$P_{Self} = (7.5 \times 0.2 \times 24) \times 4 + (0.4^2 \times (1.5 - 0.2 + (4.0 - 0.2) \times 3) \times 24 = 193\ kN$■

- Axial force at foundation level due to superimposed dead load:
  $P_{Superimposed} = 7.5 \times (3.0 + 3 \times 2.0) = 67.5\ kPa$ ■
- Axial force at foundation level due to floor live load:
  Firstly, check to see if floor live load is reducible:
  According to ***Table 1.3-2*** above, and as there is no cantilever slab,
  $K_{LL} = 4$,
  The influence area is:
  $\because K_{LL}A_T = 4 \times 7.5 \times 3 = 90\ m^2 > 37.16\ m^2 \therefore Ok.$
  $\because L = 1.92\ kPa < 4.79\ kPa \therefore Ok.$
  As two conditions are satisfy, therefore floor live load can be reduced according to following relation:
  $$L = L_o(0.25 + \frac{4.57}{\sqrt{K_{LL}A_T}})$$
  $$L = L_o\left(0.25 + \frac{4.57}{\sqrt{4 \times 7.5 \times 3}}\right) = 0.732\ L_o > 0.4L_O \therefore Ok.$$
  $P_L = 0.732 \times 1.92 \times (7.5 \times 3) = 31.6\ kPa$
- Axial force at foundation level due to roof live load:
  Firstly, check to see if roof live load is reducible:
  $\because A_T = 7.5\ m^2 < 18.58\ m^2$
  Therefore, roof live load cannot be reduced, and the axial force due to roof live would be:
  $P_{L_r} = 7.5 \times 0.96 = 7.2\ kN$ ■
- Maximum ultimate axial load, P_u:
  $P_u = Maximum\ (1.2P_D + 1.6P_L + 0.5P_{L_r}\ or\ 1.2P_D + 1.0P_L + 1.6P_{L_r})$
  $$P_u = Maximum\ (1.2(193 + 67.5) + 1.6 \times 31.6 + 0.5 \times 7.2\ or\ 1.2(193 + 67.5) + 1.0 \times 31.6 + 1.6 \times 7.2)$$
  $P_u = Maximum\ (367\ kN\ or\ 356) = 367\ kN$ ■
- Column Adequacy:
  With a nominal strength, P_n, of 3550 kN, it is easy to show that the proposed column is adequate:
  $P_u = 367\ kN \ll \phi P_n = 0.65 \times 3550 = 2308\ kN \therefore Ok.$

1.13 CONTENTS

CHAPTER 2
MATERIALS

2.1 INTRODUCTION

- The structures and component members treated in this course are composed of:
  - Concrete,
  - Reinforcing steel bars,
- An understanding of the materials characteristics and behavior under load is fundamental to understanding the performance of structural concrete, and to safe, economical, and serviceable design of concrete structures.
- Although ***prior exposure to the fundamentals of material behavior is assumed***, a brief review is presented in this chapter

2.2 CONCRETE, CHEMICAL ASPECTS

2.2.1 Cement

2.2.1.1 Hydraulic Cement

For making structural concrete, hydraulic cements are used exclusively. ***Water is needed for the chemical process*** (***<u>hydration</u>***) in which the cement powder sets and hardens into one solid mass.

2.2.1.2 Portland Cement

- Of the various hydraulic cements that have been developed, ***portland cement***, which was first patented in England in 1824, is by far ***the most common***.
- Portland cement is a finely powdered, grayish material that consists chiefly of ***calcium*** and ***aluminum silicates***.

2.2.1.2.1 Common Raw Materials for Portland Cement

- Limestones, which provide ***CaO***,
- Clays or shales, which furnish SiO_2 and Al_2O_3.

2.2.1.2.2 Manufacturing of Portland Cement

- Raw materials are ground, blended,
- Then fused to clinkers in a kiln, and cooled,
- Gypsum is added to the mixture,
- Mixture is ground to the required fineness.

2.2.1.2.3 Types of Portland Cements

Five standard types of Portland cement have been developed:

- Type I, Normal Portland Cement:
  - It is used for ***over 90 percent of construction***.
  - Concretes made with Type I Portland cement generally need ***one to two weeks to reach sufficient strength so that forms of beams and slabs can be removed and reasonable loads applied***; they reach their ***design strength after 28 days*** and continue to gain strength thereafter at a decreasing rate.
- Type III, High Early Strength Cements:
  - To speed construction when needed, ***Type III*** cement have been developed. They are ***costlier than ordinary Portland cement***, but ***within 7 to 14 days they reach the strength achieved using Type I at 28 days***.
  - Type III Portland cement contains the same basic compounds as Type I, but ***the relative proportions differ*** and it is ***ground more finely***.
- Type V, Sulfate-resisting Cement
  - This cement has a ***low C3A*** content to avoid ***sulfate attack from <u>outside</u> the concrete***; otherwise, the formation of ***calcium sulfoaluminate*** and ***gypsum*** would cause disruption of the concrete due to an increased volume of the resultant compounds.
  - The salts particularly active are ***magnesium*** and ***sodium*** sulfate.
  - Sulfate attack is greatly ***accelerated if accompanied by alternate wetting and drying***, e.g. in marine structures subject to tide or splash.
  - The heat developed by ***sulfate-resisting cement is not much higher than that of low-heat cement***, which is an advantage, but the cost of the former is higher due to the

special composition of the raw materials. Thus, in practice, ***sulfate-resisting cement should be specified only when necessary; it is not a cement for general use***.

2.2.1.2.4 Setting and Hydration

- When cement is mixed with water to form a soft paste, it gradually stiffens until it becomes a solid. This process is known as ***setting and hardening***.
- The cement is said to have ***set*** when it has ***gained sufficient rigidity to support an arbitrarily defined pressure***, after which it continues for a long time to ***harden***, i.e., ***to gain further strength***.
- The water in the paste dissolves material at the surfaces of the cement grains and forms a ***gel*** that gradually increases in volume and stiffness. This leads to a rapid stiffening of the paste ***2 to 4 hours*** after water has been added to the cement.
- Hydration continues to proceed deeper into the cement grains, at decreasing speed, with continued stiffening and hardening of the mass. The ***principal products of hydration*** are ***calcium silicate hydrate***, which is insoluble, and ***calcium hydroxide***, which is soluble.
- Water/Cement Ratio for Hydration
    - For complete hydration of a given amount of cement, an amount of water equal to about ***25 percent*** of that of cement, by weight-i.e., a water-cement ratio of ***0.25***, is needed ***chemically***.
    - An additional amount must be present, however, ***to provide mobility for the water in the cement paste during the hydration process so that it can reach the cement particles*** and to ***provide the necessary workability of the concrete mix***.
    - For ***normal concretes***, the water-cement ratio is generally ***in the range of about 0.40 to 0.60***,
    - For ***high-strength concretes***, ratios ***as low as 0.21*** have been used. In this case, the needed workability is obtained through the use of ***admixtures***.
- Heat of Hydration
    - The chemical process involved in the setting and hardening liberates heat, known as ***heat of hydration***.
    - In ***large concrete masses***, such as dams, ***this heat is dissipated very slowly*** and results in a temperature rise and volume expansion of the concrete during hydration, with subsequent cooling and contraction.

2.2.2 Aggregates

- In ordinary structural concretes, the aggregates occupy ***65 to 75 percent of the volume of the hardened mass***.
- The ***remainder*** consists of ***hardened cement paste***, ***uncombined water*** (i.e., water not involved in the hydration of the cement), and ***air voids***.

2.2.2.1 Gradation of Aggregate

Gradation of Aggregate versus Durability of Concrete

- In general, ***the more densely the aggregate can be packed***, the ***better the durability*** and ***economy*** of the concrete.
- For this reason, the ***gradation of the particle sizes in the aggregate***, to produce ***close packing***, is of considerable importance.

2.2.2.2 Important Properties of Aggregate

It is important that the aggregate

- have good strength,
- have good durability,
- have good weather resistance;
- its surface be free from impurities such as loam, clay, silt, and organic matter that may weaken the bond with cement paste;
- have no unfavorable chemical reaction with the cement.

2.2.2.3 Fine and Coarse Aggregate

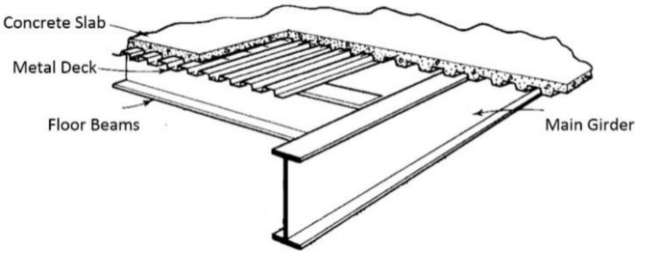
- Natural ***aggregates*** are generally ***classified*** as ***fine*** and ***coarse***.
- Fine aggregate (typically natural sand) is any material that will pass a ***No.4 sieve,*** i.e***., a sieve with four openings per linear inch***.
- Material coarser than this is classified as coarse aggregate.

2.2.2.4 Maximum Size of Coarse Aggregate

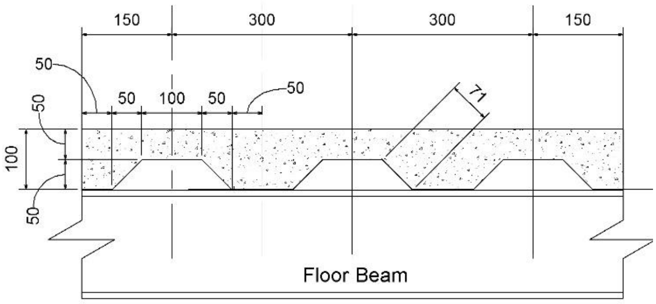
- The ***maximum size of coarse aggregate*** in reinforced concrete is ***governed by*** the requirement that it shall ***easily fit into the forms*** and ***between the reinforcing bars***.
- For this purpose, it should ***not be larger*** than ***one-fifth of the narrowest dimension of the forms*** or ***one-third of the depth of slabs***, nor ***three-quarters of the minimum distance between reinforcing bars***.
- Requirements for satisfactory aggregates are found in ***ASTM C33, "Standard Specification for Concrete Aggregates,"***

Example 2.2-1

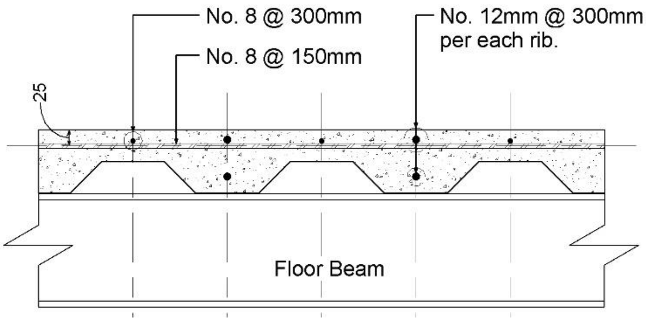
Can a coarse aggregate with a maximum size of 20mm be adopted for the one-way slab indicates in Figure 2.2-1?



Three-dimensional view.



Slab dimensions.



Slab reinforcement.

Figure 2.2-1: One-way slab.

