and again thinner slabs.
- Increased flexural toughness, or the ability to absorb energy.
- Increased impact resistance and thus reduced chipping and joint spalling.
- Increased shear strength and thus the ability to transfer loads across joints in thin sections.
- Increased tensile strength and tensile strain capacity thus allowing increased contraction/construction joint spacing.

The six major areas in which Steel Fibers can be used to achieve high-strength, durable and economical concrete are:

a) Overlays

Roads, Airfields, Runways, Container, Movement and Storage Yards, Industrial Floors and Bridges.

Advantages of using SFRC

- Fatigue and impact resistance increased
- Wear and tear resistance increased
- Joint spacing increased
- Thinner pavements possible due to higher flexural strength of SFRC
- Long service life with little or no maintenance
b) Pre-cast Concrete Products
Manhole covers and Frames, Pipes, Break-Water Units, Building Floor and Walling Components, Acoustic Barriers, Krebs, Impact Barriers, Blast Resistant Panels, Vaults, Coffins etc.

Advantages of using SFRC
• Fatigue and impact resistance increased
• Thinner sections possible with SFRC reducing handling and transportation costs.
• Reduced consumption and savings in cost of materials makes pre-cast products competitive in price with cast iron or reinforced concrete products.
• Products possess increased ductility and resistance to chipping and cracking.
SFRC products suffer less damage and loss during handling and erection
• Overall improvement in all structural properties
• Many different sizes and shapes of pre-cast units possible with SFRC.

c) Hydraulic and Marine Structures
Dams, Spillways, Aprons, Boats and Barges, Sea Protection Works.

Advantages of using SFRC
• Outperforms conventional materials by exhibiting superior resistance to cavitations and impact damage due to wave action, hydraulic heads and swirling water currents.
• Ideally suitable for repair of hydraulic and marine structures

d) Defence and Military Structures
Aircrafts Hangers, Missile and Weaponry Storage Structures, Blast Resistant Structure, Ammunition Production and Storage Depots, Underground Shelters etc.

Advantages of using SFRC
• Exhibits high ductile and toughness resulting in superior resistance to blast, impact and falling loads and missiles.
• Fragmentation effect very less compared to other material due to confinement effect of fibers on concrete.
• Far superior resistance to fire and corrosion
• High resistance to penetration by drills hammers etc, almost impenetrable.
• A highly versatile material with longer service life.

e) Shotcreting Applications
Tunnel Linings, Domes, Mine Linings, Rock-Slope Stabilization, Repaint and Restoration Distresses Concrete Structures etc.

Advantages of using SFRC
• Highly efficient, convenient and economical compared to mesh and bar reinforcement used in conventional shot crating.
• One stage operation for irregular profiles.
• High resistance to abrasion and impact loads.
• Reduction in 'shadow' effects resulting in compact and dense layer.
• Improvement in ductility
• Only high performing technique suitable for tunnel and drainage lining, rock stabilization jobs and also for repair of bridges, dams, storage tanks etc.
• Construction of energy-efficient domes and shell structures possible.

f) Special Structures
Machine Foundations, Currency Vaults and Strong Rooms, Impact and Fiber-Protective Shells and Lost Forms, Column-Beam Joints in Seismic-Resistant Structures, End Zones of Prestressed Concrete Elements, High Volume Steel Fiber Reinforce Concrete structures made out of SIFCON and CRC (Slurry Infiltrated Fiber Concrete and Compact Reinforced Concrete)

Advantages of using SFRC
• Improved performances under action of any kind of loading
• High seismic-resistance in buildings due to ductile behaviours of joints and Connections
Some applications in India
Fiber reinforced concrete is in use since many years in India, but the structural applications are very much limited. However, its application is picking up in the recent days. Following are some of the major projects where large quantities of steel fibers are used.
1. More than 400 tones of Shaktiman Steel Fibers have been used recently in the construction of a road overlay for a project at Mathura (UP).
2. They have also been successfully used at the end anchorage zones of prestressed concrete girders for resisting bursting and spalling forces in bridge projects in Bangalore and Ahmedabad executed by one of the reputed construction companies.
3. The fibers have also been used for heavy-duty industrial floors.
4. Other projects include Samsonity Factory-Nasik, BIPL Plant-Pune, KRCLMSRDC tunnels, Natha Jakri Hydro Electric Plant, Kol HEP, Baglihar HEP, Chamera HEP, Sala HEP, Ranganadi HEP, Sirsisilam project, Tehri Dam project, Uri Dam Project, etc.
5. Used in many tunnelling projects and for slope stabilisation in India.

2. High-Performance Composite Infrastructural Systems Utilizing Advanced Cementitious Composites
This system is a partially cast-in-place high-performance composite frame system (HPCFS) developed by selectively using high-performance materials, including (continuous fiber-mat high performance fiber reinforced concrete (HPFRCs) called slurry infiltrated mat concrete (SIMCON), (2) discontinuous fiber HPFRCs called slurry infiltrated fiber concrete (SIFCON), and (3) high-strength, lightweight aggregate fiber reinforced concrete (HS-LWA FRC). These advanced composites exhibit superior strength, energy-absorption capacity, and/or decreased weight, and are thus ideally suited for an innovative seismic-resistant design. No conventional concrete materials are used.
Technical Approach

Partially cast-in-place HPCFSs are built using stay-in-place formwork elements made by encasing light steel sections and tubes into advanced cementitious composites including (1) continuous HPFRCs and (2) discontinuous fiber HPFRCs. The "core" of the beam and column members is cast-in-place HS-LWS FRC. The stay-in-place formwork also serves as surface reinforcement, thus replacing conventional steel reinforcement and simplifying casting of the member core by eliminating reinforcement congestion. Furthermore, by encasing steel elements into HPFRC, their fire resistance and durability is improved. The construction procedure consists of first welding or bolting together of the stay-in-place formwork, followed by casting in place of HS-LWA FRC in both (1) the member core and (2) the beam-column joint region.

Since the subsequent floor can be erected as soon as the steel elements are bolted together, it is anticipated that the speed of construction per story can be comparable to that of conventional, prefabricated steel frames. If successful, the proposed concept will result in advanced concrete frame systems exhibiting high strength and seismic resistance, while being faster and more cost effective to construct than conventional cast-in-place systems.

2.3 Slurry Infiltrated Fibrous Concrete (SIFCON)

SIFCON is a high-strength, high-performance material containing a relatively high volume percentage of steel fibres as compared to SFRC. It is also sometimes termed as ‘high-volume fibrous concrete’. The origin of SIFCON dates to 1979, when Prof. Lankard carried out extensive experiments in his laboratory in Columbus, Ohio, USA and proved that, if the percentage of steel fibres in a cement matrix could be increased substantially, then a material of very high strength could be obtained, which he christened as SIFCON.
While in conventional SFRC, the steel fibre content usually varies from 1 to 3 percent by volume, it varies from 4 to 20 percent in SIFCON depending on the geometry of the fibres and the type of application. The process of making SIFCON is also different, because of its high steel fibre content. While in SFRC, the steel fibres are mixed intimately with the wet or dry mix of concrete, prior to the mix being poured into the forms, SIFCON is made by infiltrating a low-viscosity cement slurry into a bed of steel fibres ‘pre-packed’ in forms/moulds. The matrix in SIFCON has no coarse aggregates, but a high cementitious content. However, it may contain fine or coarse sand and additives such as fly ash, micro silica and latex emulsions.

The matrix fineness must be designed so as to properly penetrate (infiltrate) the fibre network placed in the moulds, since otherwise, large pores may form leading to a substantial reduction in properties. A controlled quantity of high-range water-reducing admixture (super plasticizer) may be used for improving the flowing characteristics of SIFCON. All types of steel fibres, namely, straight, hooked, or crimped can be used.

Proportions of cement and sand generally used for making SIFCON are 1:1, 1:1.5, or 1:2. Cement slurry alone can also be used for some applications. Generally, fly ash or silica fume equal to 10 to 15% by weight of cement is used in the mix. The water-cement ratio varies between 0.3 and 0.4, while the percentage of the super plasticizer varies from 2 to 5% by weight of cement. The percentage of fibres by volume can be anywhere from 4 to 20%, even though the current practical range ranges only from 4 to 12%.
Slurry Infiltrated Mat Concrete (SIMCON)

SIMCON can also be considered a pre-placed fibre concrete, similar to SIFCON. However, in the making of SIMCON, the fibres are placed in a “mat form” rather than as discrete fibres. The advantage of using steel fibre mats over a large volume of discrete fibres is that the mat configuration provides inherent strength and utilizes the fibres contained in it with very much higher aspect ratios.

