Lecture 02

Materials

By:
Prof. Dr. Qaisar Ali
Civil Engineering Department
UET Peshawar

drqaisarali@uetpeshawar.edu.pk
https://drqaisarali.com

Lecture Contents

- 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

Learning Outcomes

- **At the end of this lecture, students will be able to;**
  - ***Understand*** the fundamentals of concrete, including its properties, composition, various types, and the advantages it offers as a construction material.
  - ***List*** different types of admixtures, along with their respective uses in concrete applications.
  - ***Distinguish*** various types of reinforcing steel, understanding their unique properties and applications in construction.
  - ***Outline*** the ACI Code provisions for both concrete and reinforcing steel.

Concrete

❑ Definition

- Concrete is a mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials.(ACI Concrete Terminology, Page 16).
- The properties of concrete depend on the quantity and proportions of ingredients used in the mix but can also be modified using various admixtures.

Concrete

❑ Components

- Concrete is generally composed of:

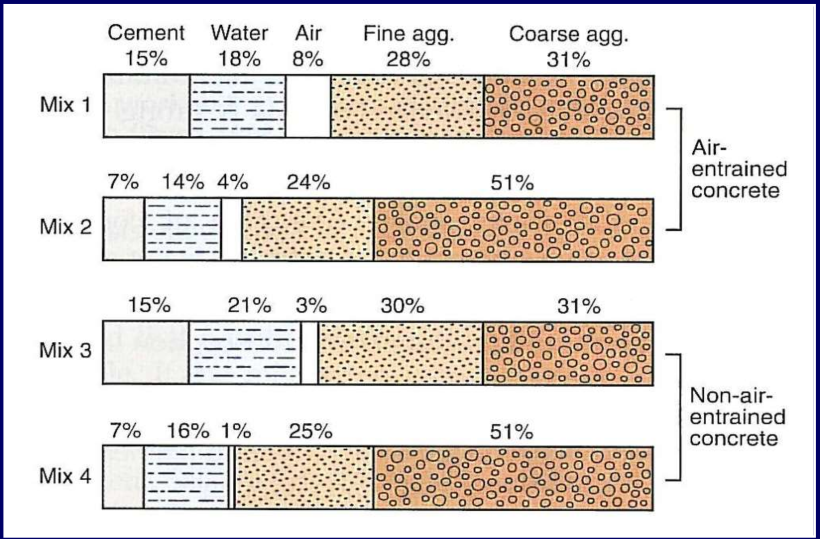
1. **Cementitious materials**
   - Portland cement
   - Pozzolans (fly ash, silica fume, ground granulated blast furnace slag)
2. **Aggregates**
   - Fine aggregate (Sand)
   - Coarse aggregate (gravel, crushed stone)
3. **Water**

Concrete

❑ Composition

- The typical percentages of each component present in concrete are provided below.

Components	Percentage
Paste	25% - 40%
Cement	07% - 15%
Water	14% - 21%
Air	01% - 08%
Aggregates	60% - 75%



Concrete

- **Types**

1. **Normal weight concrete**
   - Concrete having a density of approximately 150 lb/ft3 (2400 kg/m3) made with normal-density aggregates.
2. **Light weight concrete**
   - Lightweight concrete is characterized by significantly lower density compared to standard concrete.
   - It is composed of either lightweight aggregate alone or a mixture of lightweight and normal-density aggregate.

Concrete

❑ Types

3. High Performance Concrete

- High-performance concrete is a specialized type of concrete designed to meet specific performance and uniformity requirements beyond standard mixes and practices.
- It is often used in tall building columns to reduce cross-sectional size and maximize floor space.

4. Fibrous Concrete

- Concrete that incorporates dispersed, randomly oriented fibers, which can be made of materials such as steel, glass, synthetics, or natural fibers. These fibers enhance tensile strength, durability, and reduce air voids in the concrete mix.

Properties of Concrete

Compressive Strength

- The compressive strength of concrete is a measure of the concrete's ability to resist loads which tend to compress it.
- 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.

Properties of Concrete

Compressive Strength

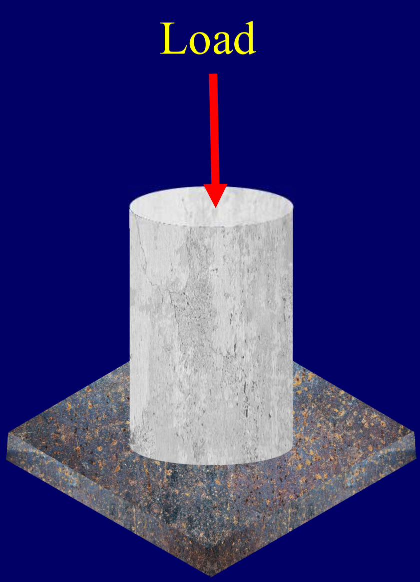
- Following are the two standard methods devised by ASTM to test the compressive strength of concrete.

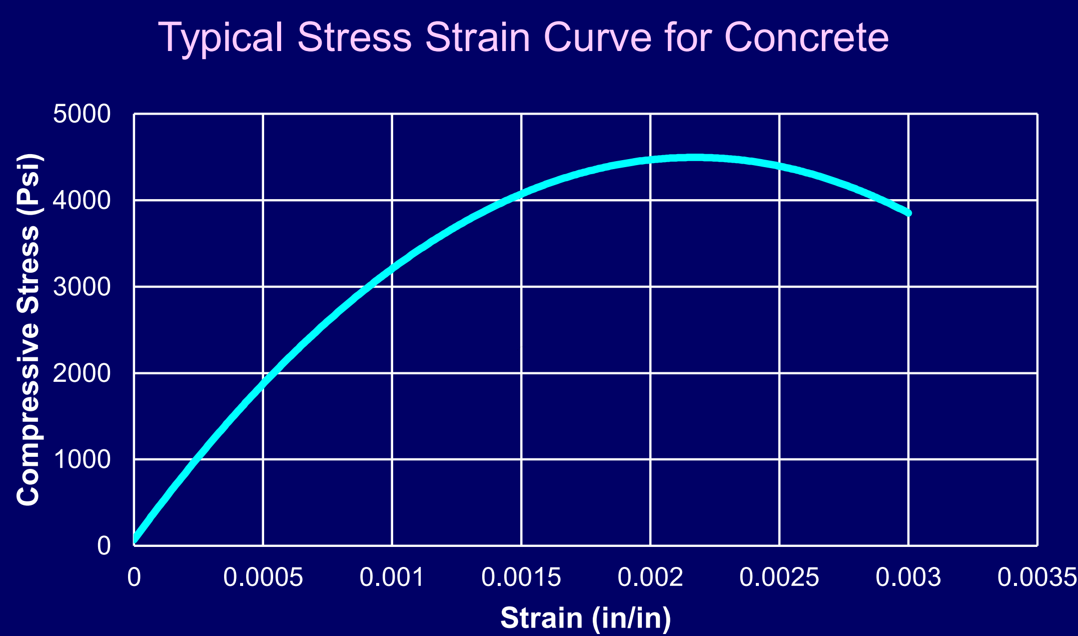
1. ASTM C31/C31M−17: *Standard Practice for Making and Curing Concrete Test Specimens in the Field*.

