CHAPTER

REINFORCED CONCRETE

A Fundamental Approach - Fifth Edition

CONCRETE

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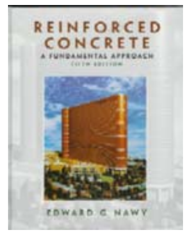

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ENCE 454 – Design of Concrete Structures
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Introduction

- Compactness
  - The space occupied by concrete should be filled with solid aggregate and cement gel free of honeycombing.
  - Compactness may be the primary *criterion* for those types of concrete that intercept nuclear radiation.
- Strength
  - Concrete always has sufficient strength and internal resistance to various types of failures.

Introduction (cont'd)

- Water/Cement (*w*/*c*) and Water/Cementitious Ratio
  - The water/cement (*w*/*c*) ratio should be suitably controlled to give the required design strength.
- Texture
  - Exposed concrete surfaces should have a dense and hard texture that can withstand adverse weather conditions.

Introduction (cont'd)

- Parameters Affecting Concrete Quality:
  1. Quality of cement.
  2. Proportion of cement in relation to water in the mixture.
  3. Strength and cleanliness of aggregates.
  4. Interaction or adhesion between cement paste and aggregate.
  5. Adequate mixing of the ingredients.
  6. Proper placing, finishing, and compaction of the fresh concrete.

Introduction (cont'd)

7. Curing at a temperature not below 50° F while the placed concrete gains strength.
8. Chloride content not to exceed 0.15% in reinforced concrete exposed to chlorides in service and 0.5 to 1% for dry protected concrete.

Proportioning Theory – NSC

- Factors Affecting Strength
  - Strength affected by water/cement ratio, type of cement, aggregate, additives, curing conditions, rate of loading (strength ↑ with increase in strain rate), age at testing (strength ↑ with age but rate of increase can vary widely).
  - The aim of a designer should be to get concrete mixtures of optimum strength at minimum cement content and acceptable workability.

Proportioning Theory – NSC

- The lower the *w/c* ratio is, the higher the concrete strength.
- Once the *w/c* ratio is established and the workability or consistency needed for specific design is chosen, the rest should be simple manipulation with diagrams and tables based on large numbers of trial mixes.

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete
  - One aim of the design is to produce workable concrete that is easy to place in the forms.
  - ***Slump.*** A measure of the degree of consistency and extent of workability is the slump.
    - In the slump test, the plastic concrete specimen is formed into a conical metal mold. The mold is lifted, leaving the concrete to "slump," that is, to drop in height. This drop in height is the slump measure of degree of workability of the mix.

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete (cont'd)

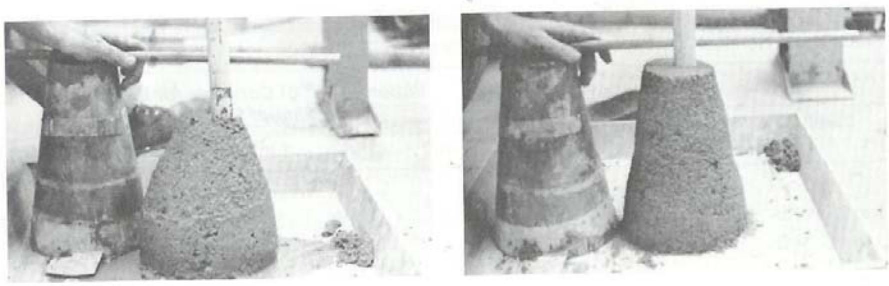


Figure 1. Left, 4½-in slump mix; right 1½-in slump mix.