The fibre volume can, hence, be substantially less than that required for making of SIFCON, still achieving identical flexural strength and energy absorbing toughness. SIMCON is made using a non-woven “steel fibre mats” that are infiltrated with a concrete slurry. Steel fibres produced directly from molten metal using a chilled wheel concept are interwoven into a 0.5 to 2 inches thick mat. This mat is then rolled and coiled into weights and sizes convenient to a customer’s application (normally up to 120 cm wide and weighing around 200 kg).

As in conventional SFRC, factors such as aspect ratio and fibre volume have a direct influence on the performance of SIMCON. Higher aspect ratios are desirable to obtain increased flexural strength. Generally, because of the use of mats, SIMCON the aspect ratios of fibres contained in it could well exceed 500. Since the mat is already in a preformed shape, handling problems are significantly minimised resulting in savings in labour cost. Besides this, “balling” of fibres does not become a factor at all in the production of SIMCON.

Indian Scenerio

In India, SIFCON, CRC, SIMCON and RPC are yet to be used in any major construction projects. For that matter, even the well-proven SFRC has not found many applications yet, in spite of the fact that its vast potentials for civil engineering uses are quite well known. The reason for these materials not finding
favour with designers as well as user agencies in the country could be attributed to the non-availability of steel fibres on a commercial scale till a few years ago. The situation has now changed. Plain round or flat and corrugated steel fibres are presently available in the country in different lengths and diameters. It is, therefore, possible now to use new-age construction materials like SIFCON and CRC in our country in the construction of several structures that demand high standards of strength coupled with superior performance and durability.

**Carbon Fiber Based Linear Reinforcing Elements**

Due to their light weight (about one fifth that of steel), high tensile strength (higher than steel) and good overall environmental durability, carbon fiber based tendons and cables are increasingly being used for reinforcement of concrete structures in Japan. The reduction in weight facilitates better handling and easier field installation compared to steel. These elements also cause significantly less sag under their own weight, which increases load capacity while enabling the construction of longer bridge spans.

**Leadline Rods/Tendons**

Leadline reinforcing elements are circular rods that are pultruded using unidirectional carbon fibers at 65% fiber volume fraction with an epoxy resin. The rods have a specific gravity of 1.6, a relaxation ratio of 2-4% at 20°C, and a coefficient of thermal expansion of 0.68 x 10^-6 /°C in the longitudinal direction. The rods have a tensile modulus of 147 GPa and 1.5 to 1.7% elongations at break. Rods are available in a number of diameters with four major surface types.
High-Performance Fiber-Reinforced Concrete (HPFRC)

Introduction

High-Performance Fiber-Reinforced Concrete (HPFRC), a series of new generation concrete, results from the addition of either short discrete fibers or continuous longfibers to the cement based matrix. Due to the superior performance characteristics of this category of SFRC or HPC, its use by the construction industry has significantly increased in the last 5 years. A very good guide to various Portland cement-based composites as well as their constituent materials is available in a recently published book.

For highway pavement applications, concretes with early strength are attractive for potential use in repair and rehabilitation with a view towards early opening of traffic. In this direction lot of work has been done on high early strength fiber reinforced concrete (HESFRC) and is being used in practice. Technical papers and reports provide an extensive database and a summary of comprehensive experimental investigation on the fresh and mechanical properties of HESFRC. The control high early strength (HES) concrete (used with the fiber addition) were

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Round Rods</th>
<th>Indented Rods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
<td>R1 R3 R5 R8 R10 R12 R17</td>
<td>D5 D8 D10 D12</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>1 3 5 8 10 12 17</td>
<td>5 8 10 12</td>
</tr>
<tr>
<td>Tension (kN)</td>
<td>1.8 16 44 111 170 255 512</td>
<td>40 104 162 245</td>
</tr>
<tr>
<td>C/S Area (mm²)</td>
<td>0.8 7.1 19.6 49.0 75.4 113.1 227</td>
<td>17.8 46.1 71.8 108.6</td>
</tr>
<tr>
<td>Weight (g/m)</td>
<td>1.2 11 32 78 119 178 360</td>
<td>30 77 118 177</td>
</tr>
</tbody>
</table>

Table: Characteristics of Leadline Rods
defined as achieving a target minimum compressive strength of 35 MPa in 24 hours, as measured from 100 x 200 mm cylinders.

**Continuous Fiber-Reinforced Concrete**

In the last 5 years, there has been significant interest and development in the use of continuous fiber reinforcement for improving the behavior of cementitious composites and/or concrete. Fiber Reinforced Polymers (FRP) or sometime also referred to Fiber Reinforced Plastic are increasingly being accepted as an alternative for uncoated and epoxy-coated steel reinforcement for prestressed and non-prestressed concrete applications.

In 1990, the American Concrete Institute formed the ACI Committee 440 on Non-Metallic Reinforcement. The Committee has just developed a state-of-the-art report on Fiber Reinforced Plastic (FRP) for Concrete Structures [ACI Committee 440 1996].

**4.2.1 Reinforcing Fibers**

The principal fibers in common commercial use for civil engineering applications include glass, carbon and aramid. The most common form of fiber-reinforced composites used in structural applications is called a laminate. Laminates are made by stacking a number of thin layers (laminae) or fibers and matrix and consolidating them into the desired thickness. Fiber orientation in each layer as well as the stacking sequence of the various layers can be controlled to generate a wide range of physical and mechanical properties for the composite laminate. A composite can be any combination of two or more materials as long as the material properties are different and there is a recognizable region for each material.
The materials are intermingled. There is an interface between the materials, and often an inter phase region such as the surface treatment used on fibers to improve matrix adhesion and other performance parameters via the coupling agent. Glass has been the predominant fiber for many civil engineering applications because of an economical balance of cost and specific strength properties. Glass fibers are commercially available in "E-Glass" formulation (for "Electrical" grade), the most widely used general-purpose form of composite reinforcement, high strength S-2 glass and ECR Glass, a modified E-Glass which offers greater alkali resistance. Although considerably more expensive than glass, other fibers including carbon and aramid are used for their strength or modulus properties or in special situations as hybrids with glass.

Field Applications
Composite materials have been used in a variety of civil engineering applications with both reinforced and prestressed concrete. They are manufactured as reinforcing elements, as prestressing and post-tensioning tendons and rods, and as strengthening materials for rehabilitation of existing structures. Several new structures utilizing FRP reinforcement are currently underway in USA and Japan.

applications of high performance SFRC Pavements
During the past decade, there has been an increasing interest in using high performance concrete for highway pavements. The main reason for this heightened interest is the potential economic benefit that can be derived from the early strength gain of high performance concrete, its improved freeze-thaw durability, reduced permeability, and increased wear and impact resistance. pavement repairs for early opening to traffic
"Fast Track" Concrete

"Fast track" concrete is designed to give high strength at a very early age without using special materials or techniques, and it is durable. The early strength is controlled by the water-cement ratio, cement content and characteristics. Typically, a rich, low-watercontent mix containing 1 to 2 percent calcium chloride will produce adequate strength and abrasion resistance for opening to traffic in 4-5 hours at temperatures above 10 C.

Fast track concrete paving (FTCP) was developed originally by the concrete paving industry in Iowa. It was pointed out that the benefits of applying FTCP technology in such applications are (1) a reduced contract period, thus reducing the contract overhead cost, (2) early opening of the pavement to traffic, (3) minimizing the use of expensive concrete paving plant and traffic management systems, and (4) reduced traffic delay costs.

High Strength Concrete Pavement and Bridges

The benefits of using high strength concrete for bridges are well known to bridge engineers. Over the past several years, there have been a series of design studies published in the literature, all leading to the same conclusion that the use of high strength concrete would enable the standard prestressed concrete girders to span longer distances or to carry heavier loads.

recent activities of organized programs on HPC

Reactive powder Concrete

The need

The upper limit of compressive strength for materials that can be used in commercial applications continues to be pushed higher and higher. Within the past three years Portland cement based materials have been developed which have compressive strengths greater than 200 MPa (2 to 4 times greater than High
Performance Concrete). These materials allow remarkable flexural strength and extremely high ductility, more than 250 times greater than that of conventional concrete.

The Technology
Reactive Powder Concrete is an ultra high-strength and high ductility composite material with advanced mechanical properties. Developed in the 1990s by Bouygues' laboratory in France, it consists of a special concrete where its microstructure is optimized by precise gradation of all particles in the mix to yield maximum density. It uses extensively the pozzolanic properties of highly refined silica fume and optimization of the Portland cement chemistry to produce the highest strength hydrates. RPC represents a new class of Portland cement-based material with compressive strengths in excess of 200 MPa range. By introducing fine steel fibers, RPC can achieve remarkable flexural strength up to 50 MPa. The material exhibits high ductility with typical values for energy absorption approaching those reserved for metals.

