Lecture-02

Materials

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Topics Addressed

- Concrete
- Properties of Concrete
- High Strength Concrete
- Advantages of Concrete as Construction Material
- Concrete Admixtures
- Types of Reinforcing Steel
- Deformed Bar Reinforcement
- ACI Code Provisions for Concrete and Steel
Concrete

• A composite material composed of:
  • Paste (Portland Cement + water)
  • Aggregates (generally sand and gravel)

Concrete Components

• Paste
  • Cementitious materials
    • Portland cement
    • Pozzolans (fly ash, silica fume, ground granulated blast furnace slag)
  • Water
Concrete

- Concrete Components
  - Aggregates
    - Coarse
      - Gravel
      - Crushed stone
    - Fine
      - Sand

- Percentage Composition
  - Paste: 25% - 40%
  - Cement: 7% - 15%
  - Water: 14% - 21%
  - Air: 4% - 8%
  - Aggregates: 60% - 75%
Properties of Concrete

- Compressive Strength
  - The uniaxial compressive strength is measured by a compression test of a standard test cylinder. This test is used to monitor the concrete strength for quality control or acceptance purposes.
  - The specified compressive strength is measured by compression tests on 6 by 12 inches cylinders, tested after 28 days of moist curing (testing methods: ASTM Standards C31 and C39).
Properties of Concrete

• Tensile Strength
  • Varies between 8% and 15% of the compressive strength.
  • The type of test that is used to determine the tensile strength has a strong effect on the value that is obtained.
  • Two types of tests are widely used:
    • Modulus of Rupture (Flexural Test)
    • Split Cylinder Test

Properties of Concrete

• Tensile Strength
  • Modulus of Rupture (Flexural Test)
    • ASTM C 78 – Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
    • ASTM C 293 – Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)
    • The beams are 6 in. x 6 in. x 30 in. long
**Properties of Concrete**

- **Tensile Strength**
  - Modulus of Rupture (Flexural Test)

\[ f_r = \frac{6M}{bh^2} \]

- **Split Cylinder Test:** The requirements of ASTM C 496 are used to conduct a split cylinder test on 6 in. x 12 in. cylinder.
Properties of Concrete

• Relationship Between Compressive and Tensile Strengths
  • Tensile strength increases with an increase in compressive strength
  • Ratio of tensile strength to compressive strength decreases as the compression strength increases
  • Tensile strength $\propto \sqrt{f'_c}$

Mean $f_{ct} = 6.4\sqrt{f'_c}$

For deflections (ACI 19.2.3):
  • $f_r = 7.5\sqrt{f'_c}$

For strength
  • $f_s = 6\sqrt{f'_c}$
Properties of Concrete

- Factors Affecting Concrete Strength
  - In addition to mixing, conveying, placing and compaction, the strength of concrete primarily depends on:
  - Water Cement Ratio: Decrease in water cement ratio increases the strength.
  - Aggregate Cement Ratio: Decrease in aggregate cement ratio increases the strength up to a value of around 2.0. Further decrease may cause decrease in strength.

- Aggregate:
The concrete strength is affected by the aggregate strength, its surface texture, its grading and maximum size of the aggregate.

- Curing: Prolonged moist curing leads to the highest concrete strength
Properties of Concrete

- **Rate of Strength Gain**
  - ACI Committee 209 [3-21] has proposed the following equation to represent the rate of strength gain for concrete made from Type 1 cement and moist-cured at 70°F.
    \[ f'_{c(t)} = f'_{c(28)} \left\{ \frac{t}{4 + 0.85t} \right\} \]
  - Where \( f'_{c(t)} \) is the compressive strength at age \( t \) in days.

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**Figure**

![Diagram showing the effect of type of cement on strength gain of concrete (moist cured; w/c = 0.49).](image)

I = Normal  
II = Modified  
III = High early strength  
IV = Low heat  
V = Sulfate resisting
Properties of Concrete

• Variation in Strength
  • Variations in the properties or proportions of constituents of concrete, as well as variations in transporting, placing, and compaction of the concrete, lead to variations in the strength of the finished concrete. In addition, discrepancies in the tests will lead to apparent differences in strength.