2. ASTM C39/C39M−17b: *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*.

Properties of Concrete

- **Compressive Strength**
  - **Stress-Strain Curve**

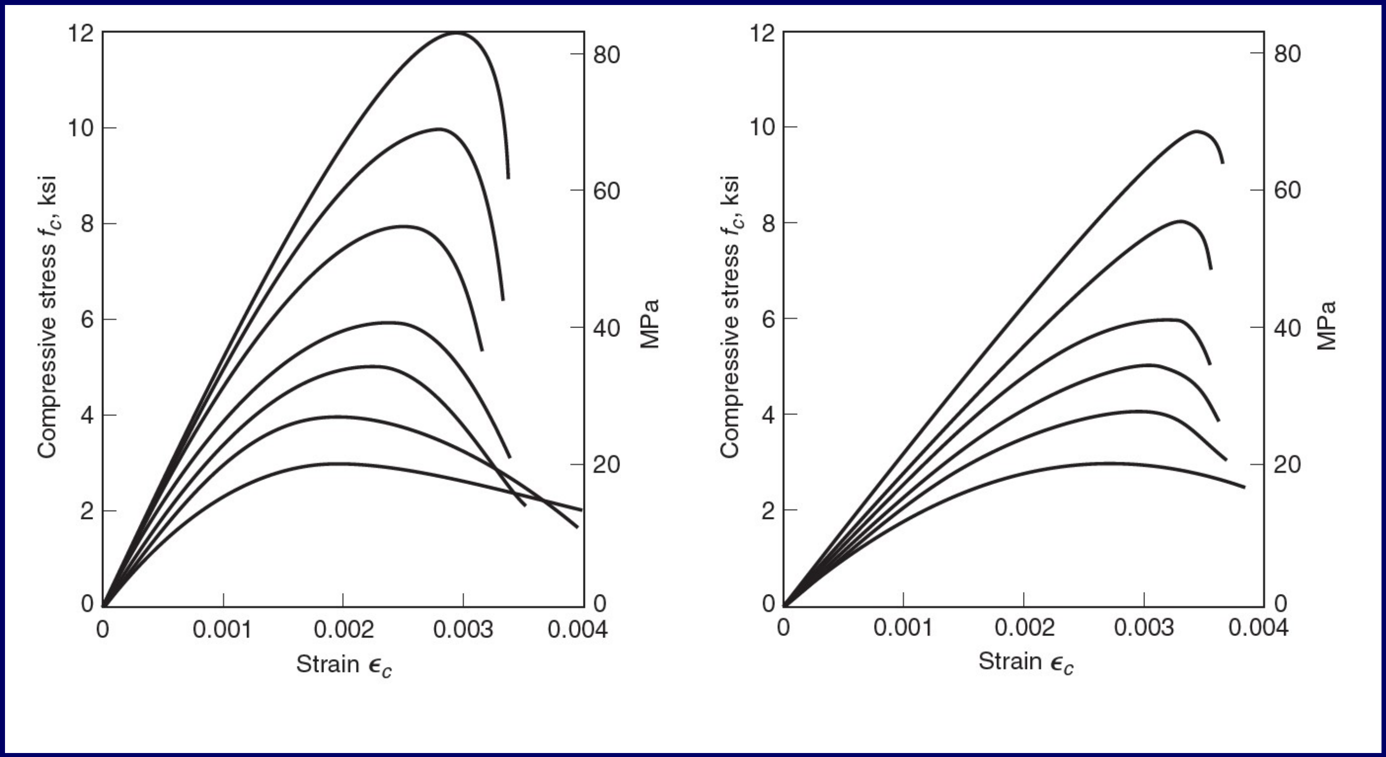




Properties of Concrete

❑ Compressive Strength

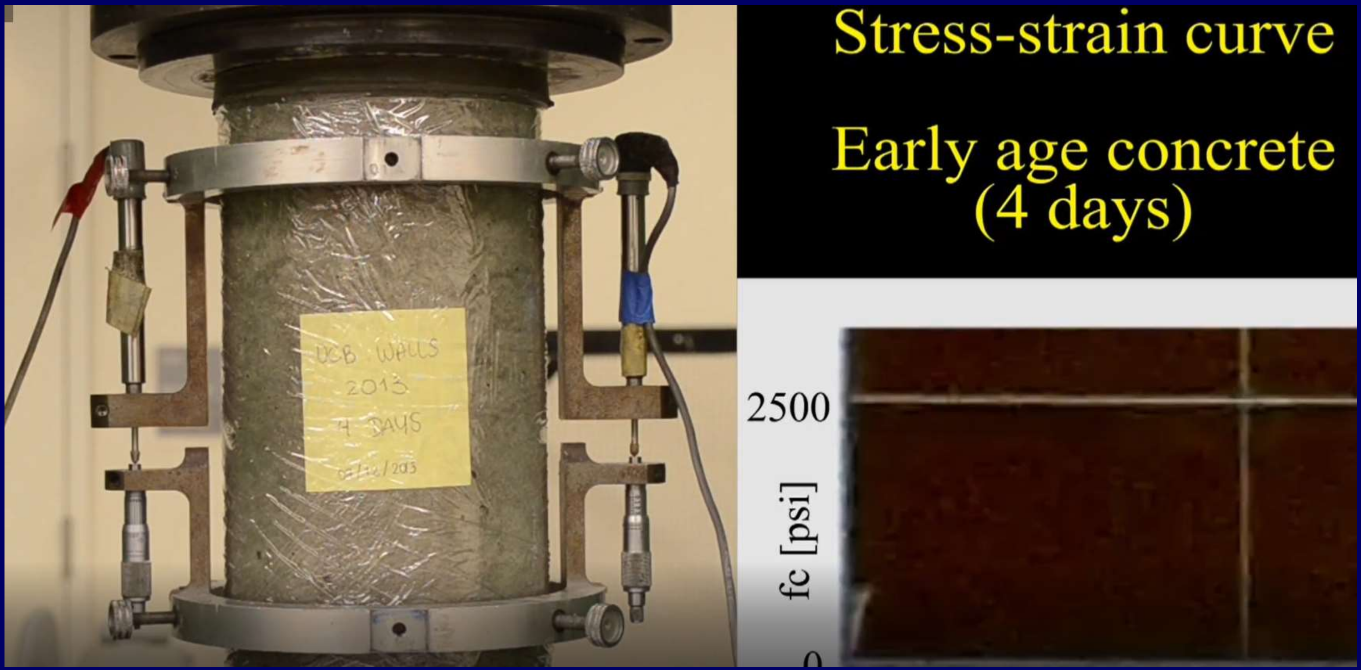
- **Typical Stress-Strain Curves**



(Ref: Design of concrete structures, 15th edition, chapter 2, page 37)

Properties of Concrete

- **Compressive Strength**
  - **Test for Compressive Strength of Cylindrical Concrete Specimen**



Properties of Concrete

❑ Tensile Strength

- It is a measure of the maximum stress on the tension face of an unreinforced concrete beam or slab at the point of failure in bending.
- The type of test that is used to determine the tensile strength has a strong effect on the value that is obtained.
- There are three methods to determine the tensile strength of concrete;

  i. Direct tensile strength (f_t')

  ii. Split cylinder strength (f_{ct})

  iii. Modulus of rupture (f_r)

  (ii and iii) Most widely used.

Properties of Concrete

❑ Tensile Strength

- **Modulus of Rupture**

  - The following two standards methods are used

    1. ASTM C 78: *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*
    2. 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**

The Flexural strength or Modulus of rupture is calculated using the following formula:

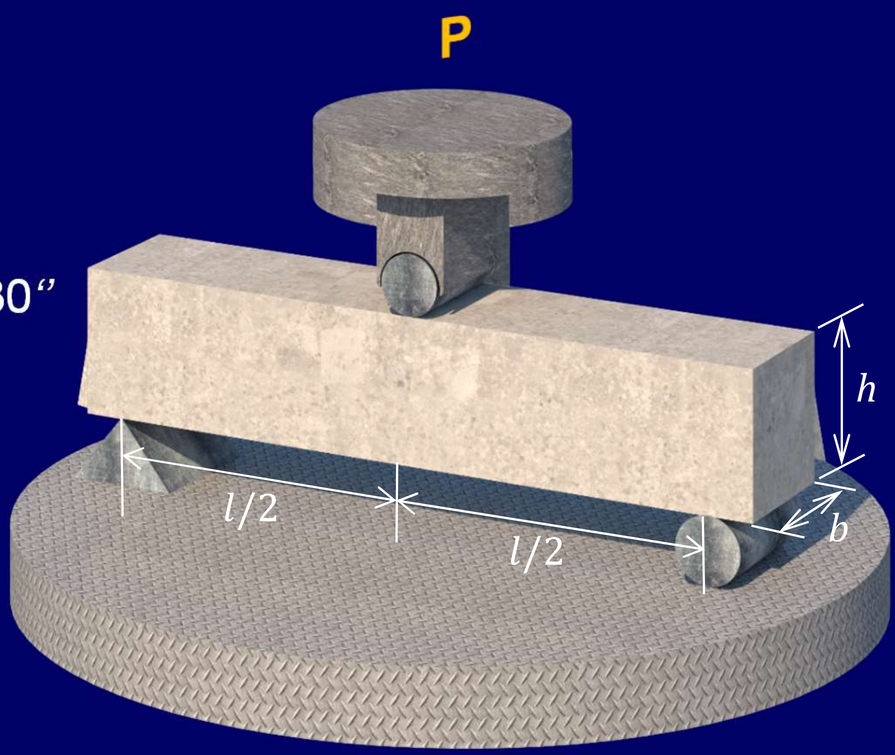
$$f_r = \frac{6M}{bh^2}$$

Where;