The benefits
• RPC is a better alternative to High Performance Concrete and has the potential to structurally compete with steel.
• Its superior strength combined with higher shear capacity results in significant dead load reduction and limitless structural member shape.
• With its ductile tension failure mechanism, RPC can be used to resist all but direct primary tensile stresses. This eliminates the need for supplemental shear and other auxiliary reinforcing steel.
• RPC provides improve seismic performance by reducing inertia loads with lighter members, allowing larger deflections with reduced cross sections, and providing higher energy absorption.
• Its low and non-interconnected porosity diminishes mass transfer making
penetration of liquid/gas or radioactive elements nearly non-existent. Cesium diffusion is non-existent and Tritium diffusion is 45 times lower than conventional containment materials.

**Compact Reinforced Concrete**

CRC is a new type of composite material. In its cement-based version, CRC is built up of a very strong and brittle cementitious matrix, toughened with a high concentration of fine steel fibres and an equally large concentration of conventional steel reinforcing bars continuously and uniformly placed across the entire cross section. CRC was initially developed and tested by Prof. Bache at the laboratories of Aalborg Portland cement factory in Denmark. The pioneering experiments carried out at this laboratory established the vast potential of CRC for applications that warrant high strength, ductility and durability.

CRC has structural similarities with reinforced concrete in the sense that it also incorporates main steel bars, but the main bars in CRC are large in number and are uniformly reinforced. Owing to this and also because of the large percentage of fibres used in its making, it exhibits mechanical behavior more like that of structural steel, having almost the same strength and extremely high ductility.

CRC specimens are produced using 10-20% volume of main reinforcement (in the form of steel bars of diameter from about 5 mm to perhaps 40 or 50 mm) evenly distributed across the cross section) and 5-10% by volume of fine steel fibres. The water-cement ratio is generally very low, about 0.18% and the particle size of sand in the cement slurry is between 2 and 4mm. The flow characteristics while mixing and pouring is aided by the use of micro silica and a dispersant. High-frequency vibration is often resorted to for getting a the mix compacted and to obtain homogeneity. Prolonged processing time for mixing, about 15-20 minutes, ensures effective particle wetting and high degree of microhomogeneity.
Such highly fibre-reinforced concrete typically has compressive strengths ranging from 150 to 270 MPa, and fracture energy from 5,000 to as much as 30,000 N/m. CRC beams exhibit load capacities almost equivalent to those of structural steel and remain substantially uncracked right up to the yield limit of the main reinforcement (about 3 mm/m), where as conventional reinforced concrete typically cracks at about 0.1- 0.2 mm/m. It is very strong concrete or composite. It consists of very strong cementitious matrix, high fraction of steel fiber and high percentage of continuous steel bars. Main reinforcement is in the form of long bars of 5mm to 40 mm diameter, 10 to 20 percent are used. Very fine steel fibers are also used to an extent of 5-=10%. Some of the properties are tabulated below.

Applications

• Large plates and shells designed for very large local loads from shocks and explosives, large pressure tanks
• High strength to density ratio-used where weight and inertia are important as in ships and vehicles
• To support large machinery parts
• Used in Hybrid structures-High performance structural joints in steel-concrete structures
• Used as an alternative to steel where corrosion and fire are the main criterion.
### Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>CRC</th>
<th>RCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load capacity up to</td>
<td>2mm to 3mm per m</td>
<td>0.1 to 0.2 mm per m</td>
</tr>
<tr>
<td>Ultimate flexural strength, MPa</td>
<td>140-260</td>
<td>5-25</td>
</tr>
<tr>
<td>Ultimate shear strength, MPa</td>
<td>100-150 with shear steel</td>
<td>3-20</td>
</tr>
<tr>
<td></td>
<td>15-20 without shear steel</td>
<td>0.25 to 3</td>
</tr>
<tr>
<td>Ultimate tensile strength, MPa</td>
<td>100-200</td>
<td>2-12</td>
</tr>
<tr>
<td>Ultimate compressive strength, MPa</td>
<td>150-400</td>
<td>20-80</td>
</tr>
<tr>
<td>Young’s Modulus, GPa</td>
<td>30-100</td>
<td>20-40</td>
</tr>
<tr>
<td>Density Kgm$^{-3}$</td>
<td>3000-4000</td>
<td>2400-2500</td>
</tr>
<tr>
<td>Toughness</td>
<td>Several times</td>
<td></td>
</tr>
<tr>
<td>Fatigue-At 65% Max. load</td>
<td>5 million compressive stress cycles</td>
<td>Few hundreds of cycles</td>
</tr>
<tr>
<td>Fracture energy, N/m</td>
<td>5000-30,000</td>
<td>100-1000</td>
</tr>
</tbody>
</table>
UNIT - 8
HIGH PERFORMANCE CONCRETE

INTRODUCTION
Concrete is the most widely used construction material in India with annual consumption exceeding 100 million cubic metres. It is well known that conventional concrete designed on the basis of compressive strength does not meet many functional requirements such as impermeability, resistance to frost, thermal cracking adequately. Conventional Portland cement concrete is found deficient in respect of:

• Durability in severe environs (Shorter service life and require maintenance)
• Time of construction (longer release time of forms and slower gain of strength)
• Energy absorption capacity (for earthquake-resistant structures)
• Repair and retrofitting jobs

High performance concrete (HPC) successfully meets the above requirement.

HPC is an engineered concrete possessing the most desirable properties during fresh as well as hardened concrete stages. HPC is far superior to conventional cement concrete as the ingredients of HPC contribute most optimally and efficiently to the various properties.

High performance concrete (HPC) is a specialized series of concrete designed to provide several benefits in the construction of concrete structures that cannot always be achieved routinely using conventional ingredients, normal mixing and curing practices. In the other words a high performance concrete is a concrete in which certain characteristics are developed for a particular application and environment, so that it will give excellent performance in the structure in which it will be placed, in the environment to which it will be exposed, and with the loads to which it will be subjected during its design life. It includes concrete that provides either substantially improved resistance to
environmental influences (durability in service) or substantially increased structural capacity while maintaining adequate durability. It may also include concrete, which significantly reduces construction time without compromising long-term serviceability. While high strength concrete, aims at enhancing strength and consequent advantages owing to improved strength, the term high-performance concrete (HPC) is used to refer to concrete of required performance for the majority of construction applications.

The American Concrete Committee on HPC includes the following six criteria for material selections, mixing, placing, and curing procedures for concrete.

1. Ease of placement
2. Long term mechanical properties
3. Early-age strength
4. Toughness
5. Life in severe environments
6. Volumetric stability

The above-mentioned performance requirements can be grouped under the following three general categories.

(a) Attributes that benefit the construction process
(b) Attributes that lead to enhanced mechanical properties
(c) Attributes that enhance durability and long-term performance

**Definition of HPC**

The performance requirements of concrete cannot be the same for different applications. Hence the specific definition of HPC required for each industrial application is likely to vary. The Strategic Highway Research Programme (SHRP) has defined HPC for highway application on the following strength, durability, and w/c ratio criteria.

(a) It should satisfy one of the following strength criteria:
4 hour strength _17.5 Mpa
24 hour strength _35.0 Mpa
28 days strength _ 70.0 Mpa
(b) It should have a durability factor greater than 80% after 300 cycles of freezing and thawing.
(c) It should have a water-cement ratio of 0.35 or less.

In general, a “High performance Concrete” can be defined as that concrete which has the highest durability for any given strength class, and comparison between the concretes of different strength classes is not appropriate. This means that, with the available knowledge, one can always strive to achieve a better (most durable) concrete required for a particular application.

HPC is a concrete, which meets special performance, and uniformity requirements that cannot be always achieved by using only the conventional materials and normal mixing, placing, and curing practices. The performance requirements may involve enhancement of placement and compaction without segregation and long term mechanical properties, early age strength, toughness, volume stability, service life.

A High Performance concrete element is that which is designed to give optimized performance characteristics for a given set of load, usage and exposure conditions, consistent with requirement of cost, service life and durability.