Proportioning

- Flowchart for Normal-Strength Concrete mixture Design

Start

If slump is not given, decide the slump: use Table 1

Decide the maximum size of aggregate; choose the maximum possible size using the following guidelines:
maximum size > 1/5 narrower dimension between forms
> 1/3 depth of slab
> ¾ of clear spacing between reinforcing bars

Decide the amount of water and air (Table 2)

Select the w/c ratio (Table 3)

Calculate cement content (= c/w x wt of water)

Choose the amount of coarse aggregate (Table 4)

Calculate the amount of fine aggregate using the estimated weight of fresh concrete (Table 5) and the known weights of water, cement, and coarse aggregate

Adjust for moisture content in coarse and fine aggregate

Adjust for moisture content in coarse and fine aggregate

Trial mix

End

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete (cont'd)

Table 1. Recommended Slumps for Various Types of Construction

Types of Construction	Slump (in.)[a] Maximum[b]	Minimum
Reinforced foundation walls and footings	3	1
Plain footings, caissons, and substructure walls	3	1
Beams and reinforced walls	4	1
Building columns	4	1
Pavements and slabs	3	1
Mass concrete	2	1

[a]1 in. = 25.4 mm.
[b]May be increased 1 in. for methods of consolidation other than vibration.

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete (cont'd)

Table 2. Recommended Slumps for Various Types of Construction

Slump (in.)	Water (lb/yd^3 of Concrete for Indicated Nominal Maximum Sizes of Aggregate) $\frac{3}{8}$ in.[a]	$\frac{1}{2}$ in.[a]	$\frac{3}{4}$ in.[a]	1 in.[a]	$1\frac{1}{2}$ in.[a]	2 in.[a,b]	3 in.[b,c]	6 in.[b,c]
Nonair-Entrained Concrete								
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
Approximate amount of entrapped air in nonair-entrained concrete (%)	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-Entrained Concrete								
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
Recommended average total air content[d] (percent for level of exposure)								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5[e,f]	1.0[e,f]
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5[e,f]	3.0[e,f]
Extreme exposure[g]	7.5	7.0	6.0	6.0	5.5	5.0	4.5[e,f]	4.0[e,f]

[a]These quantities of mixing water are for use in computing cement factors for trial batches. They are maximal for reasonably well

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete (cont'd)

Table 3. Relationship Between Water/Cement Ratio and Compressive Strength of Concrete

Compressive Strength at 28 days (psi)	***Water/Cement Ratio, by Weight***	
	Nonair-entrained Concrete	**Air-entrained Concrete**
6000	0.41	-
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete (cont'd)

Table 4. Volume of Coarse Aggregate per Unit of Volume of Concrete

Maximum Size of Aggregate (in.)	**Volume of Dry-rodded Coarse Aggregate Per Unit Volume of Concrete for Different Fineness Moduli of Sand**			
	2.40	**2.60**	**2.80**	**3.00**
3/8	0.50	0.48	0.46	0.44
1/2	0.59	0.57	0.55	0.53
3/4	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1½	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

Proportioning Theory – NSC

- ACI Method of Mixture Design for Normal Strength Concrete (cont'd)

Table 5. First Estimate of Weight of Fresh Concrete

Maximum Size of Aggregate (in.)	First Estimate of Concrete Weight (lb/yd^3)	
	Nonair-entrained Concrete	Air-entrained Concrete
3/8	3840	3690
1/2	3890	3760
3/4	3960	3840
1	4010	3900
1½	4070	3960
2	4120	4000
3	4160	4040
6	4230	4120

Proportioning Theory – NSC

- Example 1

  Design a concrete mixture using the following details:

  - Required strength: 4000 psi (27.6 MPa)
  - Type of structure: beam
  - Maximum size of aggregate = ¾ in. (19 mm)
  - Fineness modulus of sand = 2.6
  - Dry-rodded weight of coarse aggregate = 100 lb/ft^3
  - Moisture absorption 3% for coarse aggregate and 2% for fine aggregate

Proportioning Theory – NSC

- Example 1 (cont'd)

Required slump for beam = 3 from Table 1

maximum aggregate size = ¾ in.