Figure shows the distribution of strengths in a sample of 176 concrete cylinder tests for the concrete having nominal strength of 3000 psi
• Strength less than nominal = 9
• Strength more than nominal = 167
Properties of Concrete

• Time Dependent Volume Changes
  • Concrete undergoes three main types of volume change, which may cause stresses, cracking, or deflections.
    • Shrinkage
    • Creep
    • Thermal expansion

Properties of Concrete

• Shrinkage
  • Shrinkage occurs as the moisture diffuses out of the concrete. The exterior shrinks more than the interior, which leads to tensile stresses in the outer layer of the concrete.
  • Shrinkage occurs during hardening and drying of concrete under constant temperature.
Properties of Concrete

• Shrinkage
  • Shrinkage increases with time, as shown in the figure. Shrinkage strains are partially recoverable, once the concrete is rewetted. Seasonal changes in humidity may lead to the expansion and contraction of a structure due to changes in shrinkage strains.

![Shrinkage Curve](image)

Shrinkage of an unloaded specimen.

When not adequately controlled, can cause:
  • Unsightly or harmful cracks
  • Large and harmful stresses
  • Partial loss of initial prestress
  • Reinforcement restrains the development of shrinkage.
Properties of Concrete

- Creep

Creep strains can lead to:

- Increase in deflections with time
- Redistribution of stresses
- Decrease in prestressing forces
Properties of Concrete

- Thermal Expansion or Contraction
  - Expansion or contraction due to change in temperature
    - Coefficient of Thermal Expansion or Contraction
      - Affected by:
        - Composition of the concrete
        - Moisture content of the concrete
        - Age of the concrete

Properties of Concrete

- Thermal Expansion
  - Coefficient of Thermal Expansion or Contraction
    - Normal weight concrete
      - Siliceous aggregate: 5 to $7 \times 10^{-6}$ strain/F
      - Limestone/calcareous aggregate: 3.5 to $7 \times 10^{-6}$ strain/F
    - Lightweight concrete
      - 3.6 to $6.2 \times 10^{-6}$ strain/F
      - For calculation purposes, a value of $5.5 \times 10^{-6}$ strain/F is satisfactory
Properties of Concrete

- **Durability**
  - Three most common durability problems in concrete are:
    - Corrosion of steel in concrete.
    - Breakdown of the structure of concrete due to freezing and thawing.
    - Breakdown of the structure of concrete due to chemical action.

  Note: ACI Chapter 19: "Concrete Design and Durability Requirements" provides details of durability requirements for concrete.

- **Fire Resistance**
  - Concrete is the most highly fire-resistive structural material used in construction.
  - Nonetheless, the properties of concrete and the reinforcing steel change significantly at high temperatures.
    - Strength, modulus of elasticity are reduced, the coefficient of thermal expansion increases, and creep and stress relaxations are considerably high.
**Properties of Concrete**

- **Fire Resistance**

  Compressive Strength of Concrete at High Temperatures

  ![Graph showing compressive strength of concrete at high temperatures](image)

  Reinforced Concrete Mechanics and Design by Macgregor, Page 92, Chapter # 3 (6th edition)

  The temperatures stated (in previous slide) are the internal temperatures of the concrete and are not to be confused with the heat intensity of the exposing fire.

  For example, in testing a solid carbonate aggregate slab, the ASTM standard fire exposure (ASTM E 119) after 1 hour will be 1700 °F, while the temperatures within the specimen will vary:

  - 1225 °F at ¼ inch from exposed surface
  - 950 °F at ¾ inch
  - 800 °F at 1 inch
Properties of Concrete

• Fire Resistance
  • Because of variable complexities and the unknowns of dealing with the structural behavior of the buildings under fire as total multidimensional systems, building codes continue to specify minimum acceptable levels of fire endurance on a component by component basis.