High Performance concrete has,
(a) Very low porosity through a tight and refined pore structure of the cement paste.
(b) Very low permeability of the concrete
(c) High resistance to chemical attack.
(d) Low heat of hydration
(e) High early strength and continued strength development
(f) High workability and control of slump
(g) Low water binder ratio
(h) Low bleeding and plastic shrinkage

2.4 Civil Engineering Research Foundation (CERP)

High performance construction materials and systems: An essential program for American and infrastructure. HPC is a concrete in which some or all of the following properties have been enhanced
(a) Ease of placement
(b) Long term mechanical properties
(c) Early age strength
(d) Toughness
(e) Volume stability
(f) Extended service life in severe environments

A more broad definition of HPC was adopted by the ACI. HPC was defined as concrete, which meets special performance and uniformity requirements that cannot be always be achieved routinely by using only conventional materials and normal mixing, placing and curing practices. The requirements may involve enhancement of placement and compaction without segregation, long term mechanical properties, early age strength, volume stability or service life in severe environments. Concretes possessing many of these characteristics often achieve higher strength. Therefore, HPC is often of high strength, but high strength concrete may not necessarily be of high performance.
Methods for achieving High Performance

In general, better durability performance has been achieved by using high-strength, low w/c ratio concrete. Though in this approach the design is based on strength and the result is better durability, it is desirable that the high performance, namely, the durability, is addressed directly by optimizing critical parameters such as the practical size of the required materials.

Two approaches to achieve durability through different techniques are as follows.

1. Reducing the capillary pore system such that no fluid movement can occur is the first approach. This is very difficult to realize and all concrete will have some interconnected pores.

2. Creating chemically active binding sites which prevent transport of aggressive ions such as chlorides is the second more effective method. There are two approaches are shown in Fig

![Diagram of Techniques of production of HPC]

- Reduced capillary pore
- Use fine filler (silica fume)
- Improved curing
- Binding sites for chloride
- Increased physical resistance
- Durable concrete
- Supplementary cementitious materials (SCM)
  - GGBS
  - Fly ash
  - Meta
  - Kaolin
  - Risk
  - Husk
  - Blends
  - Ash

Techniques of production of HPC
Requirements for High-performance Characteristics

Permeation is a major factor that causes premature deterioration of concrete structures. The provision of high-performance concrete must centre on minimizing permeation through proportioning methods and suitable construction procedures (curing) to ensure that the exposure conditions do not cause ingress of moisture and other agents responsible for deterioration. Permeation can be divided into three distinct but connected stages of transportation of moisture, vapour, air, gases, or dissolved ions.

It is important to identify the dominant transport phenomenon and design the mix proportion with the aim of reducing that transport mechanism which is dominant to a predefined acceptable performance limit based on permeability. Like the requirement of permeation characteristics, there can be other performance characteristics which may become the specific need for which HPC is used. Table 1 gives a list of such desired characteristics for which HPC has been used.

**salient high-performance requirements**

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compressive strength $&gt;70$ MPa</td>
</tr>
<tr>
<td>2</td>
<td>Very early strength (4 h) $&gt;17.5$ MPa</td>
</tr>
<tr>
<td>3</td>
<td>Early strength (24 h) $&gt;35$ MPa</td>
</tr>
<tr>
<td>4</td>
<td>High degree of impermeability to prevent ingress of water/moisture/CO$_2$/SO$_4$/air/oxygen/chloride</td>
</tr>
<tr>
<td>5</td>
<td>High resistance to sulphate attack</td>
</tr>
<tr>
<td>6</td>
<td>Smooth fractured surface</td>
</tr>
<tr>
<td>7</td>
<td>Absence of micro-cracking</td>
</tr>
<tr>
<td>8</td>
<td>High level of corrosion resistance</td>
</tr>
<tr>
<td>9</td>
<td>High electrical resistivity</td>
</tr>
<tr>
<td>10</td>
<td>High chemical resistivity</td>
</tr>
<tr>
<td>11</td>
<td>High resistance to abrasion, erosion, and cavitation</td>
</tr>
</tbody>
</table>
The parameter to be controlled for achieving the required performance criteria could be any of the following.

1. Water/(cement + mineral admixture) ratio
2. Strength
3. Densification of cement paste
4. Elimination of bleeding
5. Homogeneity of the mix
6. Particle size distribution
7. Dispersion of cement in the fresh mix
8. Stronger transition zone
9. Low free lime content
10. Very little free water in hardened concrete

**Material Selection**

The main ingredients of HPC are almost the same as that of conventional concrete. These are

1. Cement
2. Fine aggregate
3. Coarse aggregate
4. Water
5. Mineral admixtures (fine filler and/or pozzolonic supplementary cementitious materials)
6. Chemical admixtures (plasticizers, superplasticizers, retarders, air-entraining agents)

**Cement**

There are two important requirements for any cement: (a) strength development with time and (b) facilitating appropriate rheological characteristics when fresh. Studies made by Perenchio (1973) and Hanna et al. (1989) have led to the following observations.
1) High C3A content in cement generally leads to a rapid loss of flow in fresh concrete. Therefore, high C3A content should be avoided in cements used for HPC.

2) The total amount of soluble sulphate present in cement is a fundamental consideration for the suitability of cement for HPC.

3) The fineness of cement is the critical parameter. Increasing fineness increases early strength development, but may lead to rheological deficiency.

4) The superplasticizer used in HPC should have long molecular chain in which the sulphonate group occupies the beta position in the poly condensate of formaldehyde and melamine sulphonate or that of naphthalene sulphonate.

5) The compatibility of cement with retarders, if used, is an important requirement. Ronneburg and Sandrik (1990) suggested tailor-made cements with characteristics suitable for HPC (Table 2). Note that SP30 is ordinary Portland cement. SP30-4A and SP30-4A (mod) are two varieties of tailor-made special cements. It is to be noted that the two special cements recommended to produce very high strength concrete have low C3A content, sulphate level, and heat of hydration apart from phase composition.
Composition of special cement for HPC

<table>
<thead>
<tr>
<th>Particulars</th>
<th>SP30</th>
<th>SP30-4A</th>
<th>SP30-4A(mod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2S (%)</td>
<td>18</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>C3S (%)</td>
<td>55</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>C3A (%)</td>
<td>8</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>C4AF (%)</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Mgo (%)</td>
<td>3</td>
<td>1.5-2.0</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>SO3 (%)</td>
<td>3.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Na2O equivalent (%)</td>
<td>1.1</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Blain fineness (μm/kg)</td>
<td>300</td>
<td>310</td>
<td>400</td>
</tr>
<tr>
<td>Heat of hydration (kcal/kg)</td>
<td>71</td>
<td>56</td>
<td>70</td>
</tr>
<tr>
<td>Setting time critical (min)</td>
<td>120</td>
<td>140</td>
<td>120</td>
</tr>
<tr>
<td>Final</td>
<td>180</td>
<td>200</td>
<td>170</td>
</tr>
</tbody>
</table>

Coarse aggregate

The important parameters of coarse aggregate that influence the performance of concrete are its shape, texture and the maximum size. Since the aggregate is generally stronger than the paste, its strength is not a major factor for normal strength concrete, or for HES and VES concretes. However, the aggregate strength becomes important in the case of high performance concrete. Surface texture and mineralogy affect the bond between the aggregates and the paste as well as the stress level at which micro cracking begins. The surface texture, therefore, may also affect the modulus of elasticity, the shape of the stress-strain curve and to a lesser degree, the compressive strength of concrete. Since bond strength increases at a slower rate than compressive strength, these effects will be more pronounced in HES and VES concretes. Tensile strengths may be very sensitive to differences in aggregate surface texture and surface area per unit volume.
Effect of Aggregate Type

The intrinsic strength of coarse aggregate is not an important factor if water-cement ratio falls within the range of 0.50 to 0.70, primarily due to the fact that the cement-aggregate bond or the hydrated cement paste fails long before aggregates do. It is, however, not true for very high strength concretes with very low water-cement ratio of 0.20 to 0.30. For such concretes, aggregates can assume the weaker-link role and fail in the form of transgranular fractures on the failure surface. However, the aggregate minerals must be strong, unaltered, and fine grained in order to be suitable for very high strength concrete. Intra- and inter-granular fissures partially decomposed coarse-grained minerals, and the presence of cleavages and lamination planes tend to weaken the aggregate, and therefore the ultimate strength of the concrete.

The compressive strength and elastic modulus of concrete are significantly influenced by the mineralogical characteristics of the aggregates. Crushed aggregates from fine-grained diabase and limestone give the best results. Concretes made from smooth river gravel and from crushed granite containing inclusions of a soft mineral are relatively weaker in strength. There exists a good correlation between the compressive strength of coarse aggregate and its soundness expressed in terms of weight loss. There exists a close correlation between the mean compressive strengths of the aggregate and the compressive strength of the concrete, ranging from 35 to 75 MPa, at both 7 days and 28 days of age.