Solution

To fit easily into the forms and between the reinforcing bars, the maximum size of aggregate shall be:

- Not be larger than one-fifth of the narrowest dimension of the forms:

$$\frac{50}{5} > 20 \therefore Not\ ok.$$

- Or one-third of the depth of slabs:

$$\frac{1}{3} \times \left(\frac{50+100}{2}\right) = \frac{75}{3} = 25 > 20 \therefore Ok.$$

- Nor three-quarters of the minimum distance between reinforcing bars:

$$\frac{3}{4} \times 150 = 112.5 > 20 \therefore Ok.$$

- -

Example 2.2-2

Can a coarse aggregate with a maximum size of 20mm be adopted for a precast pile indicates in Figure 2.2-1?

Solution

To fit easily into the forms and between the reinforcing bars, the maximum size of aggregate shall be:

- Not be larger than one-fifth of the narrowest dimension of the forms:
  $$\frac{285}{5} = 57 > 20 \therefore Ok.$$
- Or one-third of the depth of slabs:
  This is inapplicable for pile section.
- Nor three-quarters of the minimum distance between reinforcing bars:
  $$\frac{3}{4} \times \left(\frac{285 - 20 \times 2 - 8 \times 2 - \frac{16}{2} \times 2}{2}\right) \approx 80mm > 20$$
  $$\therefore Ok.$$

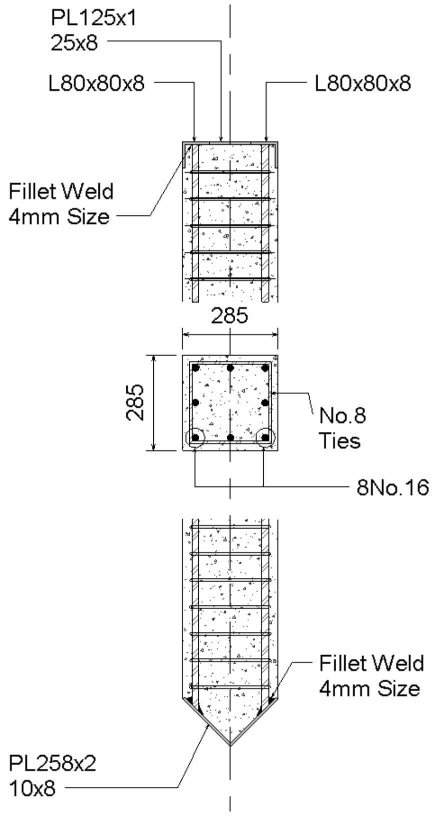


Figure 2.2-2: Precast pile details.

2.2.2.5 Lightweight Aggregate

- A ***variety of lightweight aggregates*** are available. Some ***unprocessed*** aggregates, such as ***pumice*** or ***cinders***, are suitable for ***insulating concretes***.
- For ***structural lightweight concrete***, ***processed aggregates are used because of better control***. These consist of expanded shales, clays, slates, slags, or pelletized fly ash. They are ***light in weight*** because of the ***porous***, ***cellular structure of the individual aggregate particle***, which ***is achieved by gas or steam formation in processing the aggregates in rotary kilns*** at high temperatures (generally in excess of 2000°F).
- Requirements for satisfactory lightweight aggregates are found in ***ASTM C330, "Standard Specification for Lightweight Aggregates for Structural Concrete."***
- Use of lightweight concrete
  - ***low-density concretes***, which are ***chiefly employed for insulation*** and whose unit weight rarely exceeds ***800*** kg/m^3;
  - ***moderate strength concretes***, with unit weights from about ***960 to 1360*** kg/m^3 are chiefly used as ***fill***, e.g., ***over light-gage steel floor panels***;
  - ***structural concretes***, with unit weights from ***1440 to 1920*** kg/m^3.

2.2.2.6 Heavyweight Concrete

- Heavyweight concrete is sometimes required
  - for ***shielding against gamma*** and ***X -radiation*** in ***nuclear reactors*** and similar installations, for protective structures,
  - to ***counterweights*** of ***lift bridges***.
- It consist of
  - heavy iron ores or barite (barium sulfate),
  - rock crushed to suitable sizes,
  - steel in the form of scrap.
- Unit weights of heavyweight concretes with natural heavy rock aggregates range from
  - ***about 3200 to 3680 kg/m^3***;
  - if iron are added to ***high-density ores***, ***weights as high as 4325 kg/m^3 are achieved***.
  - The weight may be as high as ***5290 kg/m^3*** if ores are used for the ***fines only and steel for the coarse aggregate***.

2.2.3 Proportioning and Mixing Concrete

2.2.3.1 Required Properties of Concrete

The various components of a mix are proportioned so that the resulting concrete has

- adequate strength,
- proper workability for placing,
- and low cost,

The third calls for use of the ***minimum amount of cement*** (the most costly of the components) that will achieve adequate properties.

2.2.3.2 Effect of Aggregate Gradation on Concrete Properties

The better the gradation of aggregates, i.e., the smaller the volume of voids, the less cement paste is needed to fill these voids.

2.2.3.3 Water Role in a Concrete Mixture

- Water is required for
    - hydration,
    - wetting the surface of the aggregate.
- As water is added, the plasticity and fluidity of the mix increase (i.e., its workability improves), but the strength decreases because of the larger volume of voids created by the free water.

2.2.3.4 Water-cement Ratio

- To reduce the free water while retaining the workability, cement must be added.
- The water-cement ratio is the chief factor that controls the strength of the concrete. For a given water-cement ratio, one selects the minimum amount of cement that will secure the desired workability.
- ***Figure 2.2-3*** shows the decisive influence of the water-cement ratio on the compressive strength of concrete.
- Its influence on the tensile strength, as measured by the nominal flexural strength or modulus of rupture, is seen to be pronounced but much smaller than its effect on the compressive strength.

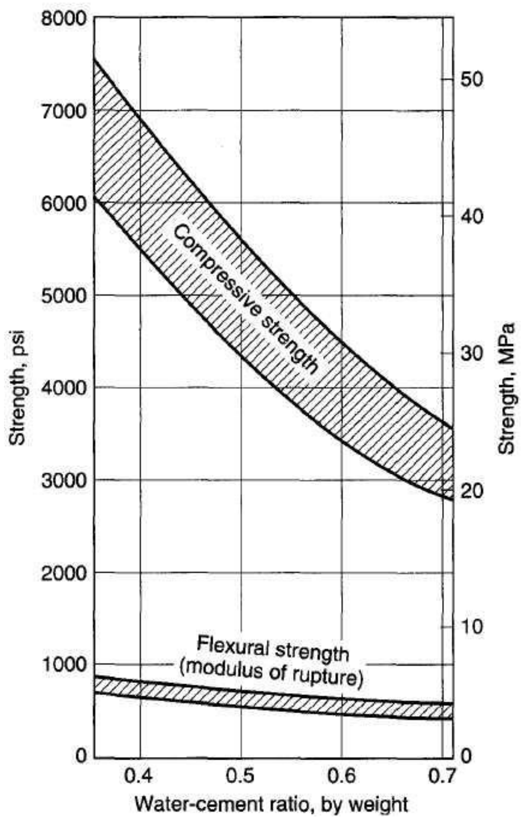


Figure 2.2-3: Effect of water-cement ratio on 28-day compressive and flexural tensile strength.

2.2.4 Conveying, Placing, Compacting, and Curing

2.2.4.1 Conveying

- Conveying of most building concrete from the mixer or truck to the form is done in
    - bottom-dump buckets
    - or by pumping through steel pipelines.
- The chief danger during conveying is that of ***segregation*** which is due to:
    - The individual components of concrete tend to segregate because of their dissimilarity. In overly wet concrete standing in containers or forms, the heavier coarse aggregate particles tend to settle, and the lighter materials, particularly water, tend to rise.
    - Lateral movement, such as flow within the forms, tends to separate the coarse gravel from the finer components of the mix.

2.2.4.2 Placing

- Placing is the process of transferring the fresh concrete from the conveying device to its final place in the forms.
- Causation prior to placing,
    - loose rust must be removed from reinforcement,

- forms must be cleaned,
- hardened surfaces of previous concrete lifts must be cleaned and treated appropriately,

- Causations during placing
  Proper placement must avoid
  - segregation,
  - displacement of forms
  - displacement of reinforcement in the forms,
  - poor bond between successive layers of concrete.
- Consolidation with Vibrators
  Consolidation, immediately upon placing, the concrete should be, by ***means of vibrators***, to
  - prevent honeycombing,
  - ensure close contact with forms and reinforcement,
  - serve as a partial remedy to possible prior segregation.

2.2.4.3 Curing

- Fresh concrete gains strength most rapidly during the first few days and weeks.
- Structural design is generally based on the 28-day strength, about ***70 percent of which is reached at the end of the first week after placing***.
- The final concrete strength depends greatly on the conditions of
  - moisture
  - temperature

  during this initial period.
- The maintenance of proper conditions during this time is known as ***curing***.
- ***Thirty percent*** of the strength or ***more*** can be ***lost*** by ***premature drying out*** of the concrete; similar amounts may be lost by permitting the concrete ***temperature to drop to 4°C or lower*** during the first few days unless the concrete is kept continuously moist for a long time.
- ***Curing Period***
  To prevent such damage, concrete should be protected from loss of moisture for
  - at least 7 days and,
  - in more sensitive work, up to 14 days.
  - When high early strength cements are used, curing periods can be cut in half.
- ***Achievement of Curing***
  Curing can be achieved by keeping exposed surfaces continually wet through
  - sprinkling,
  - ponding,
  - covering with plastic film
  - by the use of sealing compounds, which, when properly used, form evaporation-retarding membranes.
- Other Curing Advantage
  In addition to improving strength, proper moist curing provides ***better shrinkage control***.

2.2.5 Quality Control

2.2.5.1 Concrete versus Mill-produced Materials

The quality of mill-produced materials, such as structural or reinforcing steel, is ensured by the producer, who must exercise systematic quality controls, usually specified by pertinent standards. Concrete, in contrast, is produced at or close to the site, and its final qualities are affected by a number of factors. Thus, systematic quality control must be instituted at the construction site.

2.2.5.2 Compressive Strength as the Main Quality Indicator

- The main measure of the structural quality of concrete is its compressive strength.
- Tests for this property are made on cylindrical specimens of height equal to twice the diameter, ***usually 150 × 300 mm***, and subjected to a ***uniaxial monotonic loading***.
- The cylinders are ***moist-cured at about 23°C***, generally for ***28 days***, and then tested in the laboratory at a specified rate of loading.
- The compressive strength obtained from such tests is known as the ***cylinder strength*** f_c'; and is the main property specified for design purposes.

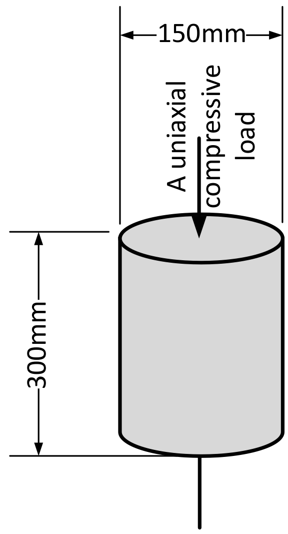


Figure 2.2-4: Standard compressive test.

2.2.5.3 Strength Test Sample

According to article ***26.12.1.1*** of ACI code, ***a strength test shall be average of the strengths of at least two 150 X 300 mm or three 100 X 200 mm cylinders***.