<table>
<thead>
<tr>
<th>Fire Resistance Rating</th>
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<tr>
<td>1hr.</td>
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<tr>
<td>3.5&quot;</td>
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</tbody>
</table>
Properties of Concrete

- Fire Resistance
  - Minimum concrete column dimensions (using normal weight concrete).

<table>
<thead>
<tr>
<th>Fire Resistance Rating</th>
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<tbody>
<tr>
<td>1 hr</td>
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<tr>
<td>8&quot;</td>
</tr>
</tbody>
</table>

- The same may be applied to beams as well.

High Strength Concrete

- Definition
  - Concretes with strengths in excess of 6000 psi are referred to as high strength concrete.
  - The resulting concrete has a low void ratio.
  - Only the amount of water needed to hydrate the cement in the mix is provided.
High Strength Concrete

- Shrinkage and Creep
  - Shrinkage of concrete is approximately proportional to the percentage of water by volume in the concrete. High-strength concrete has a higher paste content, but the paste has a lower water cement ratio. As a result, the shrinkage of high-strength concrete is about the same as that of normal concrete.
  - Test data suggest that the creep coefficient for high-strength concrete is considerably less than that for normal concrete.

UET Lab Results for Producing High Strength Concrete

- Mix design results for 6000 and 8000 psi concrete.

<table>
<thead>
<tr>
<th>Table-A</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial Test</td>
<td>Proportion</td>
<td>No. of cylinders</td>
<td>Date of preparation</td>
<td>Date of Testing</td>
<td>Avg. Strength (psi)</td>
</tr>
<tr>
<td>6000 psi</td>
<td>(1:1:2) w/c (0.36)</td>
<td>6</td>
<td>25/6/2010</td>
<td>22/7/2010</td>
<td>6100</td>
</tr>
<tr>
<td>8000 psi</td>
<td>(1:0.8:1.5) w/c (0.31)</td>
<td>6</td>
<td>28/6/2010</td>
<td>25/7/2010</td>
<td>8000</td>
</tr>
</tbody>
</table>

- Admixture used: Sikament 520BA
Advantages of Concrete as Construction Material

- **Versatility of Form**: Concrete poured in fluid state can adopt any shape.

- **Fire Resistance**: With proper concrete protection of the steel reinforcement, a reinforced concrete structure provides the maximum in fire protection.

- **Speed of construction**: A concrete building can often be completed in less time than a steel structure…?

Advantages of Concrete as Construction Material

- **Cost**: In many cases, the first cost of a structure is less than that of a comparable steel structure. In almost every case, maintenance costs are less.

- **Availability of Labor**: The materials and labor for reinforced concrete are easily available compared to steel construction.
Concrete Admixtures

• Definition
  - A material (usually in liquid form) other than cement, water and aggregates, that is used as an ingredient of concrete and is added to the batch immediately before or during mixing to change properties of fresh or hardened concrete.

• Uses
  - Admixtures are used to:
    - achieve certain properties in concrete more effectively than by other means.
    - maintain the quality of concrete during the stages of mixing, transporting, placing, and curing in adverse weather conditions.
    - reduce the cost of concrete construction.
Concrete Admixtures

• Types
  • As per ACI Committee 212, admixtures have been classified into following groups:
    • **Air-entraining Admixtures**: causes the development of a system of microscopic air bubbles in concrete, mortar, or cement paste during mixing. Air-entrained concrete should be used wherever water saturated concrete may be exposed to freezing and thawing. Air entrainment also improves the workability of concrete.