Effect of Aggregate Size

The use of larger maximum nominal size of aggregate affects the strength in several ways. First, since larger aggregates have less specific surface area and the aggregate-paste bond strength is less, the compressive strength of concrete is reduced. Secondly, for a given volume of concrete, using larger aggregate results
in a smaller volume of paste thereby providing more restraint to volume changes of the paste. This may induce additional stresses in the paste, resulting in micro cracks prior to application of load, which may be a critical factor in very high strength (VHS) concretes. Therefore, it is the general consensus that smaller size aggregate should be used to produce high performance concrete.

It is generally suggested that 10 to 12 mm is the appropriate maximum size of aggregates for making high strength concrete. However, adequate performance and economy can also be achieved with 20 to 25 mm maximum size graded aggregates by proper proportioning with a mid-range or high-range water reducer, high volume blended cements, and coarse ground Portland cement. Change in emphasis from water-cementitious material ratio versus strength relation to water-content versus durability relation will provide the incentive for much closer control of aggregate grading than in the current practices. A substantial reduction in water requirement can be achieved by using a well-graded aggregate.

### 5.3 Mineral admixtures

Mineral admixtures form an essential part of the high-performance concrete mix. These are used for various purposes, depending upon their properties. More than the chemical composition, mineralogical and granulometric characteristics determine the influence of mineral admixture’s role in enhancing properties of concrete. The fly ash (FA), the ground granulated blast furnace slag (GGBS) and the silica fume (SF) has been used widely as supplementary cementitious materials in high performance concrete. These mineral admixtures, typically fly ash and silica fume (also called condensed silica or micro silica), reduce the permeability of concrete to carbon dioxide (CO2) and chloride-ion penetration without much change in the total porosity. These pozzolanas react with OPC in two ways-by altering hydration process through alkali activated reaction kinetics of a pozzolanas called pozzolanic reaction and by micro filler effect. In pozzolanic
reaction the pozzolanas react with calcium hydroxide, Ca(OH)2, (free lime) liberated during hydration of cement, which comprises up to 25 per cent of the hydration product, and the water to fill voids with more calcium-silicate-hydrate (non-evaporable water) that binds the aggregate particles together.

The pozzolanas may also react with other alkalis such as sodium and potassium hydroxides present in the cement paste. These reactions reduce permeability, decrease the amounts of otherwise harmful free lime and other alkalis in the paste, decrease free water content, thus increase the strength and improve the durability.

Fly ash used as a partial replacement for cement in concrete, provides very good performance. Concrete is durable with continued increase in compressive strength beyond 28 days. There is little evidence of carbonation, it has low to average permeability and good resistance to chloride-ion penetration. Chloride-ion penetration rating of high volume fly ash (HVFA) concrete is less than 2000 coulombs, which indicate a very low permeability concrete. It continues to improve because many fly ash particles react very slowly, pushing the coulomb value lower and lower.

Silica fume not only provides an extremely rapid pozzolanic reaction, but its very fine size also provides a beneficial contribution to concrete. Silica fume tends to improve both mechanical properties and durability. Silica fume concretes continue to gain strength under a variety of curing conditions, including unfavorable ones. Thus the concretes with silica fume appear to be more robust to early drying than similar concretes that do not contain silica fume. Silica fume is normally used in combination with high-range water reducers and increases achievable strength levels dramatically. Since no interaction between silica fume, ground granulated blast-furnace slag and fly ash occurs, and each component manifests its own cementitious properties as hydration proceeds, higher strength and better flowability can be achieved by adding a combination of SF, FA and GGBFS to OPC which provides, a system with wider particle-size distribution.
HVFA concrete incorporating SF exceeds performance of concrete with only FA. The key to developing OPC-FA-SF and OPC-GBSF-SF concretes without reduction in strength is to incorporate within the mixture adequate amounts of OPC and water. Using both silica fume and fly ash, the strength at 12 hours has been found to improve suddenly over similar mixes with silica fume alone. This phenomenon has been attributed to the liberation of soluble alkalis from the surface of the fly ash.

The contribution of silica fume to any property of hardened concrete may be expressed in terms of cementing efficiency factor, K. For compressive strength of concrete, K is in the range of 2 to 5, which means that in a given concrete, 1 kg of silica fume may replace 2 to 5 kg of cement without impairing the compressive strength. This applies provided that the water content is kept constant and the silica fume dosage is less than about 20 per cent by weight of cement.

High-reactivity metakaolin (HRM) is a more recently developed supplementary cementitious material. It is a reactive alumino-silicate pozzolana manufactured by calcining purified kaolinite at a specific temperature range. It is classified as a natural pozzolana, with silica and alumina oxides content exceeding 95 per cent. The particle size is smaller than Portland cement but coarser than silica fume. Chemically, HRM combines with calcium hydroxide to form calcium-silicate and calcium-aluminate-hydrates. It has been reported that HRM in powder form is a quality-enhancing mineral additive that exhibits enhanced engineering properties comparable to silica fume slurry. At the present time, the supply of this material is limited and no practical cost data is available.
Typical oxide analysis of mineral admixtures.

<table>
<thead>
<tr>
<th>Mineral admixtures</th>
<th>Main oxides present</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>Diatomaceous earth</td>
<td>86</td>
</tr>
<tr>
<td>Fly ash (coal)</td>
<td>55</td>
</tr>
<tr>
<td>Fly ash (lignite)</td>
<td>44</td>
</tr>
<tr>
<td>Blast furnace slag</td>
<td>38</td>
</tr>
<tr>
<td>Silica fume</td>
<td>90</td>
</tr>
<tr>
<td>Rice husk ash</td>
<td>92</td>
</tr>
<tr>
<td>Meta-kaolin</td>
<td>52</td>
</tr>
</tbody>
</table>

A look at this table reveals that silica and alumina content vary widely. However, these chemical differences do not significantly influence the properties of concrete. Fly ashes generally contain less silica and more alumina compared to natural pozzolanas. Both fly ash and blast furnace slag have high calcium and magnesium oxide content. Highly active admixtures such as silica fume and rice husk ash contain high content of silica. Metakaolin contains roughly equal proportions of silica and alumina.

The ground, granulated blast furnace slag and rice husk ash have to be ground to the required fineness to assist pozzolanic activity. Typically, particles less than 10 μm in size contribute to early strength; particles between 10 and 45 μm show strength gain up to 28 days; particles larger than 45 μm contribute little to the strength. The slag is generally ground to Blaine fineness of 450-550 m²/kg. The typical BET surface area of silica fume is 12,000 m²/kg.

This is because the particle size of silica fume is in the range of 0.01-0.45 μm. However, the rice husk ash is ground only to a fineness of 6-10μm because of the porous structure. The metakaolin is ground to a fineness of about 1-2 μm.
The pozzolanic material with large surface area shows excellent reactivity. It imparts stability and cohesiveness to the mixture and prevents bleeding as well as segregation. A summary of the characteristics of different mineral admixtures is given in Table.

**Characteristics of mineral admixtures.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Classification</th>
<th>Chemical composition</th>
<th>Particle characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground granulated blast furnace slag</td>
<td>Cementitious and pozzolanic</td>
<td>Silicate glass containing calcium magnesium silicate</td>
<td>Unprocessed material re grains like sand. These are ground to size &lt; 45 µm (500 m²/kg Blaine) particles and have a rough texture.</td>
</tr>
<tr>
<td>Calcium-rich fly Ash</td>
<td>Cementitious and pozzolanic</td>
<td>Silicate glass containing mainly calcium, magnesium, alumina</td>
<td>Powder consists of particles &lt; 45 µm. However, 10-15% are more than 45 µm.</td>
</tr>
<tr>
<td>Condensed silica Fume</td>
<td>Highly active pozzolana</td>
<td>Pure silica of non-crystalline form</td>
<td>Extremely fine powder consisting of solid spheres of 0.1 µm average diameter.</td>
</tr>
<tr>
<td>Rice husk ash</td>
<td>Highly active pozzolana</td>
<td>Consists essentially of pure silica in non-crystalline form</td>
<td>Particles are &lt;45 mm and have cellular and porous structure.</td>
</tr>
<tr>
<td>Low-calcium fly Ash</td>
<td>Cementitious and pozzolanic</td>
<td>Mostly silicate glass containing aluminium and iron and alkide small quantities of quartz, hematite, etc.</td>
<td>Powder having particles of 15-30% &gt; 45 µm. Most particles are solid spheres.</td>
</tr>
<tr>
<td>Natural material</td>
<td>Natural pozzolana</td>
<td>Contains aluminosilicate glass, natural pozzolan material</td>
<td>Particles are &lt;45 µm and have rough texture. consist of crystalline silicate material.</td>
</tr>
<tr>
<td>Slowly cooled blast furnace slag, bottom</td>
<td>Weak pozzolana</td>
<td></td>
<td>Pulverized to fine powder, and ground materials have rough texture.</td>
</tr>
</tbody>
</table>
Superplasticizers or HRWR

The superplasticizers are extensively used in HPCs with very low watercementitious material ratios. In addition to deflocculation of cement grains and increase in the fluidity, the other phenomena that are likely to be present are the following.