$M = Pl/4$, $b = h = 6''$ and $l = 30''$

Putting values, we get;

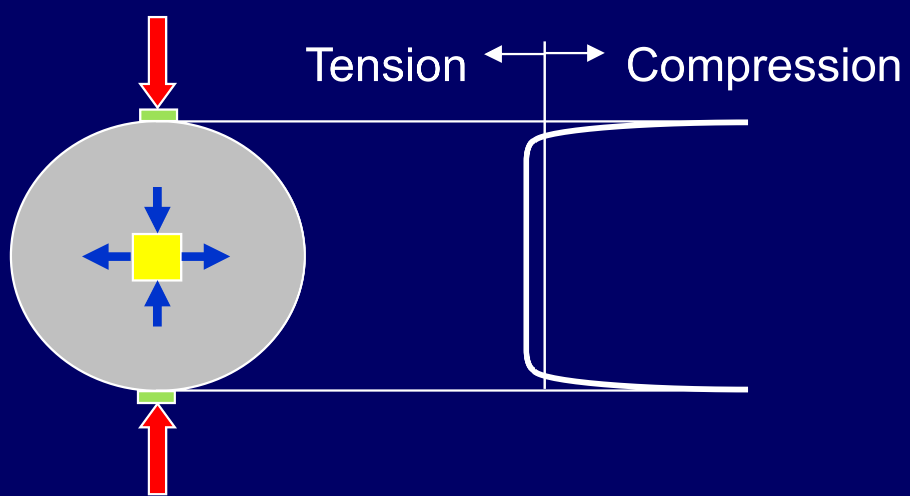
$$f_r = \frac{5}{24}P \qquad (psi)$$

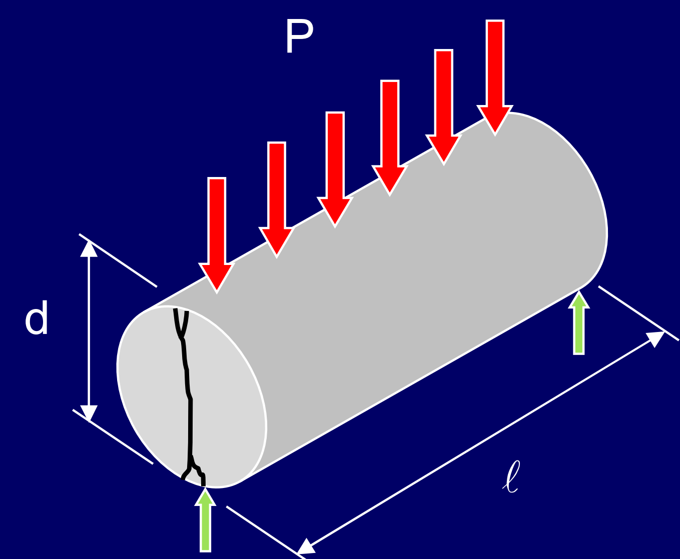


Properties of Concrete

❑ Tensile Strength

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





$$f_{ct} = \frac{2P}{\pi l d}$$

Properties of Concrete

Relationship between Compressive and Tensile Strength

- The general relationship is given by:

$$f_{ct} = \alpha\sqrt{f_c'}$$

  - $f_{ct} = 6.4\sqrt{f_c'}$ (mean value)
  - $f_{ct} = 7.5\sqrt{f_c'}$ (for deflections, ACI 19.2.3)
  - $f_{ct} = 6\sqrt{f_c'}$ (for strength)

TABLE 2.3
Approximate range of tensile strengths of concrete

	Normalweight Concrete, psi	Lightweight Concrete, psi
Direct tensile strength f_t'	3 to 5 $\sqrt{f_c'}$	2 to 3 $\sqrt{f_c'}$
Split-cylinder strength f_{ct}	6 to 8 $\sqrt{f_c'}$	4 to 6 $\sqrt{f_c'}$
Modulus of rupture f_r	8 to 12 $\sqrt{f_c'}$	6 to 8 $\sqrt{f_c'}$

(Source: Design of concrete structures, 15th edition, chapter 2, page 43)

Properties of Concrete

Modulus of Elasticity

- Modulus of elasticity also known as Young's modulus is the ratio of axial stress to the axial strain.
- ASTM C469 provides a test method for determining the modulus of elasticity for concrete in compression.

Properties of Concrete

❑ Modular Ratio

- The ratio of modulus of elasticity of steel E_s to that of concrete E_c is known as modular ratio.

- Mathematically, Poisson's ratio is expressed as;

$$n = \frac{E_s}{E_c} = \frac{29000,000}{57000 \times \sqrt{f_c'}} = \frac{508.77}{\sqrt{f_c'}}$$

- Since the modulus of elasticity of concrete changes with time, age at loading, modular ratio also changes accordingly.

- The modular ratio for a normalweight concrete having compressive strength of 3000psi is 9.3.

Properties of Concrete

❑ Poisson's Ratio

- The ratio of transverse strain to longitudinal strain in the direction of the stretching force is known as poison's ratio.
- Mathematically, Poisson's ratio is expressed as;

$$\upsilon = \frac{Transeverse\ strain}{Longitudinal\ strain}$$

- Poisson's ratio is taken as positive for tensile while negative for compressive deformation.
- The Poisson's ratio of concrete ranges from 0.1 – 0.2.

Properties of Concrete

❑ Unit Weight

- Weight of a material per unit volume is called unit weight or weight density.
- The unit weight of concrete depends on percentage of reinforcement, type of aggregate, number of voids.
- Unit weight for plain cement concrete varies from 140 to 145 lb/ft^3, while that for reinforced concrete is 150 lb/ft^3.

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.

$$f'_{ct} = f'_{c(28)} \frac{t}{4 + 0.85t}$$

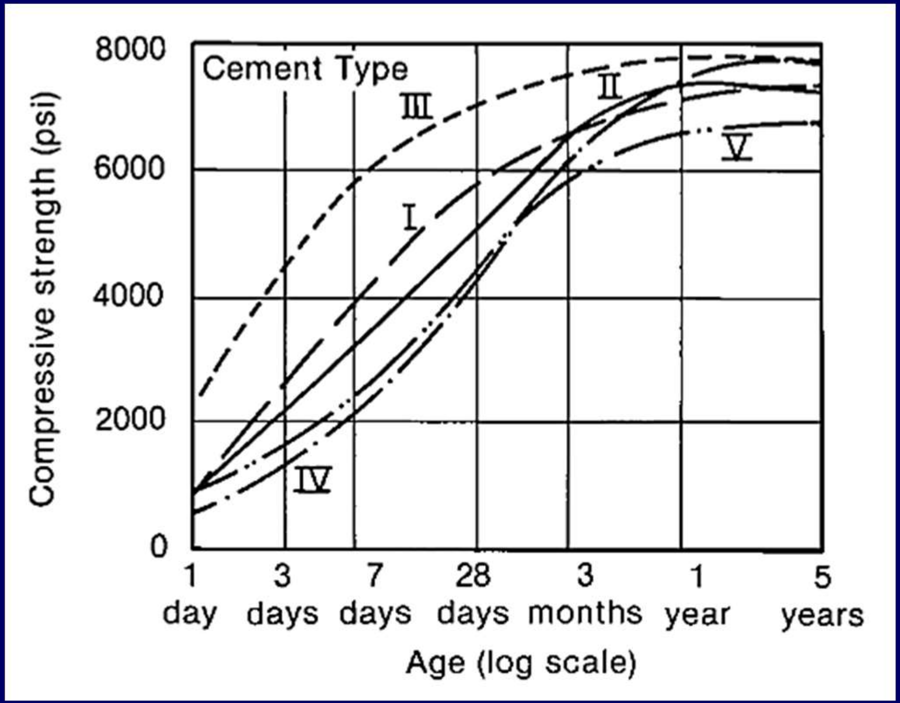
Where f'_{ct} = the compressive strength at age t in days.