• **Types**
  • **Accelerating Admixtures**: causes an increase in the rate of hydration of the hydraulic cement and thus shortens the time of setting, increases the rate of strength development, or both.
  • **Water Reducing and Set-Controlling Admixtures**: Reduce the water requirements of a concrete mixture for a given slump, modify the time of setting, or both.
Concrete Admixtures

- Types
  - Admixtures for Flowing Concrete: Flowing Concrete is concrete that is characterized as having a slump greater than 190 mm (7-1/2 in.) while maintaining a cohesive nature.
  - Miscellaneous
    - Freeze Resistant, Pigments, Bonding, Grouting etc. (Refer ACI 212 for details and more types of miscellaneous admixtures)

Types of Reinforcing Steels

- Deformed Bar Reinforcement: ACI 20.2.1.3
- Plain Reinforcement: ACI 20.2.1.4
- Prestressing Steel: ACI 20.3.1.1
- Structural Steel Shapes: ACI 20.4.1.2

Note: In the next slides only the properties of Deformed Bars will be discussed.
Deformed Bar Reinforcement

- **ASTM Specifications**
  - **ASTM A 615**, Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement.
  - **ASTM A 706**, Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement.

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**Shapes & Designations**

- Main ribs
- Letter or symbol for producing mill
- Bar size #11
- Type steel*
  - S Billet-steel (A 615)
  - I Rail-steel (A 996)
  - R Rail-steel (A 996)
  - A Axle-steel (A 996)
  - W Low-Alloy steel (A 706)
- Grade mark
- Grade line (one line only)

*Bars marked with an S and W meet both A 615 and A 706

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Reinforced Concrete Mechanics and Design by Macgregor, Page 94, Chapter # 3 (6th edition)
Deformed Bar Reinforcement

• Typical Stress-Strain Curve

\[ f_s = E_s \varepsilon_s \]

\[ f_s = f_y \]

Typical Stress-Strain Curve

Steel Grade Minimum yield stress, \( f_y \) (ksi) Ultimate strength (ksi)
40 40 70
50 50 80
60 60 90
75 75 100

Stress strain curves for different steel Grades

Reinforced Concrete Mechanics and Design by Macgregor, Page 96, Chapter # 3 (6th edition)
Deformed Bar Reinforcement

- **Variation in Yield Strength**
  - Distribution of mill test yield strength for grade 60 steel.

[Histogram showing the distribution of mill test yield strength for grade 60 steel]

Reinforced Concrete Mechanics and Design by Maegregor, Page 96, Chapter # 3 (6th edition)

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CE 5115  
Advance Design of Reinforced Concrete Structures  
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Deformed Bar Reinforcement

- **Reinforcement Fire Protection**
  - The reinforcement can lose its mechanical properties due to temperature increase from fire exposure.
    - Protection for reinforcement in concrete is mainly provided by concrete cover.
    - The concrete protection specified in ACI 318 for cast-in-place concrete will generally equal or exceed the minimum cover requirements.
Deformed Bar Reinforcement

- Reinforcement Fire Protection
  - Minimum cover for RC floors and slabs

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1 hr.</td>
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<tr>
<td>¾&quot;</td>
</tr>
</tbody>
</table>

Deformed Bar Reinforcement

- Reinforcement Fire Protection
  - Minimum cover to main reinforcement in RC beams

<table>
<thead>
<tr>
<th>Beam width, inches</th>
<th>Fire resistance rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 hr.</td>
</tr>
<tr>
<td>5</td>
<td>¾&quot;</td>
</tr>
<tr>
<td>7</td>
<td>¾&quot;</td>
</tr>
<tr>
<td>≥ 10</td>
<td>¾&quot;</td>
</tr>
</tbody>
</table>
Deformed Bar Reinforcement

- Reinforcement Fire Protection
  - Minimum cover for RC columns

<table>
<thead>
<tr>
<th>Fire resistance rating</th>
<th>1 hr.</th>
<th>2 hr.</th>
<th>3 hr.</th>
<th>4 hr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ½ ″</td>
<td>1 ½ ″</td>
<td>1 ½ ″</td>
<td>2 ″</td>
<td></td>
</tr>
</tbody>
</table>

Deformed Bar Reinforcement

- Strength of Reinforcing Steel at High temperatures
  - Deformed reinforcement subjected to high temperatures in fires tends to lose its strength.