(a) Induced electrostatic repulsion between particles.
(b) Dispersion of cement grains and consequent release of water trapped within cement flocks.
(c) Reduction of surface tension of water.
(d) Development of lubrication film between particles.
(e) Inhibition of the surface hydration reaction of the cement particles, leaving more water to fluidify the mix.
(f) Change in morphology of hydration products.
(g) Induced steric-hindrance preventing particle to particle contact.

The main objectives for using superplasticizers are the following.

(i) To produce highly dense concrete to ensure very low permeability with adequate resistance to freezing-hawing.
(ii) To minimize the effect of heat of hydration by lowering the cement content.
(iii) To produce concrete with low air content and high workability to ensure high bond strength.
(iv) To lower the water-cement ratio in order to keep the effect of creep and shrinkage to a minimum.
(v) To produce concrete of lowest possible porosity to protect it against external attacks.
(vi) To keep alkali content low enough for protection against alkali-aggregate reaction and to keep sulphate and chloride contents as low as possible for prevention of reinforcement corrosion.
(vii) To produce pumpable yet non-segregating type concrete.
(viii) To overcome the problems of reduced workability in fibre reinforce concrete and shotcrete.

(ix) To provide high degree of workability to the concretes having mineral additives with very low water-cementitious material ratios.

(x) To produce highly ductile and acid resistant polymer (acrylic latex) concrete with adequate workability and strength.

The following types of superplastisizers are used.

- Naphthalene-based
- Melamine-based
- Lignosulfonates-based
- Polycarboxylate-based
- Combinations of above

**Superplastisizer Dosage**

There is no a prior way of determining the required superplasticizer dosage; it must be determined by trial and error procedure. Basically, if strength is the primary criterion, then one should work with the lowest w/c ratio possible, and thus the highest superplasticizer dosage. However, if the rheological properties of the HPC are very important, then the highest w/c ratio possible consistent with the required strength should be used, with the superplasticizers dosage then adjusted to get the desired workability. In general, of course, some intermediate positions must be found, so that the combination of strength and rheological properties are optimized.

**Retarders**

Retarders are, generally, recommended for HSC to minimize the slump loss problem. However, it is difficult to maintain compatibility between the retarder and the superplasticizer. Therefore, the Retarders are recommended only as a last resort; the rheology is better controlled by the use of appropriate mineral admixture (supplementary cementing material).
Mix Proportion

The main difference between mix designs of HPC and CC is the emphasis laid on performance aspect also (in fresh as well as hardened stages of concrete) besides strength, in case of HPC, whereas in design of CC mixes, strength of concrete is an important criterion. By imposing the limitations on maximum water–cement ratio, minimum cement content, workability (slum, flow table, compaction factor, Vee-Bee consistency), etc., it is sought to assure performance of CC; rarely any specific tests are conducted to measure the durability aspects of CC, during the mix design. In HPC, however, besides strength, durability considerations are given utmost importance. To achieve high durability of HPC, the mix design of HPC should be based on the following considerations:

i) The water-binder (w/b) ratio should be as less as possible, preferably 0.3 and below.

ii) The workability of concrete mix should be enough to obtain good compaction (use suitable chemical admixtures such as superplasticizer (SP)).

iii) The transition zone between aggregate and cement paste should be strengthened (add fine fillers such as silica fume (SF)).

iv) The microstructure of cement concrete should be made dense and impermeable (add pozzolanic materials such as fly ash (FA), ground granulated blast furnace slag powder (GGBFSP), SF, etc.)

v) Proper curing regime of concrete should be established (this is to overcome the problems associated with usual adoption of very low water content and high cement content in HPC mixes)
LIMITATIONS OF CONVENTIONAL MIX DESIGNS: BIS method (IS: 10262 – 1982):

a). The Code lists the grade of concrete unto M60 only, while suggesting the values of standard deviation for each grade of concrete.

b). The graph of BIS Code suggesting the general relationship between water-cement (w/c) and 28-day compressive strength refers to a maximum compressive strength of 52 MPa only and another graph showing the same relationship depending upon (w/c) and 28-day strength of cement refer to a maximum compressive strength of 58Mpa only. The HPCs usually have compressive strength often more than 70Mpa (100Mpa and more). Hence, the above provisions of BIS Code cannot be applied to HPC.

c). The extrapolations of standard deviations (SD) given in the Code to obtain SD for HPC, result in very high SD values. It is observed from the literature that the SD of HPCs would be quite lower owing to the maximum care taken in selection of ingredients, proportioning mixing and curing of HPCs. Use of unrealistic high values of SDs would push up unnecessarily the cost of HPCs as the HPC’s have to be designated for much higher strength than required.

d). The BIS method gives a table for finding water content of the concrete for w/c ratio of 0.35 only. In this table, water contents of 200 and 180 kg/m3 are suggested for maximum size of aggregates (MSAs) of 10 mm and 20m respectively. The HPCs usually have w/c=0.3 or less. Even assuming w/c of 0.3, the cement contents corresponding to the above water contents work out to 667 and 600 kg/m3 respectively. These cements are too high and are never reported to be used for HPCs as seen from the published literature on HPC.

e). Maximum w/c ratio of 0.45 suggested or ‘severe’ exposure condition in IS: 10262 and IS: 456 is too high and the HPCs reported in the literature have very low w/c ratios (often 0.3 and below). Thus, the BIS suggestion of w/c=0.45, cannot be accepted for HPCs.
f). The suggestion of sand content at 28% (for MSA of 10mm) and 25% (for MSA of 25mm) in the BIS method leads to fine aggregates: coarse aggregate ratios of the order of 1:2 to 1:3 (by weight). From the published literature on HPCs these ratios seem to be quite high and hence, the cohesiveness of HPCs would be affected if these ratios are adopted. As the HPCs utilize SPs, it would be necessary to use more sand in order to avoid segregation of cement paste from aggregate due to the dispersing/flowing effect of SP on the cement paste.

g). The BIS code allows the use of Zone IV sand which may have particles passing through 300 micron sieve, to an extent of 50%. As the HPCs have usually very low water content, this large content of small particles (less than 300 microns) of sand would reduce the workability of the HPCs. Moreover, the fine particles of sand may not be required in HPCs as these concrete usually have high cement contents and also have often pozzlanic powdery materials such as FA, SF, etc.

**ACI Method**

This Code covers 28-day compressive strength upto about 60 MPa as seen from the curve of compressive strength-Vs-w/c ratio, suggested by this Code. The minimum water cement ratio covered is 0.3. As HPCs have often strengths more than 60 MPa and w/c ratio 0.3 and below, the ACI method can not give proportions for HPC.

**Road Note No.4**

This method covers up to a minimum w/c ratio of 0.35 which is more than the w/c ratio adopted usually in HPCs and hence, this method cannot be adopted for HPC.

**IRC-44 Method**

This method refers to a curve of compressive strength-Vs-w/c ratios in which minimum w /c ratio is 0.4 and maximum compressive strength is about 50 MPa. The HPCs usually have w/c ratio is 0.3 and less, which is quite less than 0.4 the value referred in this method. The HPCs usually have the strengths more than 50
MPa. Thus, it can be seen that the IRC-44 method cannot be used for the design of HPC mixes.