For slump between 3 and 4, and aggregate size = ¾ in.,

wt of water required per yd^3 = 340 lb/yd^3 (Table 2)

For a strength $f' = 4000$ psi,

$w/c = 0.57$ from Table 3

Amount of cement required per yd^3 of concrete:

$$= \frac{340}{0.57} = 596.5 \text{ lb/yd}^3$$

Proportioning Theory – NSC

- Example 1 (cont'd)

Using a sand fineness of 2.6 and Table 4,

volume of coarse aggregate = 0.64 yd^3

Using the dry-rodded weight of 100 lb/ft^3 for coarse aggregate,

wt of coarse aggregate = $0.64 \times 27 \times 100 = 1728$ lb/yd^3

Estimated wt of fresh concrete for aggregate of ¾-in. size:

= 3960 lb/yd^3 from Table 5

wt of sand = wt of fresh concrete – wt of water – wt of cement

\- wt coarse aggregate

= 3960 – 340 -596.5 – 1728 = 1295.5 lb

Net wt of sand to be taken = $1.02 \times 1295.5 = 1321.41$ lb

(moisture absorption 2%)

Proportioning Theory – NSC

- Example 1 (cont'd)

Net wt of gravel = 1.03 × 1728 = 1779.84 lb
(moisture absorption 3%)
Net wt of water = 340 – 0.02 (1295.5) – 0.03 (1728) = 262.25 lb
Therefore, final design is:

cement = 596.5 lb ≅ 600 lb (273 kg)
sand = 1321.41 lb ≅ 1320 lb (600 kg)
gravel = 1779.84 lb ≅ 1780 lb (810 kg)
water = 262.25 lb ≅ 260 lb (120 kg)

Quality Tests on Concrete

- Workability or Consistency
  - Slump test by means of the standard ASTM Code. The slump in inches recorded in the mixture indicates it workability.
  - Remolding test using Power's flow table.
  - Kelley's ball apparatus
- Air Content
  - Measurement of air content in fresh concrete is always necessary, especially when air-entraining agents are used.

Quality Tests on Concrete

- Compressive Strength of Hardened concrete
  - This is done by loading cylinders 6 in. in diameter and 12 in. high in compression perpendicular to the axis of the cylinder.
  - For high-strength concrete, cylinders 4 in. in diameter by 8 in. high can be used applying proper dimensional correction.

Quality Tests on Concrete

- Compressive Strength of Hardened concrete

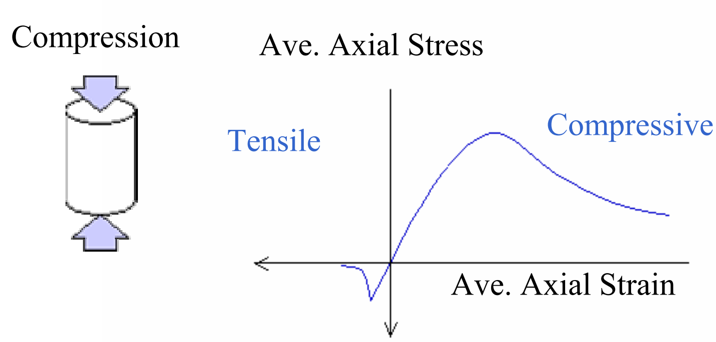


Figure 2. Left, 4½-in slump mix; right 1½-in slump mix.

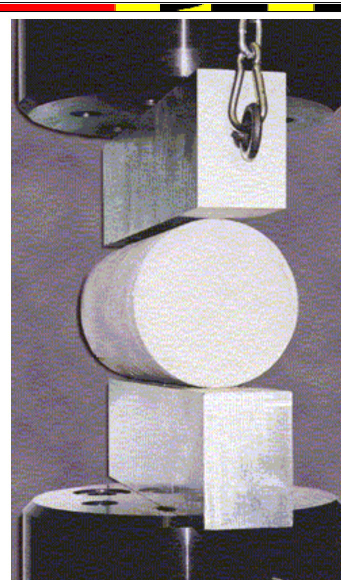
Quality Tests on Concrete

- Flexure Strength of Plain Concrete Beams
  – This test is performed by three-point loading of plain concrete beams of size 6 in. × 6 in. × 18 in. that have spans three times their depth.
- Tensile Splitting Tests
  – These tests are performed by loading 6 in. × 12 in. cylinder by a line load perpendicular to its longitudinal axis, with cylinder placed horizontally on the testing machine platten.