Reinforced Concrete Mechanics and Design by MacGregor, Page 98, Chapter # 3 (6th edition)
ACI Code Provisions for Concrete and Steel

ACI chapters 19, 20 & 26 discuss various properties and requirements for materials used in reinforced concrete. Following slides discuss only few important points from these chapters.

Chapter 19 "Concrete: Design and Durability requirements"

Chapter 20 "Steel Reinforcement Properties, Durability and Embedments"

Chapter 26 "Construction Documents and Inspection"

ACI Code Provisions for Concrete and Steel

Chapter 19: Concrete: Design and durability requirements

- In chapter 19 of the ACI code “Concrete design and durability requirements” various properties related to the design and durability of concrete are discussed. some of which are as follows
  - **Specified compressive strength** (ACI 19.2.1.1)
  - The value of $f'_c$ shall be specified in construction documents and shall be in accordance with (a) through (c):
    - (a) Limits in Table 19.2.1.1
    - (b) Durability requirements in Table 19.3.2.1
    - (c) Structural strength requirement
ACI Code Provisions for Concrete and Steel
Chapter 19: Concrete: Design and durability requirements

- Modulus of elasticity (ACI 19.2.2)
  - Modulus of elasticity, $E_c$, for concrete shall be permitted to be calculated as (a) or (b):
    
    (a) For values of $w_r$ between 90 and 160 lb/ft$^3$
    
    $$E_c = w_r^{3/3} \sqrt{f_c} \text{ (in psi)} \quad (19.2.2.1.a)$$
    
    (b) For normalweight concrete
    
    $$E_c = 57,000 \sqrt{f_c} \text{ (in psi)} \quad (19.2.2.1.b)$$

- (ASTM C469) provides a test method for determining the modulus of elasticity for concrete in compression.

Exposure Categories & Classes (ACI: 19.3.1)

- Sulfate exposures
  - Concrete to be exposed to sulfate-containing solutions or soils shall conform to requirements of Table 19.3.1.1 or shall be concrete made with a cement that provides sulfate resistance and that has a maximum water-cementitious materials ratio and minimum compressive strength from Table 19.3.2.1.
ACI Code Provisions for Concrete and Steel
Chapter 19: Concrete: Design and durability requirements

• Exposure Categories & Classes (ACI: 19.3.1)
  • Corrosion Protection
  • For corrosion protection of reinforcement in concrete, maximum water soluble chloride ion concentrations in hardened concrete at ages from 28 to 42 days contributed from the ingredients including water, aggregates, cementitious materials, and admixtures shall not exceed the limits of Table 19.3.2.1. When testing is performed to determine water soluble chloride ion content, test procedures shall conform to ASTM C 1218.

ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

• In chapter 26 of the ACI code “Construction documents and inspection” various properties related to the constituents of concrete are discussed which are as follows.
  • Cementitious materials (ACI: 26.4.1.1)
    • (a) Cementitious materials shall conform to the specifications in Table 26.4.1.1.1(a)

<table>
<thead>
<tr>
<th>Table 26.4.1.1.1(a)—Specifications for cementitious materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cementitious material</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>Portland cement</td>
</tr>
<tr>
<td>Blended hydraulic cements</td>
</tr>
<tr>
<td>Expansive hydraulic cement</td>
</tr>
<tr>
<td>Hydraulic cement</td>
</tr>
<tr>
<td>Fly ash and natural pozzolans</td>
</tr>
<tr>
<td>Slag cement</td>
</tr>
<tr>
<td>Silica fume</td>
</tr>
</tbody>
</table>
ACI Code Provisions for Concrete and Steel

Chapter 26: Concrete: Construction documents and Inspection

- Cementitious materials
  - (b) All cementitious materials specified in Table 26.4.1.1(a) and the combinations of these materials shall be included in calculating the w/cm of the concrete mixture.