Concrete Strength Gain Rate for 3000 psi					
Time, t (days)	3	7	14	21	28
Strength f'_{ct}, psi	1374.0	2110.6	2641.5	2883.3	3021.6
Percent gain	45.8	70.4	88.1	96.1	100.7

Properties of Concrete

❑ Rate of Strength Gain

- Figure shows the effect of type of cement on strength gain of concrete (moist cured; w/c = 0.49).



Reinforced Concrete Mechanics and Design
by James K. Wight, Page 51, Chapter # 3 (7th edition)

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

Properties of Concrete

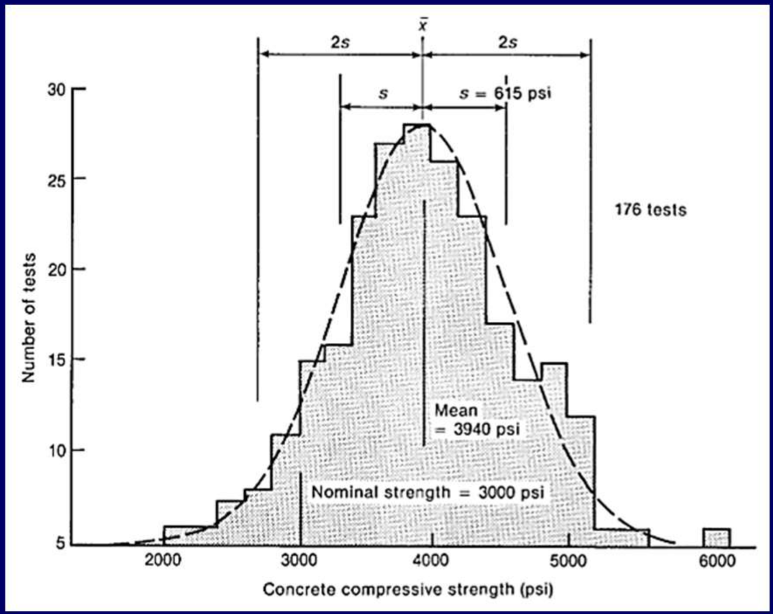
Variation in Strength

- 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.

Properties of Concrete

❑ Variation 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



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by James K. Wight, Page 48, Chapter # 3 (7th edition)

Properties of Concrete

Time Dependent Volume Changes

- Concrete undergoes three main types of volume change, which may cause stresses, cracking, or deflections.
  1. Shrinkage
  2. Creep
  3. Thermal expansion or contraction

Properties of Concrete

❑ Time Dependent Volume Changes

1. Shrinkage

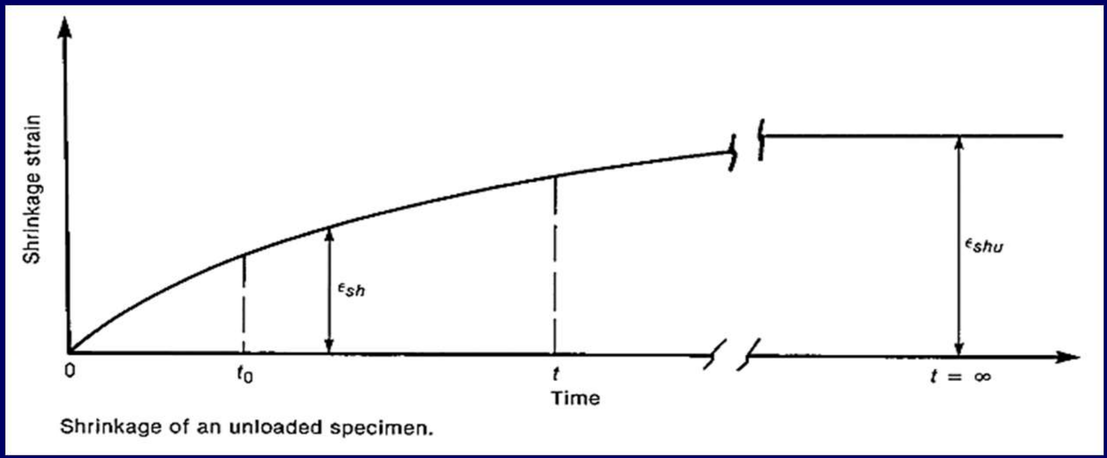
- Shrinkage occurs as the moisture diffuses out of the concrete. The exterior shrinks more than the interior, which leads to tensile stresses in the outer layer of the concrete.
- Shrinkage occurs during hardening and drying of concrete under constant temperature.

Properties of Concrete

Time Dependent Volume Changes

1. 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.



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by James K. Wight, Page 74, Chapter # 3 (7th edition)