Quality Tests on Concrete

- Schematic for Split-Cylinder Test

Figure 3



Quality Tests on Concrete

- Tensile Splitting Tests
  - This test uses a standard 6-in.-diameter, 12 in.-long cylinder placed on its in a testing machine (see Fig. 3).
  - A compressive line load is applied uniformly along the length of the cylinder.
  - The compressive load produces a transverse tensile stress, and the cylinder will split in half along the diameter when it tensile strength is reached.

Quality Tests on Concrete

- Splitting Tensile Strength, f_{ct}

  The tensile splitting stress can be calculated from the following formula:

$$f_{ct} = \frac{2P}{\pi LD} \qquad (1)$$

where

f_{cr} = splitting tensile strength of concrete (psi)

P = applied load at splitting (lb)

L = length of cylinder (in.)

D = diameter of cylinder (in.)

Placing and Curing Concrete

- Placing
  - Depends on the type of member to be cast
    - Column
    - Beam
    - Wall
    - Slab
    - Foundation
  - For columns, beams, and walls, the forms should be well oiled after cleaning them, and the reinforcement should be cleared of rust and other harmful materials.

Placing and Curing Concrete

- In foundations, the earth should be compacted and thoroughly moistened to about 6 in. in depth to avoid absorption of the moisture present in the wet concrete..
- Concrete should always be placed in horizontal layers that are compacted by means of vibrators.
- Overvibration can be harmful since it could cause segregation of the aggregate and bleeding of the concrete.

Placing and Curing Concrete

- Curing
  - Hydration of the cement takes place in the presence of moisture at temperature above 50^0F.
  - Good curing conditions include:
    - Continuously sprinkling with water.
    - Ponding with water.
    - Covering the concrete with wet plastic film or waterproof curing paper.
    - Steam curing in cases where the concrete member is manufactured under factory conditions.

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Properties of Hardened Concrete

- Compressive Strength
  - As was mentioned earlier, compressive strength of concrete is relatively *high*.
  - The compressive strength of concrete is denoted by f_c' .
  - Units commonly used for f_c' :
    - Pounds per square inch (psi)
    - Kips per square inch (ksi)

Properties of Hardened Concrete

- Compressive Strength (cont'd)
  - The curves of Fig. 4 represent the result of compression tests on 28-day standard cylinders for varying design mix.
  - f_c' is not the stress that exists in the specimen at failure but rather which occurs at a strain of 0.002 in/in.
  - 28-day concrete strength f_c' range from 2500 to 9000 psi, with 3000 to 4000 psi being common for reinforced structures, and 5000 to 6000 psi for pre-stressed concrete members.

Properties of Hardened Concrete

- Compressive Strength (cont'd)

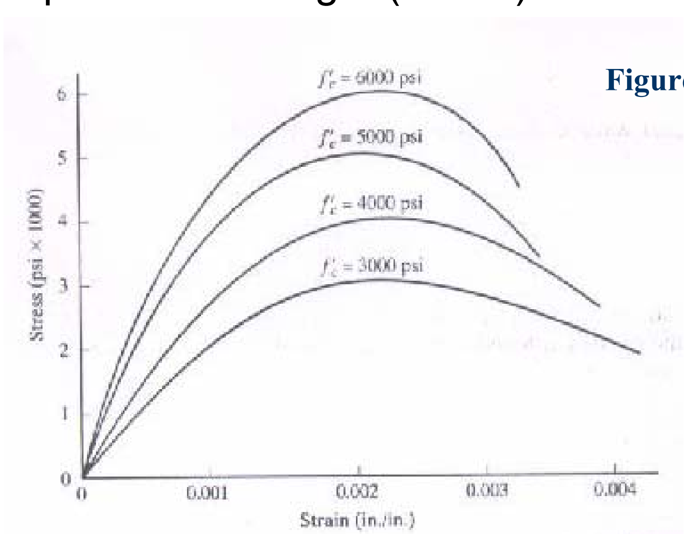


Figure 4

Properties of Hardened Concrete

- Compressive Strength
  - Concrete strength varies with time, and the specified concrete strength is usually that strength that occurs **28 days after the placing of concrete.**
  - A typical strength-time curve for normal stone concrete is shown in Fig. 5.
  - Generally, concrete attains approximately 70% of its 28-day strength in 7 days, and approximately 85% to 90% in 14 days.