2.2.5.4 Sample Size

According to article ***26.12.2.1*** of ACI code,

- A sample must be tested for each **110m^3** of concrete or for each ***460m^2*** of surface area actually placed, but ***not less than once a day***.
- On a given project, if total volume of concrete is such that frequency of testing would provide fewer than five strength tests for a given concrete mixture, strength test specimens shall be made from at least five randomly selected batches or from each batch if fewer than five batches are used.

If the total quantity of a given concrete mixture is less than 38 m^3, strength tests are not required if evidence of satisfactory strength is submitted to and approved by the building official.

2.2.5.5 Acceptance Criteria

To ensure adequate concrete strength in spite of the scatter, the (ACI318M, 2014), article 26.12.3, stipulates that concrete quality is satisfactory if

- No individual strength test result (the average of two or three cylinder tests depending on cylinder size) falls below the required f_c' by more than 3.5 MPa when f_c' is 35 MPa or less or by more than $0.1f_c'$ when f_c' is more than 35 MPa.
- Every arithmetic average of any three consecutive strength tests equals or exceeds f_c'.

2.2.5.6 Specified versus Mean Compressive Strength

- It is evident that if concrete were proportioned so that its mean strength were just equal to the required strength f_c', it would not pass aforementioned quality requirements, because about one-half of its strength test results would fall below the required f_c'.

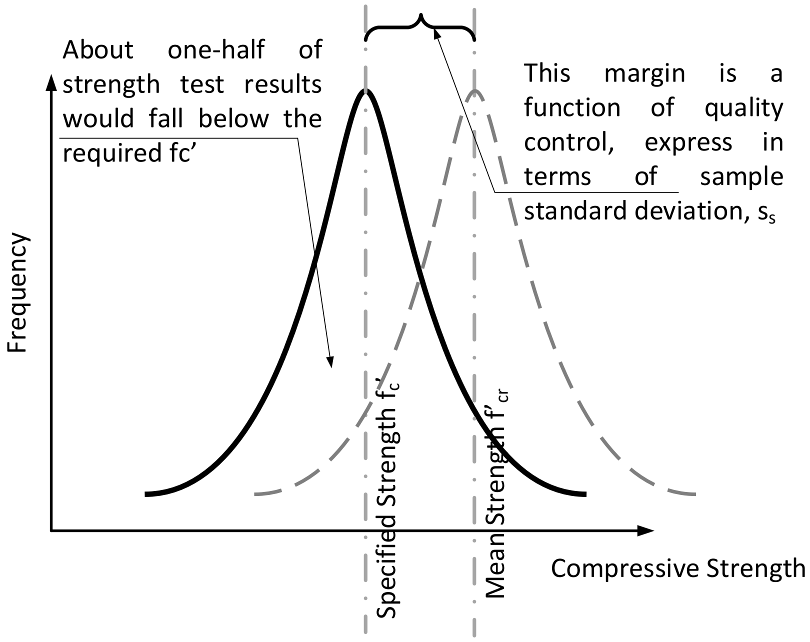


Figure 2.2-5: Strength frequency curve with adopting specified compressive strength in mix design.

- It is therefore necessary to proportion the concrete so that its ***mean strength*** f_{cr}', used as the basis for selection of suitable proportions, ***exceeds the required design strength*** f_c'; ***by an amount sufficient to ensure that the two quoted requirements are met***.
- The minimum amount by which the required mean strength, f_{cr}' must exceed f_c'; ***can be determined only by statistical methods because of the random nature of test scatter***.
- Based on statistical analysis, following recommendation have been adopted by the (ACI318, 2008) to determined required average compressive strength f_{cr}' used as the basis for selection of concrete proportions:
  - When data are available to establish a sample standard deviation, f_{cr}' shall be computed based on Table 2.2-1 below.

Table 2.2-1: Required average compressive strength when data are available to establish a sample standard deviation, Table 5.3.2.1 of (ACI318, 2008).

Specified compressive strength, MPa	Required average compressive strength, MPa
$f_c' \leq 35$	Use the larger value computed from Eq. (5-1) and (5-2) $f_{cr}' = f_c' + 1.34 s_s$ (5-1) $f_{cr}' = f_c' + 2.33 s_s - 3.5$ (5-2)
$f_c' > 35$	Use the larger value computed from Eq. (5-1) and (5-3) $f_{cr}' = f_c' + 1.34 s_s$ (5-1) $f_{cr}' = 0.90 f_c' + 2.33 s_s$ (5-3)

  - The sample standard deviation, s_s, calculated as follows:
    - When a concrete production facility has a suitable record of ***30 consecutive tests*** of similar materials and conditions expected, the sample standard deviation, s_s, is calculated from those results in accordance with the following formula:

$$s_s = \left[\frac{\sum(x_i - \bar{x})^2}{(n-1)}\right]^{\frac{1}{2}}$$

where
s_s = sample standard deviation, MPa
x_i = individual strength tests.
$\bar{x}$ = average of n strength test results
n = number of consecutive strength tests

    - If ***less than 30 tests***, but ***at least 15 tests*** are available, the calculated sample standard deviation is increased by the factor given in Table 2.2-2.

Table 2.2-2: Modification factor for sample standard deviation when less than 30 tests are available, Table 5.3.1.2 of (ACI318, 2008).

No. of tests*	Modification factor for sample standard deviation†
Less than 15	Use Table 5.3.2.2
15	1.16
20	1.08
25	1.03
30 or more	1.00

*Interpolate for intermediate numbers of tests.
†Modified sample standard deviation, s_s, to be used to determined required average strength, f'_{cr}, from 5.3.2.1

- When a concrete production facility does not have field strength test records for calculation of s_s, f'_{cr} shall be determined from Table 2.2-3 below.

Table 2.2-3: Required average compressive strength when data are not available to establish a sample standard deviation

Specified compressive strength, MPa	Required average compressive strength, MPa
$f'_c < 21$	$f'_{cr} = f'_c + 7.0$
$21 \le f'_c \le 35$	$f'_{cr} = f'_c + 8.3$
$f'_c > 35$	$f'_{cr} = 1.10f'_c + 5.0$

- The 2014 edition of the Code does not include the statistical requirements for proportioning concrete that were contained in previous editions. This information was removed from the Code because:
  - It is not the responsibility of the licensed design professional to proportion concrete mixtures.
  - This information is available in other ACI documents, such as ACI 301 and ACI 214R.
  - Finally, the quality control procedures of some concrete producers allow meeting the acceptance criteria of the Code without following the process included in previous editions of the Code.

Example 2.2-3

A building design calls for specified concrete strength f'_c of 28 MPa. Calculate the average required strength f'_{cr} if

(a) 30 consecutive tests for concrete with similar strength and materials produce a sample standard deviation s_s of 3.75 MPa,

(b) 15 consecutive tests for concrete with similar strength and materials produce a sample standard deviation s_s of 3.57 MPa,

(c) Less than 15 tests are available.

Solution

(a) 30 consecutive tests are available:

$\because f'_c < 35\ MPa$

$\therefore f'_{cr} = maximum\ (f'_c + 1.34s_s\ or\ f'_c + 2.33s_s - 3.5)$

$f'_{cr} = maximum\ (28 + 1.34 \times 3.75\ or\ 28 + 2.33 \times 3.75 - 3.5)$

$f'_{cr} = maximum\ (33.0\ or\ 33.2) = 33.2\ MPa$ ■

(b) Only 15 consecutive tests are available:

Sample standard deviation, s_s, should be modified according to Table 2.2-2 above,

$s_s = 3.57 \times 1.16 = 4.14\ MPa$

$f'_{cr} = maximum\ (28 + 1.34 \times 4.14\ \ or\ 28 + 2.33 \times 4.14\ - 3.5)$

$f'_{cr} = maximum\ (33.5\ \ or\ 34.1) =\ 34.1\ MPa$ ■

(c) Less than 15 tests are available

According to Table 2.2-3 above,

$\because 21 < f'_c < 35$

$\therefore f'_{cr} = f'_c + 8.3 = 28 + 8.3 = 36.3\ MPa$ ■

This example demonstrates that:

- In cases where test data are available, good quality control, represented by a low sample standard deviation, s_s, can be used to reduce the required average strength $f_{cr}{}'$.

- A lack of certainty in the value of the standard deviation due to the limited availability of data results in higher values for f_{cr}', as shown in parts (b) and (c). As additional test results become available, the higher safety margins can be reduced.

Example 2.2-4

Determine the minimum number of test cylinders that must be cast to satisfy the code minimum sampling frequency for strength tests. Concrete placement is 150 m^3 per day for 7 days, transported by 7.6 m^3 truck mixers.

Solution

- Total concrete placed on project = 150x(7) = 1050 m^3
- Total truck loads (batches) required ≈ 1050/7.6 ≈ 138
- Truck loads required to be sampled per day = 150/110 = 1.36
  Therefore, 2 truck loads must be sampled per day.
- Total truck loads required to be sampled for project = 2 (7) = 14
- Total number of cylinders required to be cast for project = 14 (2 cylinders per test) = 28 (minimum).

It should be noted that the total number of cylinders required to be cast for this project represents a code required minimum number only that is needed for determination of acceptable concrete strength. Addition cylinders should be cast to provide for 7-day breaks, to provide field cured specimens to check early strength development for form removal, and to keep one or two in reserve, should a low cylinder break occur at 28-day.

Example 2.2-5

Determine the minimum number of test cylinders that must be cast to satisfy the code minimum sampling frequency for strength tests. Concrete is to be placed in a 30m × 23m × 200mm slab, and transported by 7.6 m^3 truck mixers.

Solution

Total surface area placed,

$$A_{Surface} = 30 \times 23 = 690\ m^2$$

Volume to be placed,

$$Vol. = 690 \times \frac{200}{1000} = 138\ m^3$$

Total truck loads (batches) required,

$$Total\ Trucks\ Required = \frac{138}{7.6} \approx 18 > 5$$

Therefore,

$$Sample\ Size\ based\ on\ Surface\ Area = \frac{690}{460} = 1.5$$

$$Sample\ Size\ based\ on\ Vol. = \frac{138}{110} = 1.25$$

$$Sample\ Size\ based\ on\ Trucks\ (Batches) Number\ = 5_{Randomly\ Selected\ from\ 18\ Trucks}$$

The govern sample size is that determined based on trucks (batches) number:

$$Sample\ Size = 5\ Samples\ or\ 10\ Cylinders\ with\ dimensions\ of\ 150 \times 300\ \text{mm} \blacksquare$$

It should again be noted that the total number of cylinders cast represents a code required minimum number only for acceptance of concrete strength. A more prudent total number for a project may include additional cylinders.

Example 2.2-6

The following table lists strength test data from 5 truck loads (batches) of concrete delivered to the job site. For each batch, two cylinders were cast and tested at 28 days. The specified strength of the concrete f_c' is 28 MPa. Determine the acceptability of the concrete based on the strength criteria.