Properties of Concrete

❑ Time Dependent Volume Changes

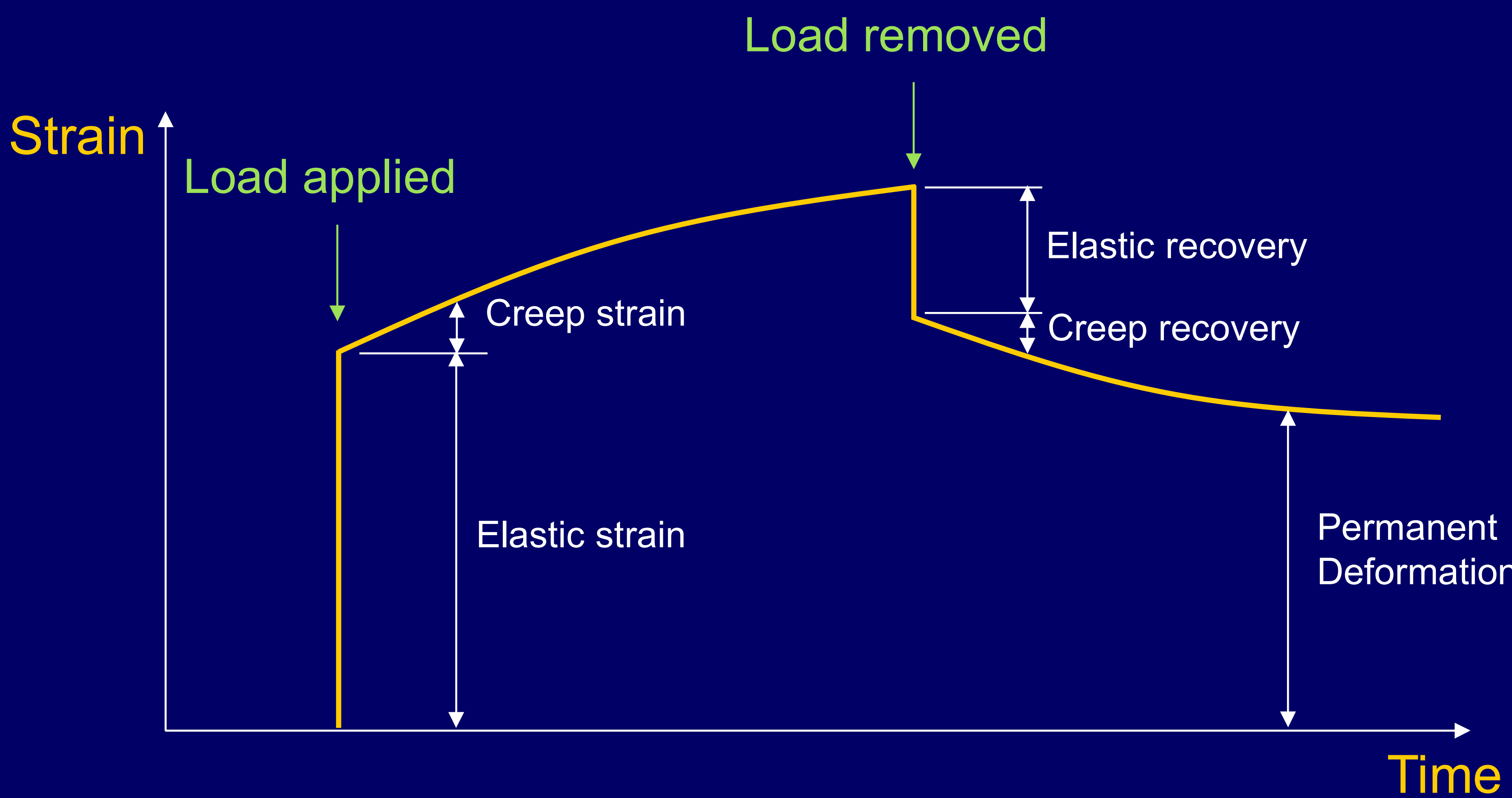
1. Shrinkage

- 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

❑ Time Dependent Volume Changes

2. Creep



Properties of Concrete

❑ Time Dependent Volume Changes

2. Creep

- Creep strains can lead to:
  1. Increase in deflections with time
  2. Redistribution of stresses
  3. Decrease in prestressing forces

Properties of Concrete

Time Dependent Volume Changes

3. Thermal Expansion or Contraction

- Coefficient of Thermal Expansion or Contraction is affected by:
  - Composition of the concrete
  - Moisture content of the concrete
  - Age of the concrete

Properties of Concrete

❑ Time Dependent Volume Changes

3. Thermal Expansion or Contraction

1. **Normal weight concrete**
   - Siliceous aggregate: $5 \text{ to } 7 \times 10^{-6}$ strain/°F.
   - Limestone/calcareous aggregate: $3.5 \text{ to } 7 \times 10^{-6}$ strain/°F.
2. **Lightweight concrete**
   - $3.6 \text{ to } 6.2 \times 10^{-6}$ strain/°F.

- For calculation purposes, a value of 5.5×10^{-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.

Properties of Concrete

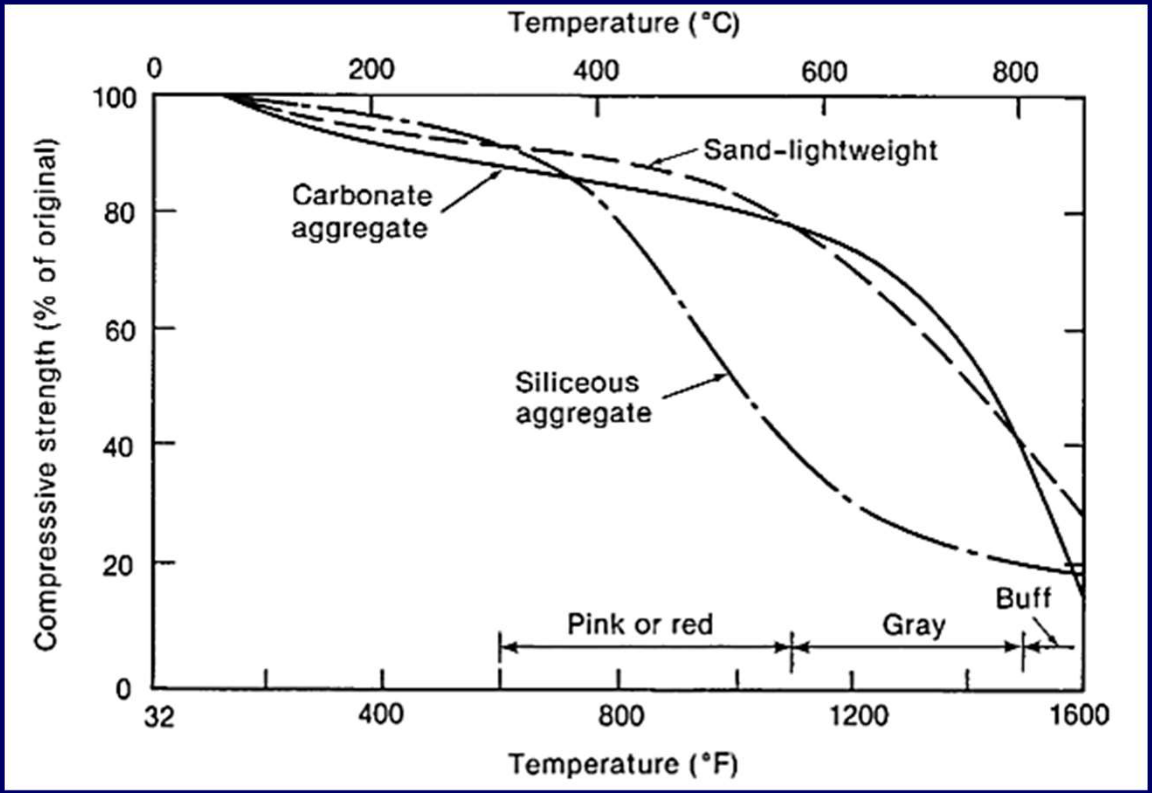
❑ Fire Resistance

- 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



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Properties of Concrete

❑ Fire Resistance

- 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 ^{o}F, while the temperatures within the specimen will vary:
  - 1225 ^{o}F at ¼ inch from exposed surface
  - 950 ^{o}F at ¾ inch
  - 800 ^{o}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.

Properties of Concrete

❑ Fire Resistance

- Minimum thicknesses of RC members (load bearing and non load bearing) using normal weight concrete are provided below.

Fire Resistance Rating							
Slabs and Cast in Place Walls (in.)				Concrete Column/ Beam Dimensions (in.)			
1hr.	*2 hr.*	*3 hr.*	*4 hr.*	*1 hr*	*2 hr.*	*3 hr.*	*4 hr.*
3.5″	4.5″	6.0″	7.0″	8″	10″	12″	14″

Properties of Concrete

Factors Effecting Concrete Strength

- In addition to mixing, conveying, placing and compaction, the strength of concrete primarily depends on the following factors.

Factors	Effects
Water-cement ratio	Water/Cement ratio is inversely proportional to the strength of concrete. Higher the w/c ratio, lower will be 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.
Curing	Curing of concrete is the most essential to prevent plastic shrinkage, temperature control, strength gain and durability.
Weather conditions	Change in temperature causes shrinkage, freezing and thawing which results in loss of concrete strength.
Age of concrete	The strength of concrete increases with its age.

High Strength Concrete

Definition

- Concrete that has a specified compressive strength of 8000 psi (55 MPa) or greater is known as high strength concrete (ACI 363R-11).
- The resulting concrete has a low void ratio.
- Admixtures such as superplasticizers improve the dispersion of cement in the mix and provide adequate workability.
- Only the amount of water needed to hydrate the cement in the mix is provided.

High Strength Concrete

❑ Creep and Shrinkage

- 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 suggests that the creep coefficient for high strength concrete is considerably less than that for normal concrete.

Advantages of Concrete as Construction Material

- Concrete serves as an invaluable construction material, offering a range of significant advantages, some of which are outlined below.

Factors	Description
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.
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 is termed as Admixture.

Concrete Admixtures

❑ 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:

  1. **Air-entraining Admixtures**

     - Cause 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.

Concrete Admixtures

❑ Types

- As per ACI Committee 212, admixtures have been classified into following groups:

2. **Accelerating Admixtures**

   - Cause 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.