Properties of Hardened Concrete

- Compressive Strength

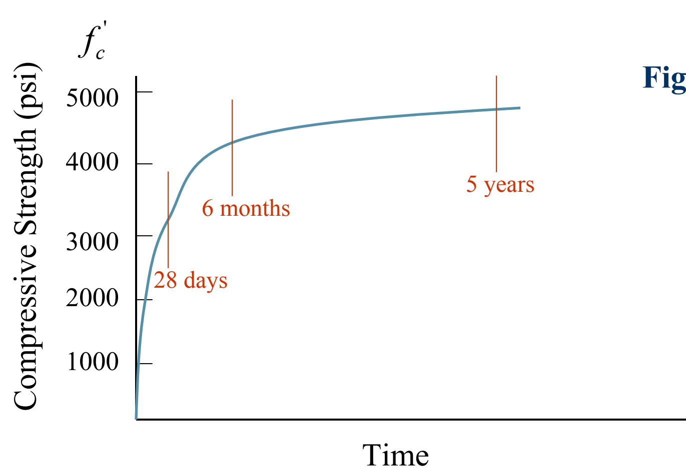


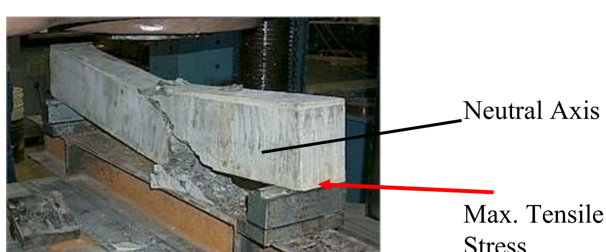
Figure 5

Properties of Hardened Concrete

- Tensile Strength
  - Concrete tensile stresses occur as a result of shear, torsion, and other actions, and in most cases member behavior changes upon cracking.
  - It is therefore important to be able to predict, with reasonable accuracy, the tensile strength of concrete.
  - The tensile and compressive strengths of concrete are not proportional, and an increase in compressive strength is accompanied by smaller percentage increase in tensile strength.

Properties of Hardened Concrete

- Tensile Strength (cont'd)
  - One common approach is to use the modulus of rupture f_r.
  - The modulus of rupture is the maximum tensile bending stress in a plain concrete test beam at failure.



Properties of Hardened Concrete

- ACI Code Recommendation

  For normal-weight concrete, the ACI Code recommends that the modulus of rupture f_r be taken as

$$f_r = 1.09 f_{ct} \le 7.5\sqrt{f'_c} \qquad (2)$$

  where f_r in psi.

Properties of Hardened Concrete

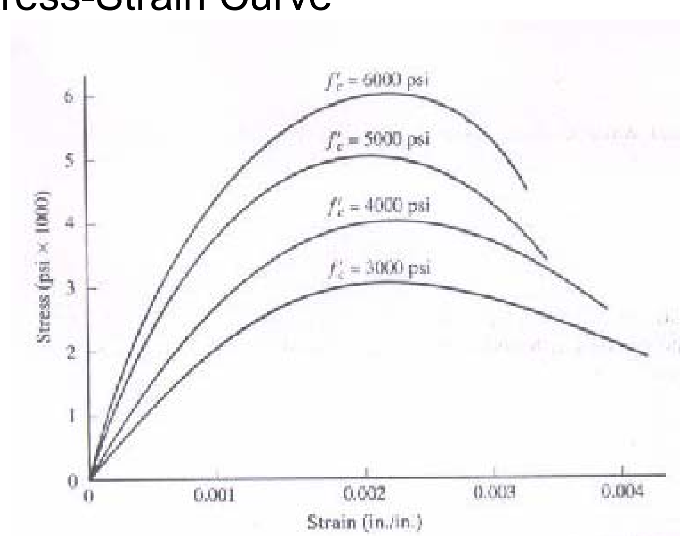
- Tensile Strength (cont'd)
  - The moment that produces a tensile stress just equal to the modulus of rupture is called cracking moment M_{cr}.
  - The split-cylinder test has also been used to determine the tensile strength of lightweight aggregate concrete.
  - It has been accepted as a good measure of the true tensile strength