Test No.	Cylinder No. 1, MPa	Cylinder No. 2, MPa
1	28.8	29.8
2	26.9	28.6
3	30.9	31.2
4	25.7	26.7
5	32.3	32.0

Solution

Compute test average and average of three consecutive tests as presented in table below:

Test No.	Cylinder No. 1, MPa	Cylinder No. 2, MPa	Test Average, MPa	Average of 3 Consecutive Tests
1	28.8	29.8	29.3	-
2	26.9	28.6	27.7	-
3	30.9	31.2	31.0	$(29.3 + 27.7 + 31.0)/3 = 29.3$
4	25.7	26.7	26.2	$(27.7 + 31.0 + 26.2)/3 = 28.3$
5	32.3	32.0	32.2	$(31.0 + 26.2 + 32.2)/3 = 29.8$

For concrete to be considered satisfactory,

- No individual test may fall below $f_c' - 3.5$
  $f_c' - 3.5 = 28 - 3.5 = 24.5\ MPa$
  The five tests meet this criterion.
- Every arithmetic average of any three consecutive tests must equal $f_c{}'$.
  The five tests meet this criterion.

Thus, based on the code acceptance criteria for concrete strength, the five strength tests results are acceptable, both on the basis of individual test results and the average of three consecutive test results.

Example 2.2-7

The following table lists strength test data from 5 truck loads (batches) of concrete delivered to the job site. For each batch, two cylinders were cast and tested at 28 days. The specified strength of the concrete $f_c{}'$ is 28 MPa. Determine the acceptability of the concrete based on the strength criteria.

Test No.	Cylinder No. 1, MPa	Cylinder No. 2, MPa
1	25.3	24.9
2	27.8	28.4
3	28.6	28.0
4	34.0	32.9
5	23.7	21.8

Solution

Compute test average and average of three consecutive tests as presented in table below:

Test No.	Cylinder No. 1, MPa	Cylinder No. 2, MPa	Test Average, MPa	Average of 3 Consecutive Tests
1	25.3	24.9	25.1	
2	27.8	28.4	28.1	
3	28.6	28.0	28.3	27.2*
4	34.0	32.9	33.5	29.9
5	23.7	21.8	22.8**	28.2

*Average of 3 consecutive tests low.
**One test more than 3.5 MPa below specified value.

For concrete to be considered satisfactory,

- No individual test may fall below $f_c' - 3.5$
  $f_c' - 3.5 = 28 - 3.5 = 24.5\ MPa$
  Test indicated with ** does not satisfy this requirement.
  Based on experience, the major reasons for low strength test results are:
  - Improper sampling and testing,
  - Reduced concrete quality due to an error in production, or the addition of too much water to the concrete at the job site, caused by delays in placement or requests for wet or high slump concrete. High air content can also be a cause of low strength.

  The test results for the concrete from Truck 5 are below the specified value, especially the value for Cylinder #2, with the average strength being only 22.8 MPa.
  Note that no acceptance decisions are based on the single low cylinder break of 21.8 MPa. Due to the many variables in the production, sampling and testing of concrete, acceptance or rejection is always based on the average of at least 2 cylinder breaks.
- Every arithmetic average of any three consecutive tests must equal $f_c{}'$:
  Consecutive average indicated with * does not satisfy this criterion.

Thus, based on the code acceptance criteria for concrete strength, the five strength tests results are rejected, both on the basis of individual test results and the average of three consecutive test results.

Example 2.2-8

The first eight compressive strength test results for the building described in Example 2.2-8c are

32.6, 29.5, 27.2, 30.1, 35.7, 33.5, 34.3, and 33.4 MPa.

(a) Are the test results satisfactory?

(b) In what fashion, if any, should the mixture proportions of the concrete be altered?

Solution

(a) For concrete to be considered satisfactory,

1. No individual test may fall below $f_c' - 3.5$

   $f_c' - 3.5 = 28 - 3.5 = 24.5\ MPa$

   The eight tests meet this criterion.

2. Every arithmetic average of any three consecutive tests must equal $f_c{}'$.

   $\frac{32.6 + 29.5 + 27.2}{3} = 29.7\ MPa$ $\frac{29.5 + 27.2 + 30.1}{3} = 28.9\ MPa$

   $\frac{27.2 + 30.1 + 35.7}{3} = 31\ MPa$ $\frac{30.1 + 35.7 + 33.5}{3} = 33.1\ MPa$

   $\frac{35.7 + 33.5 + 34.3}{3} = 34.5\ MPa$ $\frac{33.5 + 34.3 + 33.4}{3} = 33.7\ MPa$

   The eight tests meet this criterion.

(b) To determine if the mixture proportions must be altered,

1. we note that the solution to Example 2.2-3c requires that

   $$f_{cr}' \geq 36.3\ MPa$$

   The average of the first eight tests is 32.0 MPa, well below the value of $f_{cr}{}'$,. Thus, ***the mixture proportions should be modified by decreasing the water-cement ratio to increase the concrete strength***.

2. Once at least 15 tests are available, the value of $f_{cr}{}'$ can be recalculated with the appropriate factor for s_s from Table 2.2-1.

Example 2.2-9

According to durability requirement, the cylindrical compressive strength, $f_c{}'$, of $30\ MPa$ should be adopted for the spread footings of the indicated building. They have a total volume of $24\ m^3$. For this concrete volume, can an approval by the building official be adopted to accept concrete without sampling?

Solution

According to article 26.12.2.1 of the ACI code, if the total quantity of a given concrete mixture is less than 38 m^3, strength tests are not required if evidence of satisfactory strength is submitted to and approved by the building official. Therefore, for a concrete volume of 24m^3 an approval by the building official would be adequate.

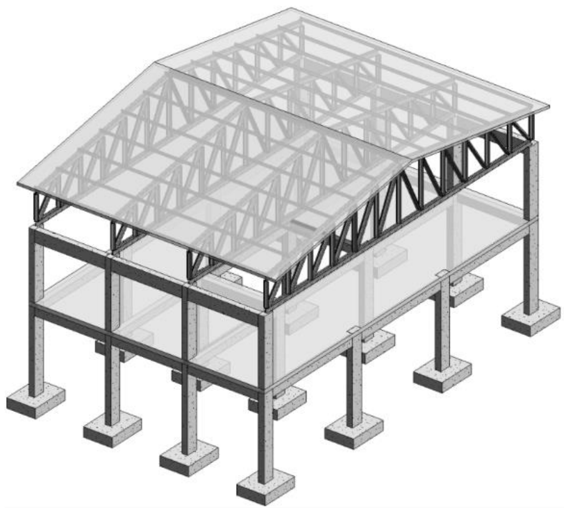


Figure 2.2-6: Building for Example 2.2-9.

2.2.6 Admixtures

2.2.6.1 Beneficial Effects of Admixtures

In addition to the main components of concretes, admixtures are often used to improve concrete performance due:

- To accelerate or retard setting and hardening,
- To improve workability,
- To increase strength,
- To improve durability,
- To decrease permeability,
- To impart other properties.

Chemical admixtures should meet the requirements of ***ASTM C494, "Standard Specification for Chemical Admixtures for Concrete."***

2.2.6.2 Air-entraining Agents

- Air-entraining agents are probably the most commonly used admixtures.
- They cause the entrainment of air in the form of small dispersed bubbles in the concrete.
- Advantages
    - Improve workability and durability (chiefly resistance to freezing and thawing)
    - Reduce segregation during placing.
- Disadvantage

  Decrease concrete density because of the increased void ratio and thereby decrease strength; however, this decrease can be partially offset by a reduction of mixing water without loss of workability.
- The ***chief use of air-entrained concretes is in pavements***, but they are also used for structures, particularly for exposed elements.

2.2.6.3 Accelerating Admixtures

- Usage

  Are used to reduce setting time and accelerate early strength development.
- Composition
    - ***Calcium chloride*** is the most widely used accelerator because of its cost effectiveness, ***but it should not be used in prestressed concrete and should be used with caution in reinforced concrete in a moist environment, because of its tendency to promote corrosion of steel***.
    - Non-chloride, noncorrosive accelerating admixtures are available, the principal one being ***calcium nitrite***.

2.2.6.4 Set-retarding Admixtures

Usage

- Are used primarily to ***offset the accelerating effect of high ambient temperature*** and ***to keep the concrete workable during the entire placing period***. This helps to ***eliminate cracking due to form deflection***
- Also keeps concrete workable long enough that succeeding lifts can be placed without the development of ***"cold" joints***.

2.2.6.5 Plasticizers

- Usage

  Are used to ***reduce the water requirement of a concrete mix for a given slump***.
- Advantaged

  Reduction in water demand may result in
    - Either a reduction in the water-cement ratio for a given slump and cement content
    - Or an increase in slump for the same water-cement ratio and cement content.
- Working Principle

  Plasticizers work by ***reducing the inter-particle forces that exist between cement grains in the fresh paste***, thereby ***increasing the paste fluidity***.

2.2.6.6 Superplasticizers

- Usage
  - High-range water-reducing admixtures, or superplasticizers, are used to produce high-strength concrete with a very low water-cement ratio while maintaining the higher slumps needed for proper placement and compaction of the concrete.
  - They are also used to produce flowable concrete at conventional water-cement ratios.
- Difference between Superplasticizers and Conventional Water-reducing Admixture
  Superplasticizers differ from ***conventional water-reducing admixtures in that they do not act as retarders at high dosages; therefore, they can be used at higher dosage rates without severely slowing hydration***.

2.2.6.7 Self-consolidating Concrete, SCC

- Composition
  When superplasticizers are combined with ***viscosity-modifying admixtures***, they can be used to produce self-consolidating concrete (SCC).
- Usage
  - Self-consolidating concrete is highly fluid and does not require vibration to remove entrapped air.
  - The viscosity modifying agents allow the concrete to remain cohesive even with a very high degree of fluidity.
  - As a result, SCC ***can be used for members with congested reinforcement***, such as
    - ***Beam-column joints in earthquake-resistant structures***,
    - Precast concrete, especially precast prestressed concrete, a manufactured product.
- Disadvantage
  - The high fluidity of the mix, however, has been shown to have a ***negative impact on the bond strength*** between the concrete and prestressing steel located in the upper portions of a member, a shortcoming that should be considered in design but is not currently addressed in the ACI Code,
  - The composition of SCC mixtures may result in ***moduli of elasticity***, ***creep***, and ***shrinkage properties*** that ***differ*** from those of more ***traditional mixtures***.

2.2.6.8 Fly Ash and Silica Fume

- Composition and Basic Reaction
  Fly ash and silica fume are pozzolans, highly active silicas, that ***combine with calcium hydroxide***, $Ca(OH)_2$ the soluble product of cement hydration, to form more ***calcium silicate hydrate***, $3CaO.2SiO_2.3H_2O$, the insoluble product of cement hydration.
- Cement versus Cementitious Materials
  Pozzolans qualify as supplementary ***cementitious materials***, also referred to as mineral admixtures, which are used to replace a part of the portland cement in concrete mixes.
- Sustainable Issue
  - In sustainable development, ***the "cost" of concrete lies primarily in the manufacture of portland cement***.
  - The production of ***a ton of portland cement requires roughly the energy needed to operate a typical U.S. household for two weeks*** and ***generates approximately 0.9 ton of $C0_2$*** (a greenhouse gas). The latter ***translates to about 150 kg of $C0_2$ for every cubic yard of concrete that is placed***.
  - The energy and greenhouse gases involved in the production of concrete, however, ***can be viewed as investments because properly designed reinforced concrete structures that take advantage of concrete's thermal mass provide significant reductions in the energy and C02 needed for heating and cooling***, and concrete's inherent durability results in structures with long service lives.
  - Because by-products, such ***as the mineral admixtures fly ash and blast furnace slag, involve minimal energy usage or greenhouse gas production***, they have the potential ***to further improve the sustainability of concrete construction when used as a partial replacement for portland cement***.