3. **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

- As per ACI Committee 212, admixtures have been classified into following groups:

4. **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.
5. **Miscellaneous**
   - Freeze Resistant, Pigments, Bonding, Grouting etc. (Refer ACI 212 for details and more types of miscellaneous admixtures)

Properties of Reinforcing Steel

Definition

- Steel is a hard, strong grey or bluish-grey alloy of iron with carbon and some other elements, used as a structural and fabricating material.

Classification of Steel (based on composition)

1. **Plain Carbon Steel**
   - Low carbon steel /Mild steel (0.16% - 0.30 % of carbon)
   - Medium carbon steel (0.30% to 0.60% of carbon)
   - High carbon steel (0.60% to 1% of carbon)
2. **Low Alloy Steel** (≤ 8% alloying element)
3. **High Alloy Steel** (> 8% alloying element)

Properties of Reinforcing Steel

❑ Classification of Steel (based on use)

Deformed Bar Reinforcement

Plain Reinforcement

Prestressing Steel

Structural Steel

Properties of Reinforcing Steel

❑ Classification of Steel (Based on use)

- Each type of Steel has its own Code provisions :
  - Deformed Bar Reinforcement ⇒ ACI Section 20.2.1.3
  - Plain Reinforcement ⇒ ACI Section 20.2.1.4
  - Prestressing Steel ⇒ ACI Section 20.3.1.1
- In the subsequent slides, only properties of deformed bars will be discussed.

Properties of Reinforcing Steel

❑ Deformed Bar Reinforcement

- As per ACI 318-19, 20.2.1.1, deformed bar reinforcement shall be used in reinforced concrete.
- Deformed bars shall conform to one of the following ASTM specifications;

  (a) ASTM A615

  (b) ASTM A706

Properties of Reinforcing Steel

❑ Deformed Bar Reinforcement

1. ASTM A615

- It covers deformed carbon-steel reinforcing bars that are currently the most widely used type of steel bar in reinforced concrete construction.
- Bars of this type are marked with the letter "S" per the specification requirements.

Properties of Reinforcing Steel

Deformed Bar Reinforcement

2. ASTM A706

- It covers low-alloy steel deformed bars intended for applications where controlled tensile properties, restrictions on chemical composition to enhance weldability, or both, are required.

- Bars of this type are marked with the letter "W" per the specification requirements.

Properties of Reinforcing Steel

❑ Deformed Bar Reinforcement

▪ Physical Properties

Bar Designation	Diameter (in)	Area (in^2)	Weight (lb/ft)
#3	0.375	0.11	0.38
#4	0.500	0.20	0.67
#5	0.625	0.31	1.04
#6	0.750	0.44	1.50
#7	0.875	0.60	2.04
#8	1.000	0.79	2.67
#9	1.128	1.00	3.40
#10	1.270	1.27	4.30
#11	1.410	1.56	5.313
#14	1.693	2.25	7.65
#18	2.257	4.00	13.60

Source: ACI 318-19 Appendix B ─ASTM Standard Reinforcing Bars

Properties of Reinforcing Steel

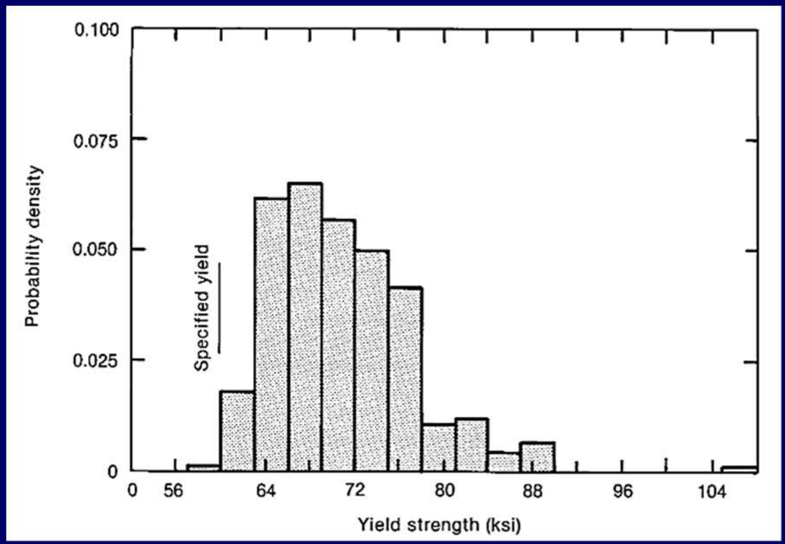
❑ Deformed Bar Reinforcement

- **Strength and Distribution of mill test yield strength**

Steel Grade	Min. Yield Strength, f_y (ksi)	Tensile Strength f_u(ksi)
40	40	60
60	60	80
80	80	100
100	100	115

Minimum Yield and Tensile Strength for Different steel grades

(ACI Table 20.2.1.3(a))



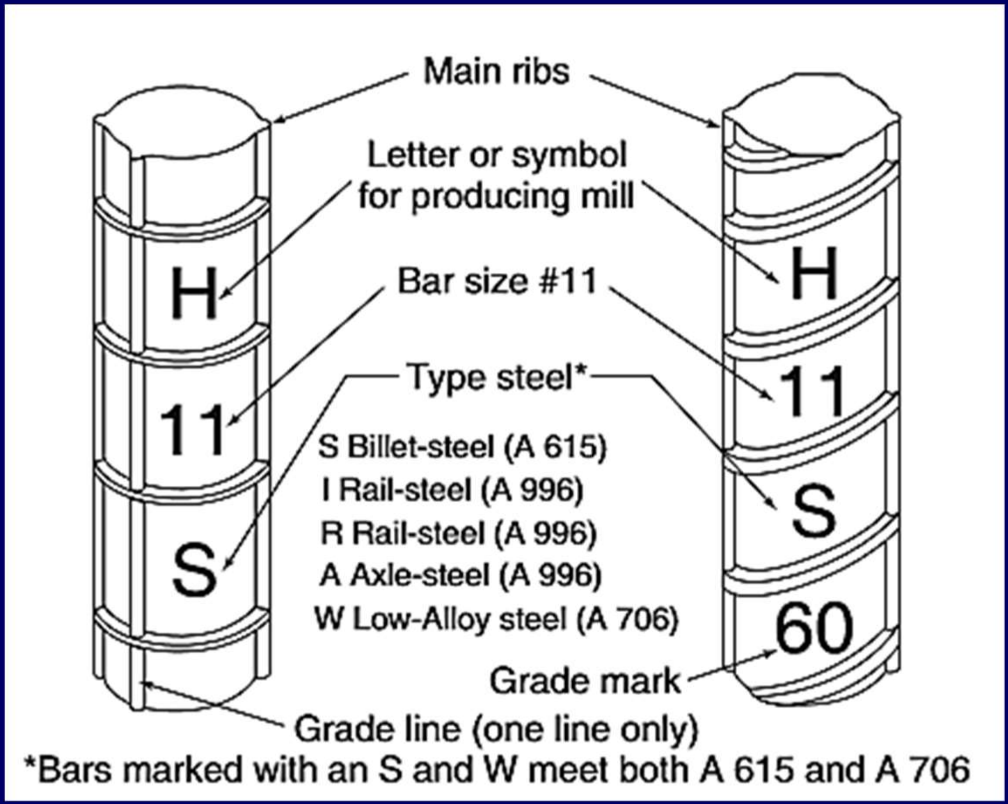
Mil Test Yield Strength for G 60 Steel

Reinforced Concrete Mechanics and Design by James K. Wight, Page 96, Chapter # 3 (7th edition)