Properties of Hardened Concrete

- Shear Strength
  - Shear strength is more difficult to determine experimentally that tests discussed previously because of the difficulty in isolating shear from other stresses.
  - Shear stress varies from 20% of the compressive strength in normal loading to a considerably higher percentage of up to 85% of the compressive strength.
  - Control of a design by shear strength is significant only in rare cases.

Properties of Hardened Concrete

- Stress-Strain Curve

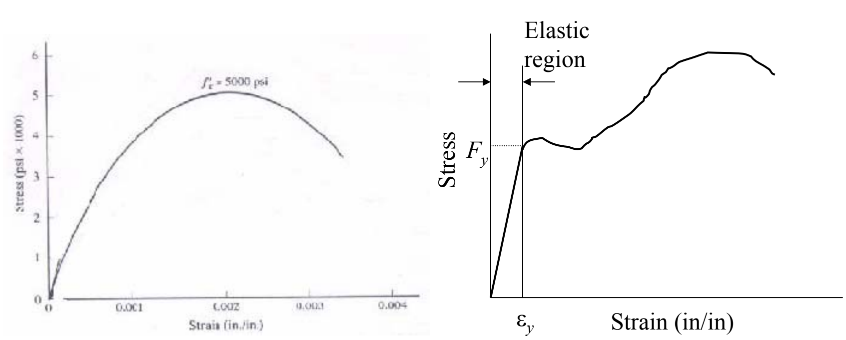


Properties of Hardened Concrete

- Modulus of Elasticity
  - In review of Fig. 6a, the initial slope of the curve varies, unlike that of steel (Fig 6b), and only approximates a straight line.
  - For steel, where stresses are below the yield point and the material behaves elastically, the stress-strain plot will be a straight line.
  - The slope of the straight line for steel is the modulus of elasticity.

Properties of Hardened Concrete

- Modulus of Elasticity (cont'd)



(a) Concrete **(b) Steel**

Figure 6

Properties of Hardened Concrete

- Modulus of Elasticity (cont'd)

At low and moderate stresses, up to about $0.5f_c'$, concrete is commonly assumed to behave elastically.

Properties of Hardened Concrete

- Empirical Expressions for the Modulus of Elasticity (by ACI Code)

For a unit weight w_c of concrete between 90 and 155 lb/ft^3:

$$E_c = w_c^{1.5} 33 \sqrt{f_c'} \qquad (3)$$

where

E_c = modulus of elasticity of concrete in compression (psi)

w_c = unit weight of concrete (lb/ft^3)

f_c' = compressive strength of concrete (psi)

Properties of Hardened Concrete

- Empirical Expressions for the Modulus of Elasticity (by ACI Code)

For a unit weight w_c taken as 144 lb/ft^3:

$$E_c = 57{,}000\sqrt{f_c'} \qquad (4)$$

where
E_c = modulus of elasticity of concrete in compression (psi)
w_c = unit weight of concrete (lb/ft^3)
f_c' = compressive strength of concrete (psi)

Properties of Hardened Concrete

- Example 1

What the modulus of elasticity E_c for concrete having a unit weight of 150 pcf and a compressive strength of 5 ksi?

Using Eq. 3,

$$E_c = w_c^{1.5} 33\sqrt{f_c'}$$
$$= (150)^{1.5}(33)\sqrt{5000} = \underline{\underline{4{,}286{,}826 \text{ psi}}}$$

Properties of Hardened Concrete

- Creep
  - Concrete under load, exhibits a phenomenon called *creep*.
  - This a property by which concrete continues to deform over long periods of time while under a constant load.
  - Creep occurs at a decreasing rate over a period of time and may cease after several years.
  - Higher strength concrete exhibits less creep.