ACI Code Provisions for Concrete and Steel

Chapter 26: Concrete: Construction documents and Inspection

- Aggregates (ACI: 26.4.1.2)
  - (a) Aggregates shall conform to (1) or (2):
    - (1) Normalweight aggregate: ASTM C33.
    - (2) Lightweight aggregate: ASTM C330.
  - (b) Aggregates not conforming to ASTM C33 or ASTM C330 are permitted if they have been shown by test or actual service to produce concrete of adequate strength and durability and are approved by the building official.

- Water (ACI: 26.4.1.3)
  - Mixing water shall conform to ASTM C1602.
  - Water used in mixing concrete shall be clean and free from injurious amounts of oils, acids, alkalis, salts, organic materials, or other substances deleterious to concrete or reinforcement.
ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

- Admixtures (ACI: 26.4.1.4)
  - (a) Admixtures shall conform to (1) through (4):
  - (b) Admixtures that do not conform to the specifications in 26.4.1.4.1(a) shall be subject to prior review by the licensed design professional.
  - (c) Admixtures used in concrete containing expansive cements conforming to ASTM C845 shall be compatible with the cement and produce no deleterious effects.

ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

- Proportioning of concrete mixtures (R26.4.3)
  - For proportioning of concrete mixtures ACI 318-14 section R26.4.3 refers to other ACI documents, such as ACI 301 and ACI 214R.

### Table 4.2.3.3.b—Required average compressive strength \( f'_{c} \)

<table>
<thead>
<tr>
<th>Specified strength amount ( f'_c ) psi</th>
<th>Required average compressive strength ( f'_c ) psi</th>
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</thead>
<tbody>
<tr>
<td>Less than 3000</td>
<td>( f'_c + 1000 )</td>
</tr>
<tr>
<td>3000 to 5000</td>
<td>( f'_c + 1200 )</td>
</tr>
<tr>
<td>Over 5000 to 10,000</td>
<td>( f'_c + 1400 )</td>
</tr>
<tr>
<td>Over 10,000 to 15,000</td>
<td>( f'_c + 1800 )</td>
</tr>
</tbody>
</table>

### Table 5.2—Minimum required average strength without sufficient historical data

<table>
<thead>
<tr>
<th>Required average compressive strength</th>
<th>Specified compressive strength</th>
</tr>
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<tbody>
<tr>
<td>( f'_c + 1000 ) psi</td>
<td>when ( f'_c &lt; 3000 ) psi</td>
</tr>
<tr>
<td>( f'_c + 1200 ) psi</td>
<td>when ( f'_c &lt; 5000 ) psi</td>
</tr>
<tr>
<td>( f'_c + 1400 ) psi</td>
<td>when ( f'_c &lt; 7000 ) psi</td>
</tr>
<tr>
<td>( f'_c + 1800 ) psi</td>
<td>when ( f'_c &lt; 10,000 ) psi</td>
</tr>
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ACI 301, Table 4.2.3.3.b

ACI 214R, Table 5.2
ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

- Requirements for proportioning concrete mixtures
  - (a) Concrete mixture proportions shall be established so that the concrete satisfies (1) through (3)
    - (1) Can be placed readily without segregation into forms and around reinforcement under anticipated placement conditions.
    - (2) Meets requirements for assigned exposure class in accordance with either 26.4.2.1(a) or 26.4.2.1(b).
    - (3) Conforms to strength test requirements for standard cured specimens.

- (b) Concrete mixture proportions shall be established in accordance with Article 4.2.3 of ACI 301 or by an alternative method acceptable to the licensed design professional.
- (c) The concrete materials used to develop the concrete mixture proportions shall correspond to those to be used in the proposed Work.
- (d) If different concrete mixtures are to be used for different portions of proposed Work, each mixture shall comply with the concrete mixture requirements stated in the construction documents.
ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

• Sampling Frequency for Strength Tests (ACI: 26.12.2)
  • ACI R26.12.2.1(a): As a measure of quality control, the code recommends following criteria for collecting samples of concrete cylinders from a given class of concrete:
    • Once each day a given class is placed, nor less than
    • Once for each 150 yd$^3$ of each class placed each day, nor less than
    • Once for each 5000 ft$^2$ of slab or wall surface area placed each day.
      • In calculating surface area, only one side of the slab or wall should be considered.