Properties of Reinforcing Steel

Deformed Bar Reinforcement

- **Bar Marking**



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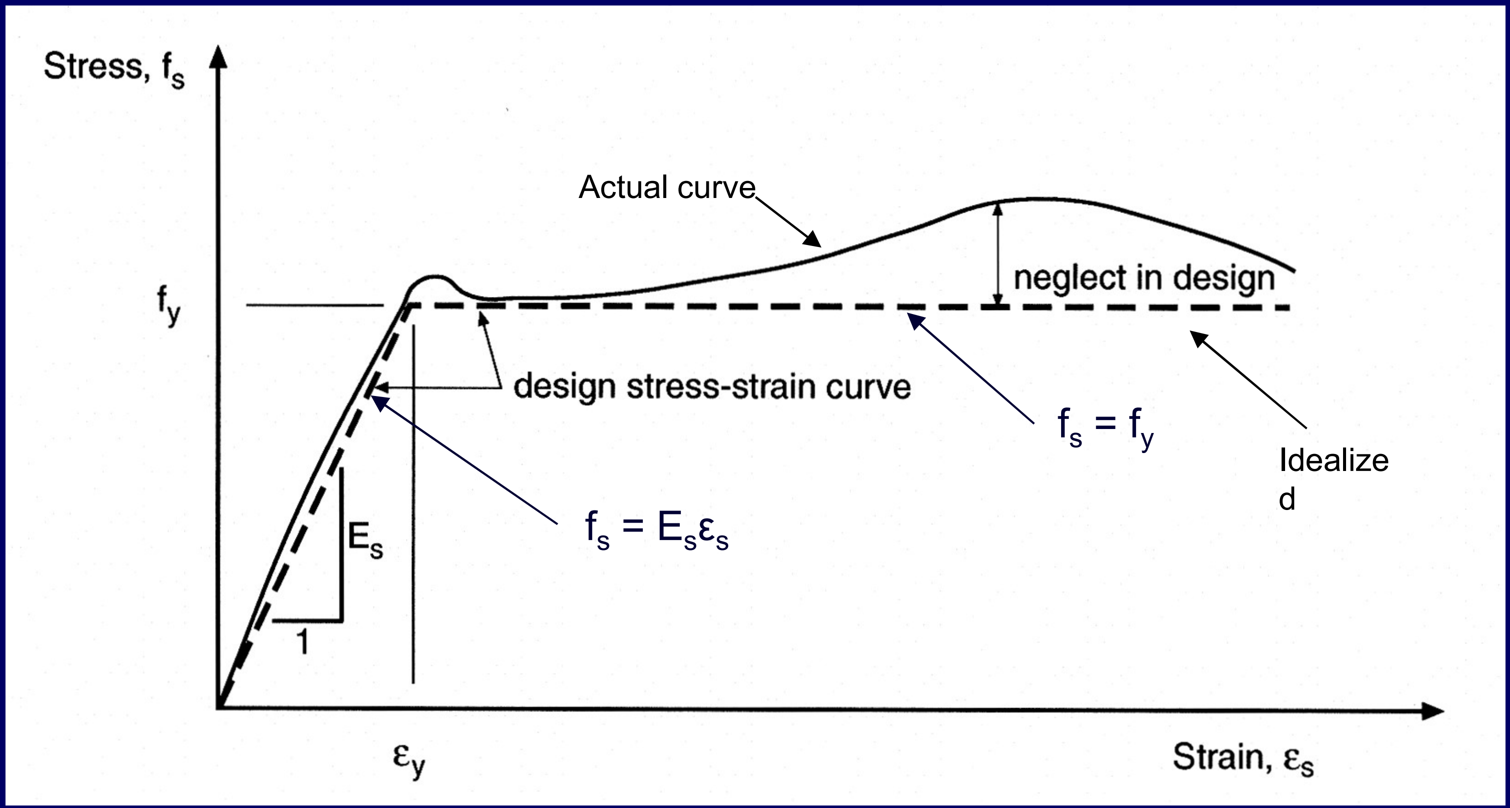
Properties of Reinforcing Steel

❑ Deformed Bar Reinforcement

- **Typical Stress-strain Curve**



Properties of Reinforcing Steel

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.

Properties of Reinforcing Steel

Deformed Bar Reinforcement

Reinforcement Fire Protection

- Minimum concrete cover to main reinforcement corresponding to each fire resisting rate for different members are given below.

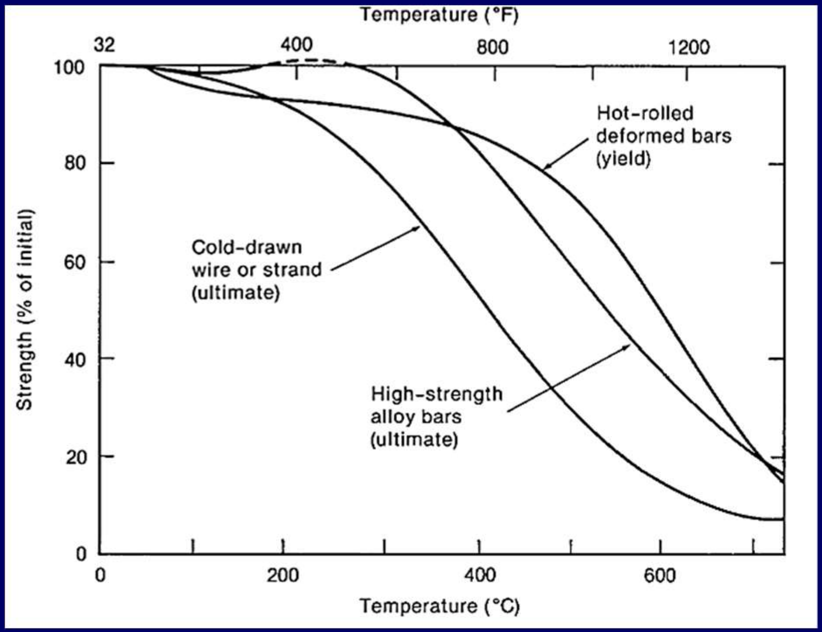
RC Floors and Slabs			RC Columns and Beams ($b \geq 10''$)			
1 hr.	*2 hr.*	*3 hr.*	*1 hr.*	*2 hr.*	*3 hr.*	*4 hr.*
¾″	1″	1 ¼″	1 ½″	1 ½″	1 ½″	2″

Properties of Reinforcing Steel

Deformed Bar Reinforcement

Reinforcement Fire Protection

- Deformed reinforcement subjected to high temperatures in fires tends to lose its strength.



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ACI Code Provisions for Concrete and Steel

General

- ACI 318 chapters 19, 20 & 26 discuss various properties and requirements for materials used in reinforced concrete.

Chapter 19	*Concrete: Design and Durability requirements*
Chapter 20	*Steel Reinforcement Properties, Durability and Embedment*
Chapter 26	*Construction Documents and Inspection*

- Following slides discuss only few important points from these chapters.

ACI Code Provisions for Concrete and Steel

Chapter 19: Concrete Design and Durability Requirements

- In this chapter various properties related to the design and durability of concrete are discussed. some of which are as follows:

1. **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 19.3.1.1

     c) Structural strength requirements

ACI Code Provisions for Concrete and Steel

Chapter 19: Concrete Design and Durability Requirements

2. Modulus of Elasticity (ACI 19.2.2)

- Modulus of elasticity E_c for concrete shall be accordance with (a) or (b):

a) For values of w_c between 90 and 160 lb/ft^3

$$E_c = w_c^{1.5} 33\sqrt{f_c'} \quad (psi) \qquad \text{(ACI 19.2.2.1.}a\text{)}$$

b) For Normal weight concrete

$$E_c = 57000\sqrt{f_c'} \quad (psi) \qquad \text{(ACI 19.2.2.1.}b\text{)}$$

- w_c in equation (a) is the equilibrium density of concrete mixture.

ACI Code Provisions for Concrete and Steel

Chapter 19: Concrete Design and Durability Requirements

2. **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

2. 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 20: Steel reinforcement properties, Durability, and Embedments

1. Materials 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

ACI Code Provisions for Concrete and Steel

- Chapter 20: Steel reinforcement properties, Durability, and Embedments

1. Materials Properties

   - 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

2. Design Properties

- For non-prestressed 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 non-prestressed bars and wires shall be permitted to be taken as 29,000,000 psi. (ACI 20.2.2.2).

ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, Durability, and Embedments

2. Design Properties

- Yield strength for non-prestressed 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 non-prestressed bars and wires to be specified for particular structural applications shall be in accordance with 20.2.2.4a deformed reinforcement and Table 20.2.2.4b plain reinforcement (ACI 20.2.2.4).

ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, Durability, and Embedments

2. Design Properties

- As per ACI 20.2.2.5, deformed nonprestressed longitudinal reinforcement resisting earthquake-induced moment, axial force, or both, in special seismic systems and anchor reinforcement in Seismic Design Categories (SDC) C, D, E, and F 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.

ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, Durability, and Embedments

2. Design Properties

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 in. steel sample, shall be at least:

- 14 percent for bar sizes No. 3 through No. 6,
- 12 percent for bar sizes No. 7 through No. 11, and
- 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

3. Durability of Steel Reinforcement

- **Specified Concrete Cover**

ACI Table 20.5.1.3.1

Concrete Exposure	Member	Reinforcement	Specified Cover, in.
Cast against and permanently in contact with ground	All	All	3
Exposed to weather or in contact with ground	All	No. 6 through No.18 bars	2
		No. 5 bar, W31 or D31 wire, and smaller	1-1/2
Not exposed to weather or in contact with ground	Slabs, joists, and walls	No. 14 and No. 18 bars	1-1/2
		No. 11 bar and smaller	3/4
	Beams, columns, pedestals, and tension ties	Primary reinforcement, stirrups, ties, spirals, and hoops	1-1/2

ACI Code Provisions for Concrete and Steel

- **Chapter 20: Steel reinforcement properties, Durability, and Embedments**

3. **Durability of Steel Reinforcement**

   - **Specified Concrete Cover**

   - 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 20.5.1.4.1).

ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, Durability, and Embedments

3. Durability of Steel Reinforcement

- **Nonprestressed Coated Reinforcement**

- Nonprestressed coated reinforcement shall conform to Table 20.5.2.1.
- 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)

ACI Table 20.5.2.1			
Concrete Exposure	**Applicable ASTM Specifications**		
	Bar	*Wire*	*Weld Wire*
Zinc-coated	A767	Not permitted	A1060
Epoxy-coated	A775 or A934	A884	A884
Zinc and epoxy dual-coated	A1055	Not permitted	Not permitted

ACI Code Provisions for Concrete and Steel

Chapter 20: Steel reinforcement properties, Durability, and Embedments

3. Durability of Steel Reinforcement

- **Embedments**

- Embedment shall not significantly impair the strength of the structure and shall not reduce fire protection (ACI 20.6.1).
- Embedment materials shall not be harmful to concrete or reinforcement (ACI 20.6.2).
- Reinforcement with an area at least 0.002 times the area of the concrete section shall be provided perpendicular to pipe embedment (ACI 20.6.4).

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction documents and Inspection

1. Cementitious Materials

a) Cementitious materials shall conform to the specifications in Table 26.4.1.1.1(a) , except as permitted in 26.4.1.1.1(b).

b) Alternative cements shall be permitted if approved by licensed design professional and the building official.

ACI Table 26.4.1.1.1.(a)	
Cementitious material	**Specification**
Portland cement	ASTM C150
Blended hydraulic cements	ASTM C595, excluding Type IS (≥70) and Type IT (S ≥ 70)
Expansive hydraulic cement	ASTM C845
Hydraulic cement	ASTM C1157
Fly ash and natural pozzolan	ASTM C618
Slag cement	ASTM C989
Silica fume	ASTM C1240

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

2. Aggregates (ACI 26.4.1.2.1)

a) Aggregates shall conform to (1) or (2):

1. Normal weight 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.

ACI Code Provisions for Concrete and Steel

❑ Chapter 26: Construction Documents and Inspection

3. **Water** (ACI 26.4.1.4)

- 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: Construction Documents and Inspection

4. **Admixtures** (ACI 26.4.1.5)

a) Admixtures shall conform to (1) through (4):

1. Water reduction and setting time modification: ASTM C494.
2. Producing flowing concrete: ASTM C1017.
3. Air entrainment: ASTM C260.
4. Inhibiting chloride-induced corrosion: ASTM C1582.

b) Admixtures that do not conform to the specifications in 26.4.1.5.1(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: Construction Documents and Inspection

5. Proportioning Concrete Mixtures (ACI 26.4.3)

a) Concrete mixture proportions shall be established so that the concrete satisfies (1) through (4).

1. Can be placed without segregation and fully encase reinforcement.
2. Meets durability requirements given in the construction documents.
3. Conforms to strength test requirements for standard cured specimens.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

5. Proportioning Concrete Mixtures (ACI 26.4.3)

a) Concrete mixture proportions shall be established so that the concrete satisfies (1) through (4).

4. Conforms to modulus of elasticity requirements (i) through (iii) for mixtures requiring testing in accordance with construction documents.

   i. The modulus of elasticity shall be determined as the average modulus obtained from at least three cylinders made from the same sample of concrete and tested at 28 days or at test age designated for E_c.

   ii. Cylinders used to determine modulus of elasticity shall be made and cured in the laboratory in accordance with ASTM C192 and tested in accordance with ASTM C469.

   iii. Modulus of elasticity of a concrete mixture shall be acceptable if the measured value equals or exceeds the specified value.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

5. Proportioning Concrete Mixtures (ACI 26.4.3)

b) Concrete mixture proportions must comply with ACI 301 Article 4.2.3 or an approved alternative method. The alternative method should have a probability of meeting or exceeding the strength requirements compared to ACI 301 Article 4.2.3. When using ACI 301 Article 4.2.3, strength test records for mixture proportions must not be older than 24 months.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

5. Proportioning Concrete Mixtures (ACI 26.4.3)

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 proportions of proposed Work, each mixture shall comply with the concrete mixture requirements stated in the construction documents.

e) Shotcrete mixture proportions shall be established so that shotcrete satisfies (1) through (3).

1) Can be placed without segregation and fully encase reinforcement.
2) Meets durability requirements given in the construction documents.
3) Conforms to strength test requirements for shotcrete.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

6. Required Average Strength (ACI R26.4.3)

- Required average compressive strength of concrete f_c' not f_{cr}' shall be calculated according to the table given below.

Table 4.2.3.3.b	
f'_c , psi	f'_{cr}* , psi
Less than 3000	$f_c' + 1000$
3000 to 5000	$f_c' + 1200$
Over 5000	$1.1f_c' + 700$
*When data are not available to establish standard deviation	

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

7. Sampling Frequency for Strength Tests (ACI 26.12.2)

- 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.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

7. **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: Construction Documents and Inspection

8. 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 $0.10f_c'$ when f_c' is more than 5000 psi.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

9. Steps to Increase Concrete Strength (ACI R26.12.3.1(b))

- It will depend on the circumstances, but could include one or more of the following:
  - Increase in cementitious materials content
  - Reduction in or better control of water content
  - Use of a water-reducing admixture
  - Other changes in mixture proportions
  - Reduction in delivery time
  - Closer control of air content
  - Improvement in the quality of the testing, including strict compliance with ASTM C172, ASTM C31, and ASTM C39.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

9. Investigation of Low Strength Test Results (ACI 26.12.6)

- Any standard-cured cylinder strength test below the allowable limit or field-cured cylinder tests showing curing issues must be addressed to safeguard the structure's integrity.
- If low-strength concrete is confirmed and calculations show reduced load-bearing capacity, perform core tests (ASTM C 42) on three samples for each strength test below the allowable limit.
- These measures ensure structural safety in cases of concrete strength deficiencies.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

9. Investigation of Low Strength Test Results (ACI 26.12.6)

- For concrete assessed through core tests, it is deemed structurally sound if the average of three cores is ≥ 85% of f_c', with no single core below 75% of f_c'.
- If core strength criteria are not met and structural integrity is uncertain, the responsible authority can order a strength evaluation per Chapter 27 or take necessary measures for the affected structure section.

ACI Code Provisions for Concrete and Steel

Chapter 26: Construction Documents and Inspection

10. Record of tests 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.

References

- Reinforced Concrete - Mechanics and Design (7th Ed.) by James MacGregor.
- Building Code Requirements for Structural Concrete (ACI 318-19)
- Portland Cement Association (PCA 2002)