**GENERAL COMMENTS ON CONVENTIONAL MIX DESIGN METHODS**

It is observed from the study of conventional mix design methods (CMDs) that they are not generally applicable to HPC because of the following reasons:

i) The compressive strength levels covered by CMDs are far less than those usually obtained in case of HPCs.

ii) W/C or W/B ratio of CMD, are generally higher or quite close to the highest level of W/b ratio encountered in HPCs.

iii) The CMDs do not take into account for changes in properties of fresh as well as hardened concrete due to incorporation of water reducing admixtures such as SP and also the permeability reducing mineral additives such as FA, SF, GGBS, SF, etc.

iv) The CMDs do not consider exclusively the durability aspects affecting properties of concrete such as porosity, impermeability, electric receptivity, etc.

v) Many a time the type and strength of aggregate limit the strength level of HPCs that can be achieved with the given aggregate. Such limitations are not usually encountered in case of CC designated by CMDs.

vi) The CMDs do not account for strength of transition zone. In HPCs, considerations with regard to the development of suitable transition zone need special attention.

vii) As the HPCs tend to have usually high cementitious content, use of cement replacement materials such as FA, SF, GGBS, SP, etc, is almost essential to reduce the ill effects of high cement content in a concrete.

viii) The strength developed in case of HPCs after conventional 28-days period is quantitatively considerable; hence, later age strength (say 90-day) is better criterion for design of HPC mixes.
ix) The standard deviations of HPCs could be less than those of CCs since the HPCs are produced under stricter quality control measures. This would help in making economical mix design of HPCs.

**TYPICAL HPC MIX DESIGN METHODS IN PUBLISHED LITERATURE**

The properties of HPCs not only depend upon the w/b ratio but also vary considerably with the richness of mix and the type and strengths of concrete of aggregates. Workability of HPCs depends upon the type of cement and its compatibility with chemical admixtures, shape of aggregate, method of mixing of ingredients of HPCs, etc. Thus, the properties of materials and mix preparation techniques have very high influence on the HPC mixes, suitable mix proportions cannot be suggested for HPCs. Therefore, any mix design procedure of HPCs can strictly be only a guideline and a separate development of HPC mix in the laboratory for the various ingredients, type of structure and concreting conditions etc., is very much essential. Hence, the HPC mix design can be only application specific. It should be noted that the strength increase as the w/c is reduced (provided the compatibility of concrete is maintained), and that for a given w/c, the strength is decreased as a mix is made richer (by adding more cement) beyond a limit. Therefore, the advantage of increase in strength due to lowering of the w/c, which also reduces consequently the workability. Hence, the HPCs require approaches other than the increase of cement content in order to achieve the high strength.

Though the strengths are not always true indicators of durability, the high strength associated with the HPCs generally tend to impart also high durability to them, due to reduced w/b and use of pozzolanic admixtures.

**Canadian Portland Cement Association**

It is explicitly suggested that the trial mix approach is the best for selecting proportions for high strength concrete.
LCPC Mix Design By Experimental Method

Various steps involved in this method are;

(i) Design a normal strength concrete (NSC) for a critical workability and the desired 28-day compressive strength.
(ii) Adjust the water content of NSC to obtain the workability with SP, to get control concrete (CC)
(iii) Measure lowing time (Marsh Cone) of binder paste of CC.
(iv) Arbitrarily choose binder mixes such as 90% cement plus 10% FA or 75% cement plus 20% FA plus 5% SF, etc. Find SP content and w/b ratio to obtain flow time of binder paste of CC.
(v) Use Feret’s law for trial casting. The HPC and CC would change in content of ingredients, if required.
(vi) Make HPC mix for trial casting. The HPC and CC could have same workability and same granular skeleton.
(vii) Depending upon the strength required, different binder paste has to be chosen

Cement and Concrete Association of Australia

The technical report No.TR/F112 clearly states that the proportions of concrete mixes with 28-day compressive strength of 60Mpa and above have to be obtained only an investigating trial mixes using locally available materials.

Method proposed by Mehta and Aitcin

1. Choice of strength: Arbitrarily divided into five grades, namely 65, 75, 95 and 120 Mpa.
2. Estimation of Mixing water: from a given strength grade, Table is used to estimate the maximum content of mixing water.
3. Volume fraction of cement paste components: From the total volume of 0.35 m3 of cement paste, the water content and entrapped air is subtracted to get cementitious material.
4. Estimation of aggregate content: From the total aggregate volume 0.65 m³, assuming a 2:3 volumetric ratio between fine and coarse aggregate, individual volume fractions are calculated.

5. Calculation of batch weights: From the typical specific gravity values of ingredients the batch weights are determined.

6. Superplastizer dosage: If there is no prior experience with the superplasticizer, it is suggested to start with 1% and continue till the required workability is obtained.

7. Moisture correction: Depending on the moisture condition of batch aggregates, the appropriate moisture correction for fine and coarse aggregate must be made.

8. Trial batch adjustment: Several laboratory trials using the actual materials may be required before one arrives at the right combination of materials and mix proportions, which satisfy the given criteria of workability and strength.

**ACI 211.4R Standard Practice**

Data needed include- F.M. of sand, dry rodded unit weight of the C.A., Specific gravity of the aggregates.

1. Slump selection: Selected from the given table
   The target strength fcr = (fc + 9.65) / 0.9
   fcr = Specified design compressive strength
   fc = Required average compressive strength

2. Selection of maximum size of aggregate (MSA): Based on the strength requirement, select the maximum size of aggregate.

3. Selection of optimum coarse aggregate content:
   Weight of C.A. = (%xDRUW)x DRUW

4. Estimation of mixing water and air content: From the table get the estimate of mixing water and air content percentage.
   Mixing Water adjustment, kg/m³ + (V-35)x4.74

5. Selection of W / (C+P) Ratio: Table gives the recommended maximum W / (C+P) ratio as the function of the maximum size of aggregate to achieve different
Compressive strengths either at 28 days or 56 days for a mix made without HRWRA and a mix made using HRWRA.

6. Calculate cementitious Materials content: obtained by dividing the amount of mixing water by the W / (C+P) ratio.

7. Sand content: After determining the weights of C.A., cement and water and air content, the sand content can be calculated using absolute volume methods.

8. Proportion Companion mixture using FLY ash:

9. Trial mixtures

10. Adjustment of Trial mix proportions

**Properties of High Performance Concrete**

**Properties of Fresh Concrete**

High performance concrete is characterized by special performance both short- and long-term and uniformity in behavior. Such requirements cannot always be achieved by using only conventional materials or applying conventional practices. It is wrong to believe that the mechanical properties of high performance concrete are simply those of a stronger concrete. It is also as wrong to consider that the mechanical properties of high-performance concrete can be deduced by extrapolating those of usual concretes as it would be wrong to consider that none of them are related. It is also wrong to apply blindly the relationships linking the mechanical properties of a usual concrete to its compressive strength that were developed through the years for usual concretes found in codes and text books.

**Workability**

The workability of HPC is normally good, even at low slumps, and HPC typically pumps very well, due to the ample volume of cementing material and the presence of chemical admixtures, particularly HRWR. Due to reduced water-cementing material ratio no bleeding occurs. In the flowing concrete bleeding is prevented by providing adequate fines in the concrete mix. The cohesiveness of superplastisized concrete is much better as a result of better dispersion of cement particles. Cohesion is a function of rheology of concrete mix, which is consequently
improved. However, excessive dosages of superplastisizer can induce some segregation, but it has little effect on physical properties of hardened concrete.

**Rheological Properties**

Widening the particle-size distribution of a solid suspension while maintaining constant solid volume reduces the viscosity of the suspension, known as the Farris effect. Thus, the blended or composite cements with wider particle-size distributions can achieve better rheological properties. The OPC-FA-SF ternary cement concrete requires less water and is less sticky than OPC-SF concrete; however, it requires more water and is stickier than OPC-FA or OPC-GGBFS based concrete. In ternary cements FA seems to compensate for the rheological problems associated with the use of high SF contents. In binary cements containing relatively coarser GGBFS for example, addition of fine pozzolanas, such as SF or rice husk ash, inhibits bleeding problems.

**Curing**

The compressive strength of HPC is less sensitive to temperature and relative humidity than the normal strength concrete. However, tensile strength of HSC has been found to be more sensitive. The concrete containing very large quantities of ground granulated blastfurnace slag requires longer moist curing times to develop adequate strength and is more sensitive to drying than plain Portland cement concretes. The higher internal temperatures frequently found with high early strength HPC can lead to a rapid strength gain in concrete accompanied by a consequent gain in elastic modulus. The larger differential temperatures occurring within a stiffer concrete will create higher stresses and can cause more pronounced cracking than with normal concrete. These cracks will occur, regardless of the method of curing, due to stress caused by differential temperatures.
Properties of Hardened concrete

The behaviour of hardened concrete can be characterized in terms of its short-term (essential instantaneous) and long-term properties. Short-term properties include strength in compression, tension and bond, and modulus of elasticity. The long-term properties include creep, shrinkage, behaviour under fatigue, and durability characteristics such as porosity, permeability, freezing-thawing resistance, and abrasion resistance.