• Strength Test (ACI: 26.12.1.1)
  • A strength test shall be the average of the strengths of at least two 6 x 12 in. cylinders or at least three 4 x 8 in. cylinders made from the same sample of concrete and tested at 28 days or at test age designated for $f'_c$. 
**ACI Code Provisions for Concrete and Steel**

**Chapter 26: Concrete: Construction documents and Inspection**

- **Criterion for Satisfactory Concrete Strength (ACI: 26.12.3)**
  - Strength level of an individual class of concrete shall be considered satisfactory if both of the following requirements are met:
    - (a) Every arithmetic average of any three consecutive strength tests equals or exceeds $f'_c$;
    - (b) No individual strength test (average of two cylinders) falls below $f'_c$ by more than 500 psi when $f'_c$ is 5000 psi or less; or by more than 0.10$f'_c$ when $f'_c$ is more than 5000 psi.

- **The steps taken to increase the average level of test results: (ACI: R26.12.4)**
  - It will depend on the particular circumstances, but could include one or more of the following:
    - An increase in cementitious materials content
    - Changes in mixture proportions
    - Reductions in or better control of levels of slump supplied
    - Closer control of air content
    - An improvement in the quality of the testing, including strict compliance with standard test procedures
ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

• Investigation of Low Strength Test Results (ACI: 26.12.4)
  • If any strength test of standard-cured cylinders falls below \( f'_c \) by more than the limit allowed for acceptance, or if tests of field-cured cylinders indicate deficiencies in protection and curing, steps shall be taken to ensure that structural adequacy of the structure is not jeopardized.

• If the likelihood of low-strength concrete is confirmed and calculations indicate that load-carrying capacity is significantly reduced, tests of cores drilled from the area in question in accordance with “Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete” (ASTM C 42) shall be permitted.
  • In such cases, three cores shall be taken for each strength test that falls below \( f'_c \) by more than the limit allowed for acceptance.
ACI Code Provisions for Concrete and Steel
Chapter 26: Concrete: Construction documents and Inspection

• Investigation of Low Strength Test Results (ACI: 26.12.4)
  • According to ACI 26.12.4.1, concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85 percent of $f_c'$ and if no single core is less than 75 percent of $f_c'$.

• If criteria for evaluating structural adequacy based on core strength results are not met, and if the structural adequacy remains in doubt, the responsible authority shall be permitted to order a strength evaluation in accordance with Chapter 27 “Strength Evaluation of Existing Structures” for the questionable portion of the structure or take other appropriate action.
ACI Code Provisions for Concrete and Steel

Chapter 26: Concrete: Construction documents and Inspection

- Record of test of materials (ACI: 26.13.2.1)
  - A complete record of tests of materials and of concrete shall be retained by the inspector for 2 years after completion of the project, and made available for inspection during the progress of the work.

ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, durability, and embedments

- Provisions for material properties
- Deformed Reinforcement (ACI 20.2.1.3)
  - Deformed bars shall conform to (a), (b), (c), (d), or (e):
    - (a) ASTM A615 – carbon steel
    - (b) ASTM A706 – low-alloy steel
    - (c) ASTM A996 – axle steel and rail steel; bars from rail steel shall be Type R
    - (d) ASTM A955 – stainless steel
    - (e) ASTM A1035 – low-carbon chromium steel
- Plain bars (ACI 20.2.1.4)
  - Plain bars for spiral reinforcement shall conform to ASTM A615, A706, A955, or A1035
ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, durability, and embedments