2.3 CONCRETE, PHYSICAL ASPECTS

2.3.1 Properties in Compression

2.3.1.1 Short-term Loading

2.3.1.1.1 Important of Stress-Strain Relationship

Performance of a structure under load depends to a large degree on the stress-strain relationship of the material from which it is made, under the type of stress to which the material is subjected in the structure.

2.3.1.1.2 Compressive Stress-strain Curve

Since concrete is used mostly in compression, its compressive stress-strain curve is of primary interest.

2.3.1.1.3 How the Curve is Obtained?

Such a curve is obtained by

- Appropriate strain measurements in cylinder tests.

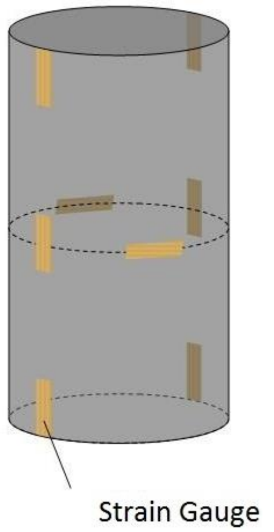


Figure 2.3-1: Stain measurement in cylindrical compression test.

- Appropriate strain measurements on the compression side in beams.

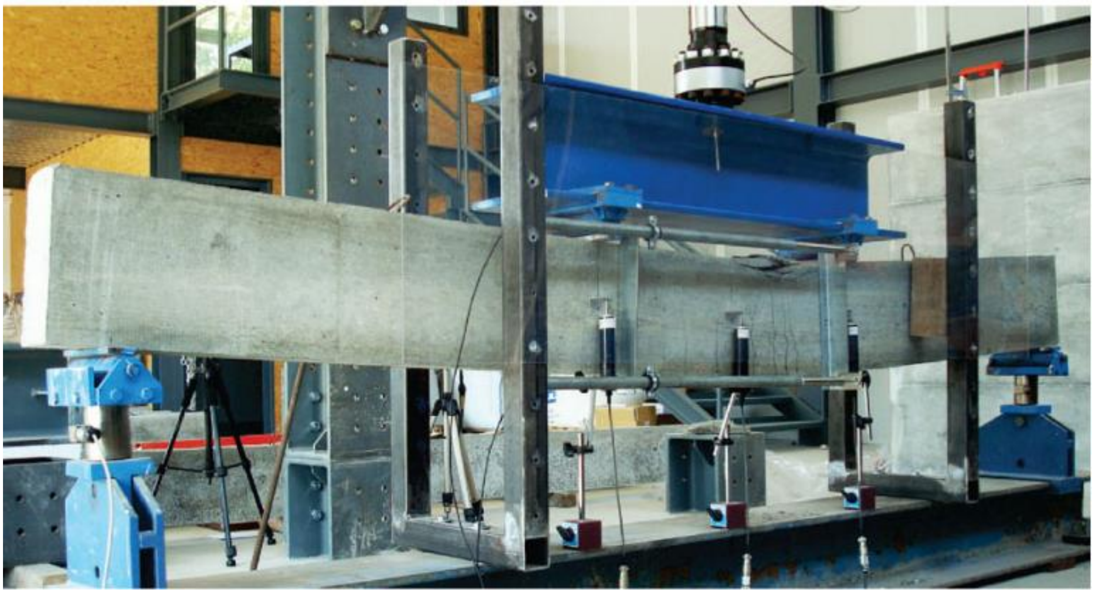


Figure 2.3-2: Stain measurement on beam compression side.

2.3.1.1.4 Typical Compression Stress-strain Diagram

- Figure 2.3-3 shows a typical set of such curves for normal-density concrete obtained from uniaxial compressive tests performed at normal, moderate testing speeds on concretes that are 28 days old.
- All of the curves have following similar character.
    - An initial relatively straight elastic portion in which stress and strain are closely proportional.
    - Curves reaching the maximum stress, i.e., the compressive strength, at a strain that ranges from about 0.002 to 0.003.

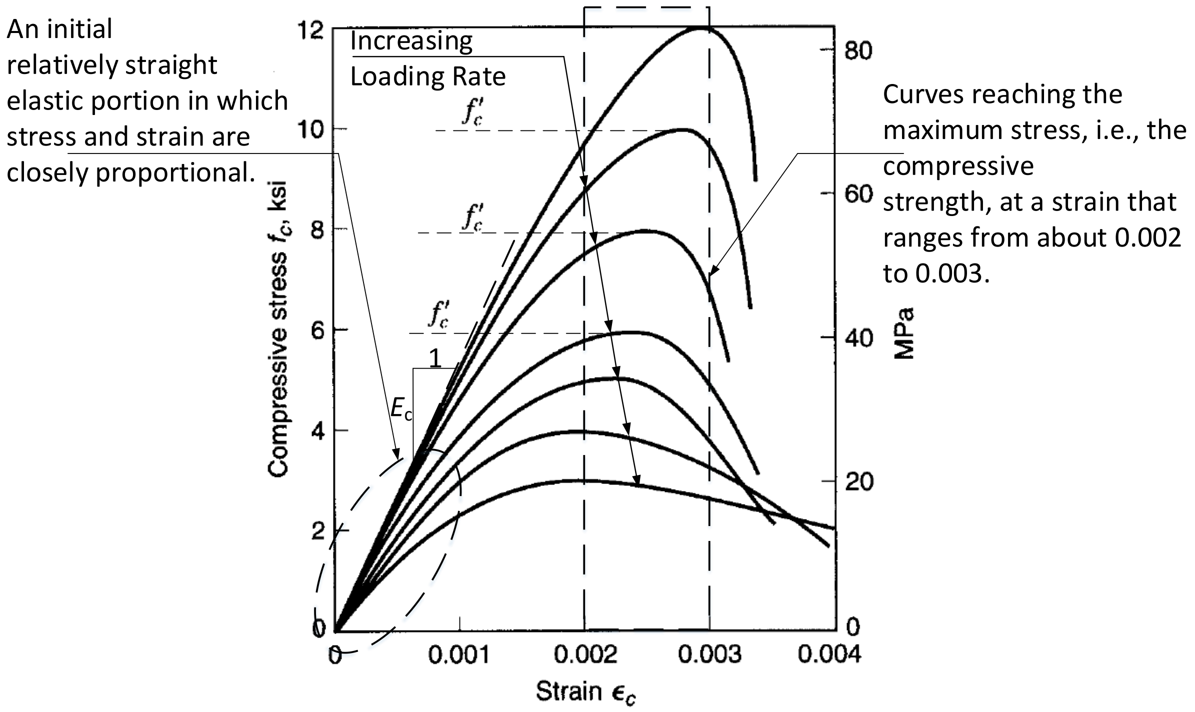


Figure 2.3-3: Typical compressive stress-strain curves for normal-density concrete with $w_c = 2300\ kg/m^3$.

2.3.1.1.5 The Modulus of Elasticity E_c

- The modulus of elasticity E_c (in MPa units), i.e., ***the slope of the initial straight portion of the stress-strain curve***, is seen to be larger as the strength of the concrete increases.
- According to (ACI318M, 2014), article 19.2.2, modulus of elasticity, E_c, for concrete can be estimated based on following correlation:
    - For values of w_c between 1440 and 2560 kg/m^3
      $E_c = w_c^{1.5} 0.043\sqrt{f_c'}\ (in\ MPa)$
    - For normalweight concrete
      $E_c = 4700\sqrt{f_c'}\ \ (in\ MPa)$

2.3.1.1.6 Poisson's Ratio

- When compressed in one direction, concrete, like other materials, expands in the direction transverse to that of the applied stress.
- The ratio of the transverse to the longitudinal strain is known as ***Poisson's ratio***.
- It depends somewhat on:
    - strength,
    - composition,
    - other factors.
- At ***stresses lower than about*** $0.7f_c'$, ***Poisson's ratio for concrete falls within the limits of 0.15 to 0.20***.

2.3.1.1.7 *Equations for Compressive Stress–Strain Diagrams of Concrete

2.3.1.1.7.1 Modified Hognestad Stress-strain Curve

- The ***modified Hognestad stress–strain curve,*** shown in ***Figure 2.3-4***, is a common representation of the stress–strain curve for concretes with strengths up to about 42 MPa is
- It consists of a second-degree parabola with apex at a strain of $1.8\, f_c'' / Ec$, where $f_c'' = 0.9 f_c'$, followed by a downward-sloping line terminating at a stress of $0.85\, f_c''$ and a limiting strain of 0.0038.
- The equation given in ***Figure 2.3-4*** describes a second-order parabola with its apex at the strain ϵ_o.
- The reduced strength, $f_c'' = 0.9 f_c'$ accounts for the ***differences between cylinder strength and member strength***. These differences result from:
  - Different curing and placing, which give rise to different water-gain effects due to vertical migration of bleed water.
  - Differences between the strengths of rapidly loaded cylinders and the strength of the same concrete loaded more slowly.

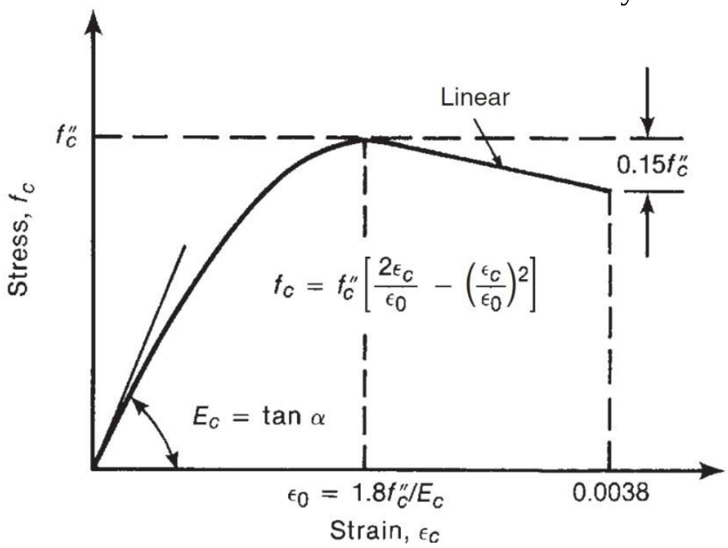


Figure 2.3-4: Modified Hognestad analytical approximations to the compressive stress–strain curve for concrete.