Stress-strain Behaviour

Axial stress versus strain curves for HPC is shown in fig. 3. The shape of the ascending part of the stress-strain curve is more linear and steeper for high-strength concrete, and the strain at the maximum stress is slightly higher for HPC. The slope of the descending part becomes steeper for high-performance concrete. To obtain the descending part of the stress-strain curve, it is generally necessary to avoid the specimen-testing system interaction. High performance concrete exhibits less internal microcracking than lower-strength concrete for a given imposed axial strain. As a result, the relative increase in lateral strain is less for HPC. The lower relative lateral expansion during the inelastic range may mean that the effects of triaxial stresses will be proportionally different for HPC. For example the influence of hoop reinforcement is observed to be different for HPC.

Strengths

Compressive, tensile and flexural strengths and modulus of elasticity of high performance concrete are much higher than those of the normal concrete of the same consistency. The enhancement in the mechanical properties is generally commensurate with reduction in water content when HRWR is used. In water reduced concrete the strength parameters can be generally increased by more than 20 percent. A strength of the order of normal concrete is achieved by superplastisized concrete with a reduced cement content. The strength of the concrete depends on a number of factors including the properties and proportions of the constituent materials, degree of hydration, rate of loading, and method.
of testing and specimen geometry. The properties of the constituent materials which affect the strength are: the quality of fine and coarse aggregates, the cement paste and the paste-aggregate bond characteristics, i.e. properties of the interfacial transition zone. These, in turn, depend on the macro- and micro-scopic structural features including total porosity, pore size and shape, pore distribution and morphology of the hydration products, plus the bond between individual components.

**Modulus of elasticity**

It is generally agreed that the elastic modulus of concrete increases with its compressive strength. The modulus is greatly affected by the properties of the coarse aggregate; the larger the amount of coarse aggregate with a high elastic modulus, the higher would be the modulus of elasticity of concrete. The concrete in wet condition has about 15 percent higher elastic modulus than that in the dry condition. This is attributed to the effect of drying of transition zone between the aggregate and the paste. The modulus of elasticity increases with the strain rate. It also increases as the concrete is subjected to very low temperatures. Addition of high volume of fly ash enhances elastic modulus significantly. The high elastic modulus of HVFA concrete is probably due to the fact that a considerable portion of the unreacted fly ash, consisting of glassy spherical particles, acts as a fine aggregate, and there is a strong interfacial bond between the paste and the aggregate.

**Poisson’s Ratio**

Experimental data on values of Poisson’s ratio for HPC are very limited. Pernchio and Klieger reported values for Poisson’s ratio with a compressive strength ranging from 55 to 80 MPa between 0.2 and 0.28. They concluded that Poisson’s ratio tends to decrease with increasing water-cement ratio. Kaplan found values for Poisson’s ratio of concrete determined using dynamic measurements to be from 0.23 to 0.32 regardless of compressive strength, coarse aggregate, and test
age for concretes having compressive strengths ranging from 17 to 79 Mpa. Based on the available information, Poisson’s ratio of HPC in the elastic range seems comparable to the expected range of values for lower strength concretes.

**Modulus of Rupture**

For usual concrete modulus of rupture and splitting tensile strength are quite low and don’t vary much, because they are very much influenced by the tensile strength of the hydrated cement paste. However, this is no longer the case for high performance concrete, for which the water binder ratio and the compressive strength can vary over a wide range. The relationships that have been suggested between compressive strength and modulus of rupture for usual concrete lose some of their predictive value when going from usual concrete to high performance concrete.

**Splitting Tensile Strength**

Dewar studied the relationship between the indirect tensile strength and the compressive strength of concretes having compressive strengths upto 83 MPa at 28 days. He concluded that at low strengths, the indirect tensile strengths may be as high as 10 percent of the compressive strength but at higher strengths it may reduce to 5 percent. He observed that the tensile splitting strength was about 8 percent higher for crushed rock aggregate concrete than for gravel aggregate concrete. He also found that the indirect tensile strength was about 70 percent of the flexural strength at 28 days.

**Shrinkage**

Little information is available on the shrinkage behaviour of High-Performance concrete. A relatively high initial rate of shrinkage has been reported, but after drying for 180 days there is little difference between the shrinkage of high-strength and lower strength concrete made with dolomite or limestone. Reducing the curing period from 28 to 7 days caused a slight increase in the shrinkage. Shrinkage was unaffected by w/c ratio but is approximately proportional to the percentage of water by volume in the concrete. Other laboratory and field studies
have shown that shrinkage of high-performance concrete is similar to that of lower
strength concrete. Nogataki and Yonekurus reported that the shrinkage of high
performance concrete containing high-range water reducers was less than for
lower-strength concrete.

Creep
Creep, the flow of the material under sustained load, is a very important factor in
the long-term deformational performance of structures. It has been found that the
specific creep and hence the creep coefficient value are less in high-performance
concrete (HPC) than in normal-strength concrete (NSC).

The creep coefficient decreases while the strength increases, that is to say while
the w/c ratio decreases. For ordinary concretes, the value of the creep coefficient $\psi$
is generally taken equal to 2.0 when loading is applied at 28 days. It seems that
this coefficient may be as low as 1.0 for some C60 concretes and 0.50 for some C
100 concretes. The creep of high-performance concrete made with high-range
water reducers is reported to be decreased significantly. The maximum specific
creep was less for high-strength concrete than for lower-strength concrete loaded
at the same age.

Ductility
Compression tests show that the stronger the concrete the more brittle it is. This
could be of concern since modern design methods take into account the plasticity
of materials. Flexural tests run on the reinforced HPC beams show that their
ductility is similar to that of beams with ordinary concrete. Care should
nevertheless be exercised concerning HPC elements such as columns submitted to
axial loads. Experiments are being carried out in France in order to set the rules
concerning minimum longitudinal and transverse reinforcements in such pieces.
Fatigue strength
As the static strength of concrete increases, it becomes increasingly more brittle and its ultimate strain capacity does not increase proportionately with the increase in strength. Therefore high performance concrete would be vulnerable to fatigue loading. However in HPC the elastic modulus of the paste and that of aggregate are more similar, thereby reducing stress concentrations at the aggregate-paste interface is less susceptible to fatigue loading. Thus due to reduced microcracking in HPC, the fatigue life built-up damages are smaller when compared with those in normal strength concrete.

Alkali-Aggregate Reaction
Fly ash, blast furnace slag, and silica fume supplementary cementitious pozzolanic additions to the concrete mixture (SCM) have shown to be effective ingredients in resisting alkali-aggregate reaction. The effect of the addition pozzolanic fly ash (PFA), blast furnace slag (BFS), and condensed silica fume (CSF) are effective in reducing the expansion in concrete, provided that they are used correctly and of the appropriate quality and amount. Coating the aggregates with acrylic or epoxy might be a solution, but effectiveness and cost does not match the other solution.

Abrasion Resistance
Abrasion resistance of concrete is of major importance in highway pavements and concrete bridge decks. Work available on the abrasion resistance of high-performance concretes has shown that increase in strength results in substantially increased service life, as documented by Gjorv et. al. In this work, an increase in concrete strength from 50 MPa to 100 MPa can reduce the abrasion deterioration by almost 50%. While the type of aggregate and its abrasion resistance affects the performance of the concrete, its effect becomes less significant at the highest compressive strength to abrasion. Service life of pavements ranged from 7 years in 40 MPa to 31 years in153 MPa ultrahigh strength concrete.
Carbonation
Carbonation is the chemical reaction caused by the defusion of carbon dioxide (CO2) in the air into the permeable concrete and its reaction with Ca(OH)2 compound of the hydrated cement such that it carbonates to CaCO3. This decomposition of the calcium compounds in the hydrated matrix combined with alternating wetting and drying in air containing CO2 leads to an increase in the magnitude of irreversible shrinkage, contributing to crazing of the exposed surface and increase in the weight of the concretes, with progressive scaling of the concrete protective cover to the reinforcement. Use of pozzolanic cementations replacements in concrete such as silica fume or fly ash does not seem to have any significant effect on the carbonation development or rate. However, if scaling is prevented because of the higher tensile strength of the high-performance concrete, its dense composition and extremely low pore volume and permeability inhibit the oxidation process that causes corrosion of the reinforcement.

Porosity and Permeability
The exceptional properties of HPCs proceed essentially from their reduced porosity and not from their high compressive strength which is only one of their many facets; it is their reduced porosity which makes them new material with multiple advantages. It is generally agreed that mixing water is indirectly responsible for permeability of the hydrated cement paste because its content determines at the first instance the total space and subsequently the unfilled space after the water is consumed by either cement hydration reactions or evaporation to the environment. In other words porosity of concrete resides principally in the cement paste.