- **Provisions for design properties**
  - For nonprestressed bars and wires, the stress below \( f_y \) shall be \( E_s \) times steel strain. For strains greater than that corresponding to \( f_y \), stress shall be considered independent of strain and equal to \( f_y \). (ACI: 20.2.2.1)
  - Modulus of elasticity, \( E_s \), for nonprestressed bars and wires shall be permitted to be taken as 29,000,000 psi. (ACI: 20.2.2.2)
  - Yield strength for nonprestressed bars and wires shall be based on the specified grade of reinforcement and shall not exceed the values given in 20.2.2.4 for the associated applications. (ACI: 20.2.2.3)

- Types of nonprestressed bars and wires to be specified for particular structural applications shall be in accordance with Table 20.2.2.4a for deformed reinforcement and Table 20.2.2.4b for plain reinforcement. (ACI 20.2.2.4)
ACI Code Provisions for Concrete and Steel
Chapter 20: Steel reinforcement properties, durability, and embedments

• Provisions for design properties
  • Deformed nonprestressed longitudinal reinforcement resisting earthquake-induced moment, axial force, or both, in special moment frames, special structural walls, and all components of special structural walls including coupling beams and wall piers shall be in accordance with (a) or (b):
    • (a) ASTM A706, Grade 60
    • (b) ASTM A615, Grade 40 reinforcement if (i) and (ii) are satisfied and ASTM A615 Grade 60 reinforcement if (i) through (iii) are satisfied.
      • (i) Actual yield strength based on mill tests does not exceed $f_y$ by more than 18,000 psi
      • (ii) Ratio of the actual tensile strength to the actual yield strength is at least 1.25
      • (iii) Minimum elongation in 8 inch steel sample shall be at least 14 percent for bar sizes No. 3 through No. 6, at least 12 percent for bar sizes No. 7 through No. 11, and at least 10 percent for bar sizes No. 14 and No. 18.

ACI Code Provisions for Concrete and Steel
Chapter 20: Steel reinforcement properties, durability, and embedments

• Provisions for durability of steel reinforcement
  • Specified concrete cover requirement
    • Nonprestressed cast-in-place concrete members shall have specified concrete cover for reinforcement at least that given in Table 20.6.1.3.1.
ACI Code Provisions for Concrete and Steel
Chapter 20: Steel reinforcement properties, durability, and embedments

• Provisions for durability of steel reinforcement
  • Specified concrete cover requirement for corrosive environment
    • In corrosive environments or other severe exposure conditions, the specified concrete cover shall be increased as deemed necessary. The applicable requirements for concrete based on exposure categories in 19.3 shall be satisfied, or other protection shall be provided. (ACI 20.6.1.4.1)

ACI Code Provisions for Concrete and Steel
Chapter 20: Steel reinforcement properties, durability, and embedments

• Provisions for durability of steel reinforcement
  • Nonprestressed coated reinforcement (ACI 20.6.2.1)
    • Nonprestressed coated reinforcement shall conform to Table 20.6.2.1.
    • Deformed bars to be zinc-coated, epoxy-coated, or zinc and epoxy dual-coated shall conform to 20.2.1.3(a), (b), or (c)

<table>
<thead>
<tr>
<th>Type of coating</th>
<th>Applicable ASTM specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc-coated</td>
<td>A767</td>
</tr>
<tr>
<td>Epoxy-coated</td>
<td>A773 or A934</td>
</tr>
<tr>
<td>Zinc and epoxy dual-coated</td>
<td>A1055</td>
</tr>
</tbody>
</table>

Table 20.6.2.1—Nonprestressed coated reinforcement

Prof. Dr. Qaisar Ali                     CE 5115       Advance Design of Reinforced Concrete Structures
ACI Code Provisions for Concrete and Steel
Chapter 20: Steel reinforcement properties, durability, and embedments

• Embedments (ACI 20.7)
  • Embedments shall not significantly impair the strength of the structure and shall not reduce fire protection. (ACI 20.7.1)
  • Embedment materials shall not be harmful to concrete or reinforcement. (ACI 20.7.2)
  • Reinforcement with an area at least 0.002 times the area of the concrete section shall be provided perpendicular to pipe embedments. (ACI 20.7.4)

References

• ACI 318-14
• PCA 2002
The End