2.3.1.1.7.2 Todeschini Stress–strain Curve

- The Todeschini stress–strain curve presented in ***Figure 2.3-5*** is ***convenient for use in analytical studies*** involving concrete strengths up to about 35 MPa because ***the entire stress–strain curve is given by one continuous function***.
- The highest point in the curve, f_c'' , is taken to equal $0.9 f_c'$ to give stress-block properties similar to that of the rectangular stress block of ***Chapter 4*** when $\epsilon_u = 0.003$ for f_c' up to $35\ MPa.$
- The strain ϵ_0, corresponding to maximum stress, is taken as $\epsilon_0 = \frac{1.71 f_c'}{E_c}$
- For any given strain ϵ, $x = \epsilon/\epsilon_0$, the stress corresponding to that strain is $f_c = \frac{2 f_c'' x}{1+x^2}$

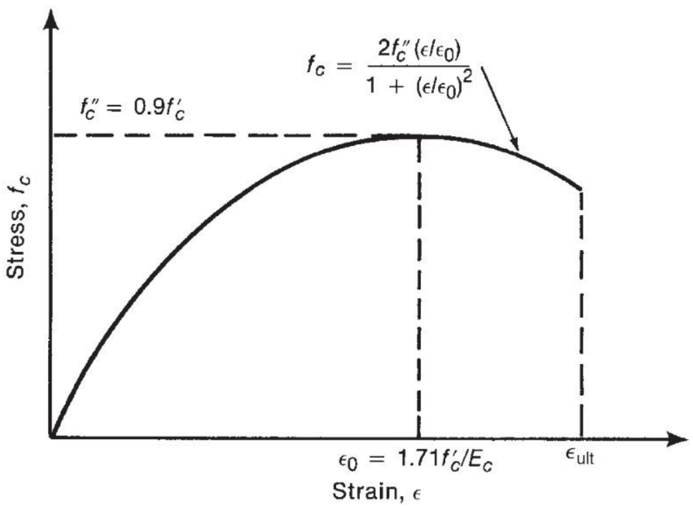


Figure 2.3-5: Todeschini analytical approximations to the compressive stress–strain curve for concrete.

Example 2.3-1

Writ to draw the modified Hognestad approximate stress-strain diagram for a concrete with $f_c' = 28\ MPa$.

Solution

Matlab code is presented in ***Table 2.3-1*** the resulting curve is indicated in ***Figure 2.3-6***.

Table 2.3-1: Matlab code to draw modified Hognestad approximated stress-strain diagram of Example 2.3-1.

```
%
% Matlab code to generate data and darw compressive
% stress-strain of concrete approximated according to
% Modified Hognestad model
%
clc
% Input of Concrete Data
%-------------------------------
fcp =28                   % Concrete cylinderical compressive strength in MPa.
Ec =4700*(fcp)^0.5        % Concrete elastic modulus according to ACI relation.
%
% Model Parameters
%
fcpp = 0.9*fcp            % Member compressive strength to reflect diffrent curing and different loading rate.
ep0 = 1.8*fcpp/Ec         % Concrete strain where stress is reached its maximum value and curved part are ended.
epu = 0.0038              % Ultimate strain where concrete is compeletly crushed.
%
% Stress-strain vectors for curved part
%------------------------------------------------
eps1= 0:0.1*ep0:ep0
fc1 = fcpp.*((2.*eps1./ep0)-(eps1./ep0).^2)
%
% Stress-strain vectors for straight part
%------------------------------------------------
eps2 = [ep0 epu]
fc2 = [fcpp 0.85*fcpp]
%
% Final stress and strain curves
%-------------------------------------
eps = [eps1 eps2]
fc=[fc1 fc2]
%
% Ploting of the curve
%----------------------
plot(eps, fc, '--k*', 'linewidth',2,'markersize',12)
% Formating of x-axis
Xmin = min(eps)
Xmax = max(eps)
xlim([Xmin Xmax])
XR = Xmax-Xmin
xlabel('Concrete strain \epsilon', 'FontSize',14)
% Formating of y-axis
Ymin = min(fc)
Ymax = max(fc)
ylim([Ymin Ymax])
ylabel(' Concrete Stress, f, in MPa', 'FontSize',14)
% Formating Grid
YR = Ymax-Ymin
X_grid=[Xmin:0.1*XR:Xmax]
Y_grid = [Ymin:0.1*YR:Ymax]
set(gca,'XTick',X_grid, 'YTick',Y_grid);
grid
```

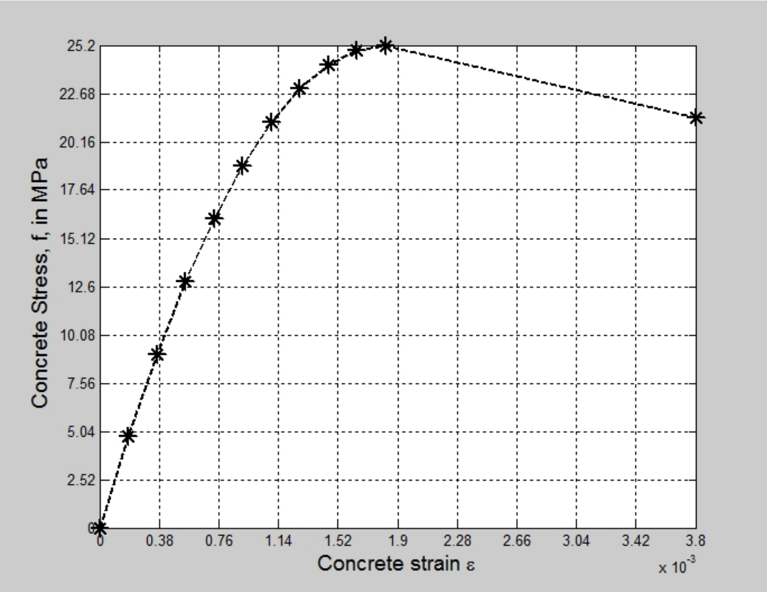


Figure 2.3-6: Modified Hognestad analytical approximations to the compressive stress–strain curve for concrete with f'_c of 28 MPa.

Example 2.3-2

Resolve ***Example 2.3-1*** above but with using of Todeschini stress-strain curve instead of Modified Hognestad curve.

Solution

Matlab code is presented in ***Table 2.3-2*** the resulting curve is indicated in ***Figure 2.3-7***.

Table 2.3-2: Matlab code to draw Todeschini approximated stress-strain diagram of Example 2.3-2.

```
%
% Matlab code to generate data and darw compressive
% stress-strain of concrete approximated according to
% Todeschini model
%
clc
% Input of Concrete Data
%------------------------------
fcp =28                 % Concrete cylinderical compressive strength in MPa.
Ec =4700*(fcp)^0.5      % Concrete elastic modulus according to ACI relation.
%
% Model Parameters
%
fcpp = 0.9*fcp          % Member compressive strength to give stress-block properties similar to that of the rectangular stress block.
ep0 = 1.71*fcp/Ec       % Concrete strain where stress is reached its maximum value.
epu = 0.0030            % Ultimate strain where concrete is compeletly crushed.
%
% Stress-strain vectors
%------------------------------------------------
eps= 0:0.05*epu:epu
fc = (2*fcpp.*(eps./ep0))./(1+(eps/ep0).^2)
%
%
% Ploting of the curve
%-----------------------
plot(eps, fc, '--k*', 'linewidth',2,'markersize',12)
% Formating of x-axis
Xmin = min(eps)
Xmax = max(eps)
xlim([Xmin Xmax])
XR = Xmax-Xmin
xlabel('Concrete strain \epsilon', 'FontSize',14)
% Formating of y-axis
Ymin = min(fc)
Ymax = max(fc)
ylim([Ymin Ymax])
ylabel(' Concrete Stress, f, in MPa', 'FontSize',14)
% Formating Grid
YR = Ymax-Ymin
X_grid=[Xmin:0.1*XR:Xmax]
Y_grid = [Ymin:0.1*YR:Ymax]
set(gca,'XTick',X_grid, 'YTick',Y_grid);
grid
```

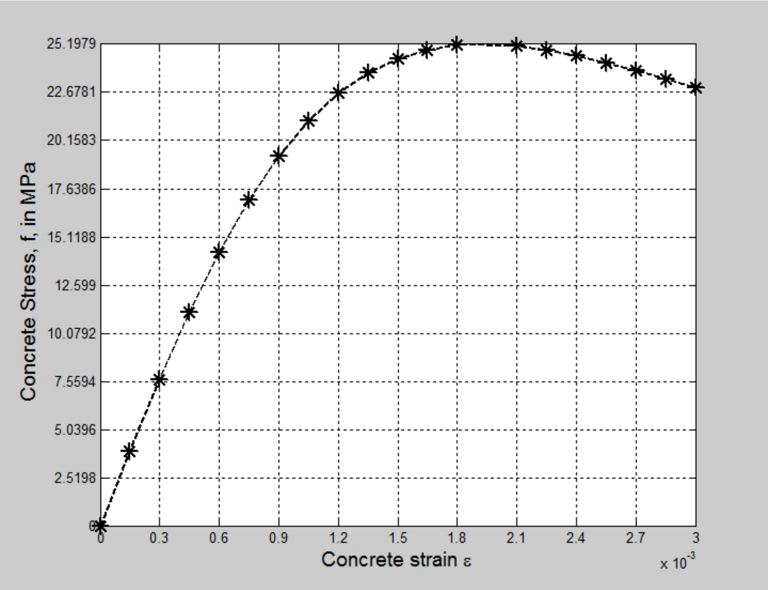


Figure 2.3-7: Todeschini analytical approximations to the compressive stress–strain curve for concrete with f'_c of 28 MPa.

2.3.1.2 Long-Term Loading

2.3.1.2.1 Steel versus Concrete

- In some engineering materials, such as ***steel***, strength and the stress-strain relationships are independent of rate and duration of loading, at least within the usual ranges of rate of stress, temperature, and other variables.
- In contrast, Figure 2.3-3 illustrates the fact that the influence of time, in this case of rate of loading, on the behavior of concrete under load is pronounced.
- The main reason is that concrete ***creeps*** under load, while steel does not exhibit creep under conditions prevailing in buildings, bridges, and similar structures.

2.3.1.2.2 Concrete Creep

- Creep ***is the slow deformation of a material over considerable lengths of time at constant stress or load***.
- The nature of the creep process is shown schematically in Figure 2.3-8.
    - This particular concrete was loaded after 28 days with resulting instantaneous strain ϵ_{inst}.
    - The load was then maintained for 230 days, during which time creep was seen to have increased the total deformation to almost 3 times its instantaneous value.
    - If the load were maintained, the deformation would follow the solid curve.
    - If the load is removed, as shown by the dashed curve, most of the elastic instantaneous strain ϵ_{inst} is recovered, and some creep recovery is seen to occur.
    - If the concrete is reloaded at some later date, instantaneous and creep deformations develop again, as shown.

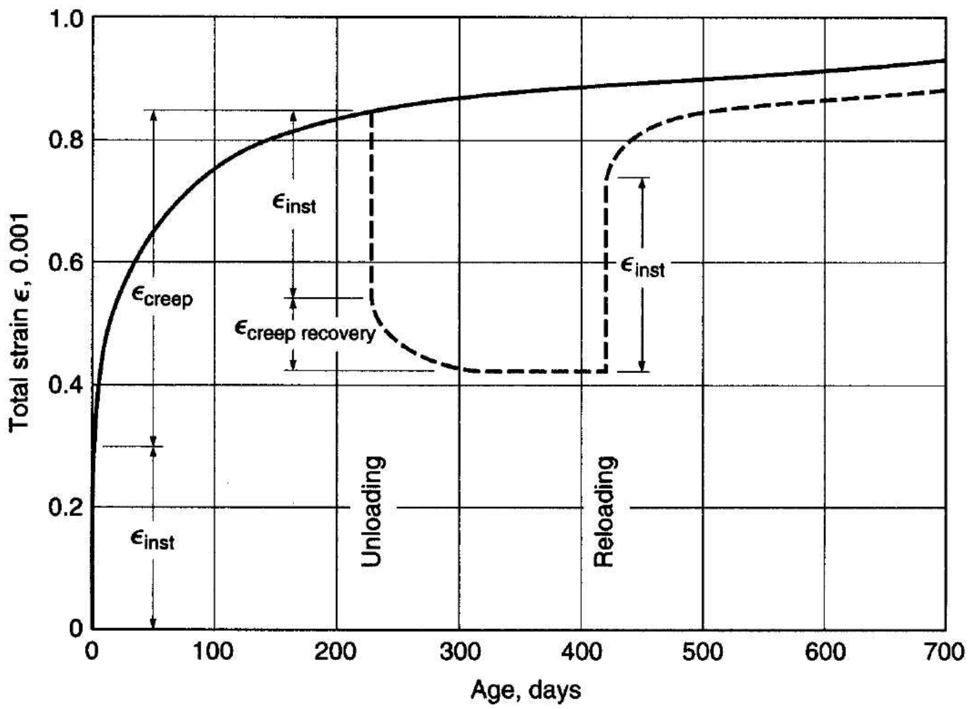


Figure 2.3-8: Typical creep curve (concrete loaded to 4.1MPa at age 28 days).

- Factor Affecting Concrete Creep
  Creep deformations for a given concrete are practically proportional:
    - To the magnitude of the applied stress;
    - To ratio of stress to compressive strength, high-strength concretes show less creep than lower-strength concretes.
    - creep depends on the average ***ambient relative humidity***, being more than ***twice*** as ***large for 50 percent as for 100 percent humidity***. This is so ***because part of the reduction in volume under sustained load is caused by outward migration of free pore water, which evaporates into the surrounding atmosphere***.
    - Other factors of importance include
        - The type of cement and aggregate,
        - age of the concrete when first loaded,
        - concrete strength.

- Creep Progress Rate
  As seen in Figure 2.3-8, with elapsing time, creep proceeds at a decreasing rate and ceases after ***2 to 5 years*** at a final value which, depending on concrete strength and other factors,
- Final Creep versus Instantaneous Strain
  Final creep is about 1.2 to 3 times the magnitude of the instantaneous strain.
- Creep versus Loading Rate
  - If, instead of being applied quickly and thereafter kept constant, the load is increased slowly and gradually, as is the case in many structures during and after construction, then instantaneous and creep deformations proceed simultaneously.
  - The effect is shown in Figure 2.3-3; i.e., the previously discussed difference in the shape of the stress-strain curve for various rates of loading is chiefly the result of the creep deformation of concrete.
- Creep Coefficient
  - For ***stresses not exceeding about one-half the cylinder strength, creep strains are approximately proportional to stress***.
  - Because ***initial elastic strains are also proportional to stress in this range***, this permits definition of the ***creep coefficient***
    $$C_{cu} = \frac{\epsilon_{cu}}{\epsilon_{ci}}$$
    where ϵ_{cu} is the final asymptotic value of the additional creep strain and ϵ_{ci} is the initial, instantaneous strain when the load is first applied.
- Specific Creep
  Creep may also be expressed in terms of the ***specific creep*** δ_{cu} defined as the additional time-dependent strain per MPa stress. It can easily be shown that,
  $$C_{cu} = E_c\delta_{cu}$$
- Typical Values for Creep Coefficient, C_{cu}, and Specific Creep, δ_{cu}:
  The values of Table 2.3-3, are typical values for ***average humidity conditions***, for ***concretes loaded at the age of 7 days***.

Table 2.3-3: Typical creep parameters

Compressive Strength		Specific Creep δ_{cu}		
psi	MPa	10^{-6} per psi	10^{-6} per MPa	Creep coefficient C_{cu}
3,000	21	1.00	145	3.1
4,000	28	0.80	116	2.9
6,000	41	0.55	80	2.4
8,000	55	0.40	58	2.0
10,000	69	0.28	41	1.6
12,000	83	0.22	33	1.4

Example 2.3-3

What is the final creep deformation for a concrete column with $f_c' = 28\ MPa$ and with length of 6m when subject to a longtime load that causes sustained stress of 8MPa?

Solution

From Table 2.3-3 above,

Compressive Strength		Specific Creep δ_{cu}		
psi	MPa	10^{-6} per psi	10^{-6} per MPa	Creep coefficient C_{cu}
3,000	21	1.00	145	3.1
4,000	28	0.80	116	2.9
6,000	41	0.55	80	2.4
8,000	55	0.40	58	2.0
10,000	69	0.28	41	1.6
12,000	83	0.22	33	1.4

$$\delta_{cu} = 116 \times 10^{-6}\ strain\ per\ each\ 1.0\ MPa$$

For long-term stress of 8MPa, creep strain would be,

$$\epsilon_{cu} = 116 \times 10^{-6} \times 8 = 0.000928$$

With length of 6m, final creep deformation would be,

$\Delta_{Creep} = \epsilon_{cu} L = \ 0.000928 \times 6000 \approx 6\ mm$ ■

- Creep Coefficient

  The creep coefficient at any time C_{ct} can be related to the ultimate creep coefficient C_{cu} can be estimated based on following relation,

  $$C_{ct} = \frac{t^{0.6}}{10 + t^{0.6}} C_{cu}$$

  where t = time in days after loading.

Example 2.3-4

For the column of Example 2.3-4, what is the creep shorting after 1 year of loading?

Solution

$$C_{ct} = \frac{t^{0.6}}{10 + t^{0.6}} C_{cu} = \frac{360^{0.6}}{10 + 360^{0.6}} C_{cu} = 0.77 C_{cu}$$

$\Delta_{creep\ after\ 1\ year} = 0.77 \times 6 = 4.6\ mm$ ■

- Concrete Compressive Strength versus Sustained Loads
  - Sustained loads affect not only the deformation but also the strength of concrete.
  - Based on experimental works, it has been shown that, for concentrically loaded unreinforced concrete prisms and cylinders, the strength under sustained load is ***significantly smaller than*** f_c', ***on the order of 75 percent off; for loads maintained for a year or more***.
  - Thus, ***a member subjected to a sustained overload causing compressive stress of over 75 percent off; may fail after a period of time, even though the load is not increased***.

2.3.1.2.3 Fatigue

- Fatigue is a phenomena noted in all materials:

  When concrete is subject to fluctuating rather than sustained loading, its fatigue strength, ***as for all other materials***, ***is considerably smaller than its static strength***.
- Order of Fatigue Strength for Plain Concrete:

  When plain concrete in compression is ***stressed cyclically from zero to maximum stress***, ***its fatigue limit is from 50 to 60 percent of the static compressive strength, for 2,000,000 cycles***.

2.3.2 Properties in Tension

2.3.2.1 Importance of Concrete Behavior in Tension

While concrete is ***best employed in a manner that uses its favorable compressive strength***, its ***behavior in tension is also important***.

- o The ***conditions under which cracks form and propagate on the tension side of reinforced concrete flexural members depend strongly on both the tensile strength and the fracture properties of the concrete***, the latter dealing with the ease with which a crack progresses once it has formed.
- o Concrete ***tensile stresses also occur as a result of shear, torsion, and other actions***, and in most cases member behavior changes upon cracking.

2.3.2.2 Predication of Concrete Tensile Strength

- Currently, one of the following three methods can be used to estimate concrete tensile strength.
- The ***results of all types of tensile tests show considerably more scatter than those of compression tests***.

2.3.2.2.1 Direct Tension Tests, f_t'

- Samples of concrete direct tension specimen are presented in Figures below.
- Main Drawbacks of Direct Tension Test:
  In direct tension tests, ***minor misalignments*** and ***stress concentrations*** in the gripping devices are apt to mar the results.

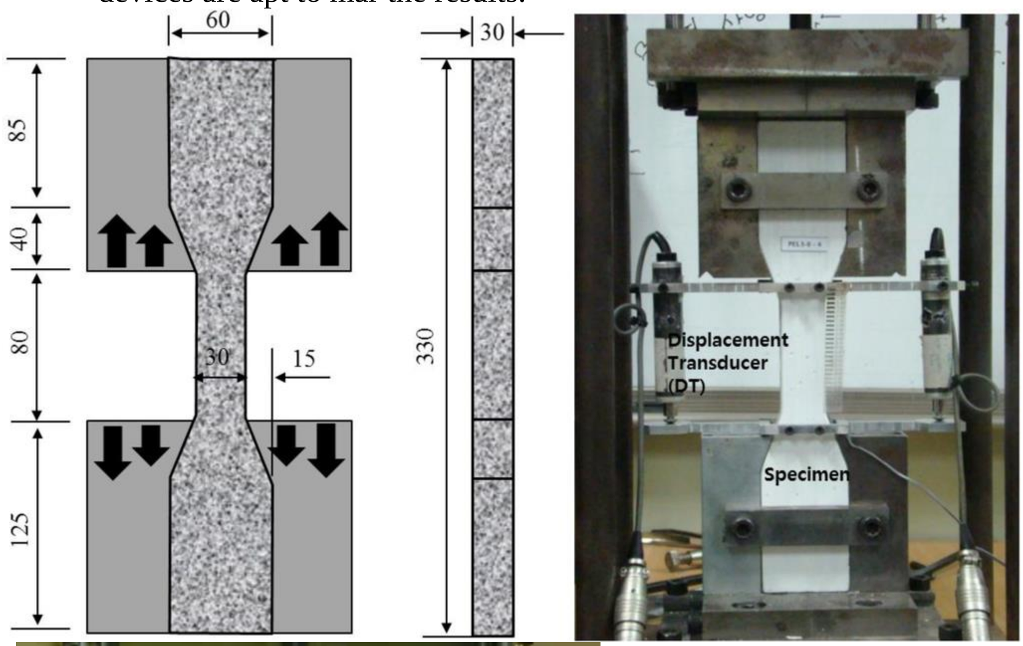


Figure 2.3-9: Samples of concrete direct tension specimen (1).

Figure 2.3-10: Samples of concrete direct tension specimen (2).

Figure 2.3-11: Samples of concrete direct tension specimen (3).

- Direct tension concrete tensile strength, $f_t{}'$, can be estimated from following correlation with concrete compressive strength, $f_c{}'$,

  $f_t' = 0.25\ to\ 0.58\sqrt{f_c{}'}$

2.3.2.2.2 Modulus of Rupture, f_r

- For many years, tensile strength has been measured in terms of the ***modulus of rupture***, f_r.
- In ***modulus of rupture test,*** a plain concrete beam, generally $\mathbf{150 \times 150 \times 750}\boldsymbol{mm}$ long, is loaded in flexure at the third points of a 600mm span until it fails due to cracking on the tension face, see Figure 2.3-12 below.
- The flexural tensile strength or modulus of rupture, from a modulus-of-rupture test is calculated from the following equation, assuming a linear distribution of stress and strain:

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

  where

  M is moment

  b is width of specimen

  h is overall depth of specimen

Figure 2.3-12: Modulus of rupture for concrete tensile strength.

- Main Drawback of Modulus of Rupture:
  - Because the f_r is computed on ***the assumption that concrete is an elastic material***, and because ***this bending stress is localized at the outermost surface***, ***it is apt to be larger than the strength of concrete in uniform axial tension***.
  - It is thus a measure of, but not identical with, the real axial tensile strength.
- According to (ACI318M, 2014), article 19.2.3, modulus of rupture, f_r, for concrete can be estimated based on following correlation with concrete compressive strength:

$f_r = 0.62\lambda\sqrt{f_c'}$

The lightweight concrete modification factor λ can be estimated from Table 2.3-4 below:

Table 2.3-4: Modification factor λ, Table 19.2.4.2 of the (ACI318M, 2014).

Concrete	Composition of aggregates	λ
All-lightweight	Fine: ASTM C330M Coarse: ASTM C330M	0.75
Lightweight, fine blend	Fine: Combination of ASTM C330M and C33M Coarse: ASTM C330M	0.75 to 0.85[1]
Sand-lightweight	Fine: ASTM C33M Coarse: ASTM C330M	0.85
Sand-lightweight, coarse blend	Fine: ASTM C33M Coarse: Combination of ASTM C330M and C33M	0.85 to 1[2]
Normalweight	Fine: ASTM C33M Coarse: ASTM C33M	1

[1]Linear interpolation from 0.75 to 0.85 is permitted based on the absolute volume of normalweight fine aggregate as a fraction of the total absolute volume of fine aggregate.

[2]Linear interpolation from 0.85 to 1 is permitted based on the absolute volume of normalweight coarse aggregate as a fraction of the total absolute volume of coarse aggregate.

2.3.2.2.3 Split-cylinder Test, f_{ct}

- More recently the result of the split-cylinder test has established itself as a measure of the tensile strength of concrete.
- A concrete cylinder, the same as is used for compressive tests, is inserted in a compression-testing machine in the horizontal position, so that compression is applied uniformly along two opposite generators. Pads are inserted between the compression platens of the machine and the cylinder to equalize and distribute the pressure.

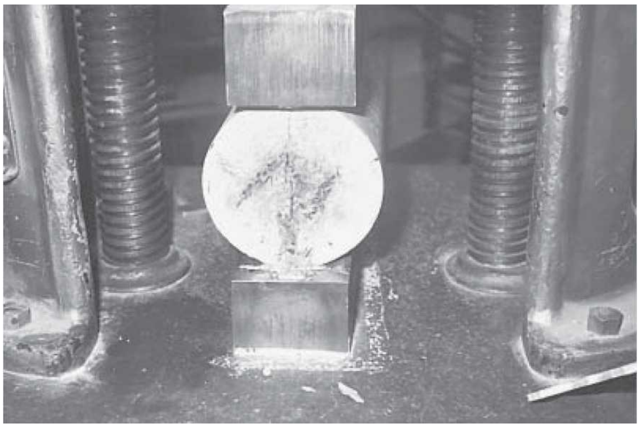
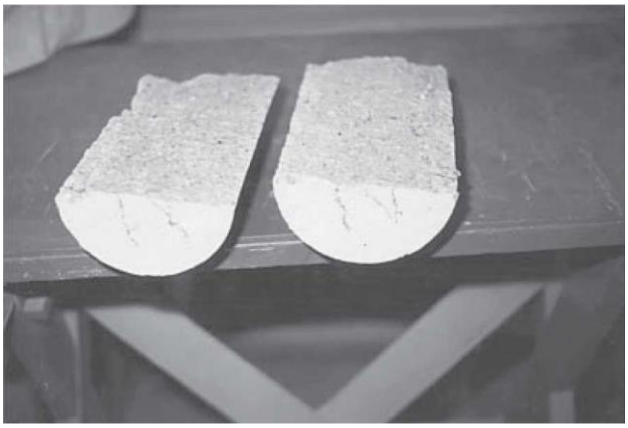



Figure 2.3-13: Concrete cylinder splitting test.

- It can be shown that in an elastic cylinder so loaded, a nearly uniform tensile stress of magnitude, see Figure 2.3-14 below,

  $f_{ct} = \sigma_1 = \frac{2P}{\pi dL}$
- Because of ***local stress conditions at the load lines and the presence of stresses at right angles to the aforementioned tension stresses***, the results of the split-cylinder tests likewise are not identical with (***but are believed to be a good measure of***) the true axial tensile strength.
- Split-cylinder strength, f_{ct}, can be estimated based on following relation with cylindrical compressive strength:

  $f_{ct} = 0.5\ to\ 0.66\sqrt{f_c'}$

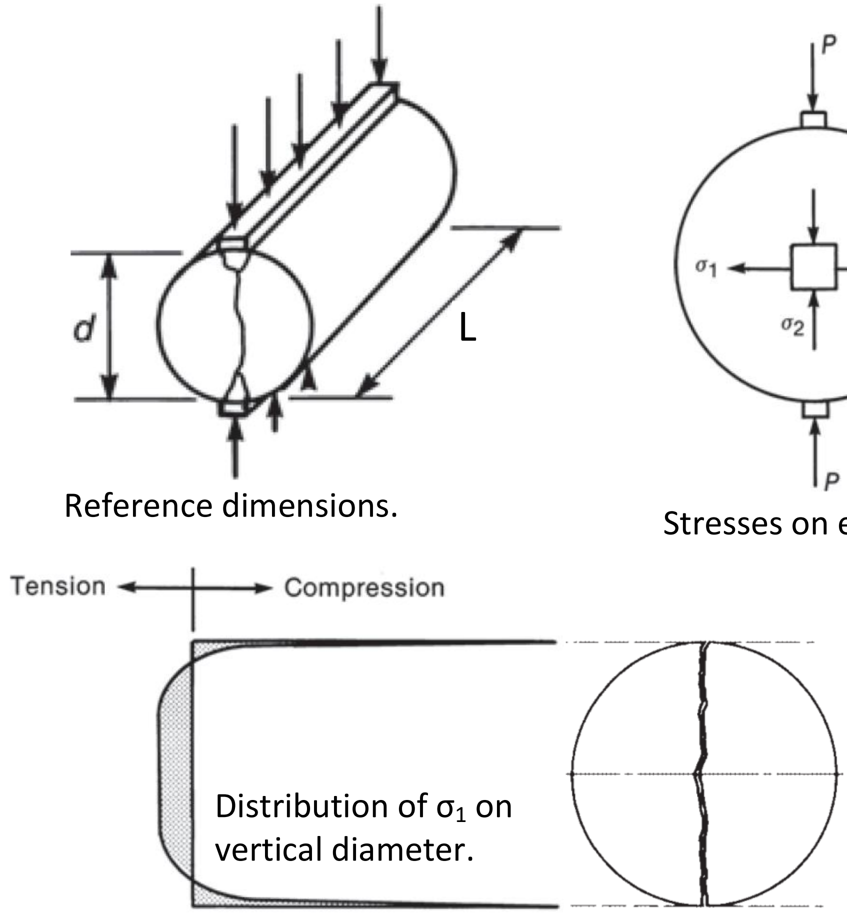
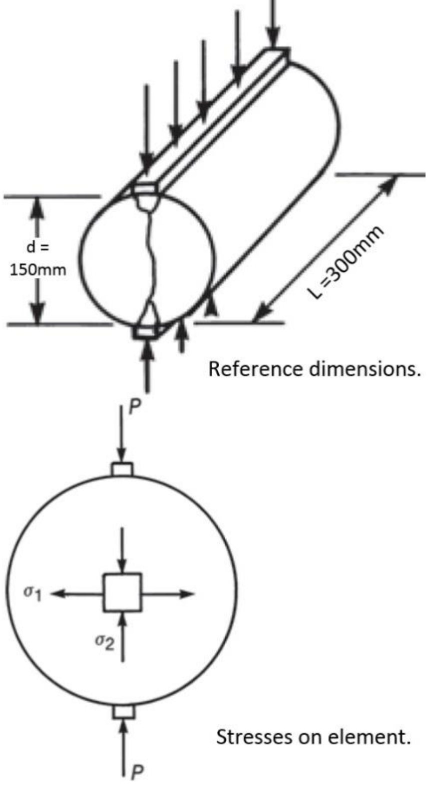


Figure 2.3-14: Stresses in splitting cylinder test.

Example 2.3-5

Use a conservative correlation to estimate the splitting tensile strength, f_{ct}, for a concrete that has a compressive strength, f_c', of 30 MPa. Then use the determined f_{ct} to estimate the force P that should be applied in an actual splitting test.

Figure 2.3-15: Concrete cylinder splitting test.



Solution

Split-cylinder strength, f_{ct}, can be estimated based on following relation with cylindrical compressive strength:

$f_{ct} = 0.5\ to\ 0.66\sqrt{f_c'}$

A conservative value of

$$f_{ct} = 0.5\sqrt{f_c'} = 0.5 \times \sqrt{30} = 2.74\ MPa$$

to be adopted according to the problem statement.

It can be shown that in an elastic cylinder so loaded, a nearly uniform tensile stress of magnitude:

$$f_{ct} = \sigma_1 = \frac{2P}{\pi d L} \Rightarrow 2.74 = \frac{2 \times P}{\pi \times 150 \times 300}$$

Solve for P:

$$P = 193679\ N = 194\ kN$$

Example 2.3-6

Use a suitable correlation to estimate the modulus of rapture, f_r, for concrete that has a compressive strength, f_c', of 30 MPa. Then use the determined f_r to estimate the force P that should be applied in an actual test for a beam specimen indicated in Figure 2.3-16 that has a cross-section of 100x200mm.

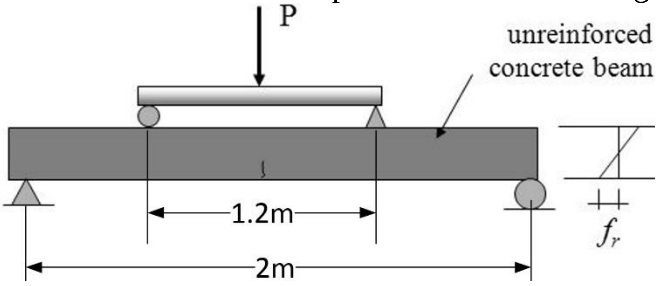


Figure 2.3-16: Concrete specimen for modulus of rapture.

Solution

According to (ACI318M, 2014), Article 19.2.3, modulus of rupture, f_r, for concrete can be estimated based on following correlation with concrete compressive strength:

$$f_r = 0.62\lambda\sqrt{f_c'} = 0.62 \times 1.0 \times \sqrt{30} \approx 3.4\ MPa \blacksquare$$

According to traditional flexural formula, the modulus of rapture, f_r, is related to sectional moment, M, as follows:

$$f_r = \frac{6M}{bh^2} \Rightarrow 3.4 = \frac{6M}{100 \times 200^2} \Rightarrow M = 2266667\ N.mm \Rightarrow M = 2.27\ kN.m$$

Finally, based on simple statics, the applied force, P, can be related to the sectional moment, M, as follows:

$$M = \frac{P}{2} \times a \Rightarrow 2.27 = \frac{P}{2} \times (2 - 1.2) \times \frac{1}{2} \Rightarrow P = 11.4\ kN \blacksquare$$

2.4 REINFORCING STEELS FOR CONCRETE

2.4.1 Joint Performance of Steel and Concrete

- The two materials, concrete and reinforcement, are best used in combination if the ***concrete is made to resist the compressive stresses*** and ***the steel the tensile stresses***.
- Flexure
  In reinforced concrete beams, the concrete resists the compressive force, longitudinal steel reinforcing bars are located close to the tension face to resist the tension force.

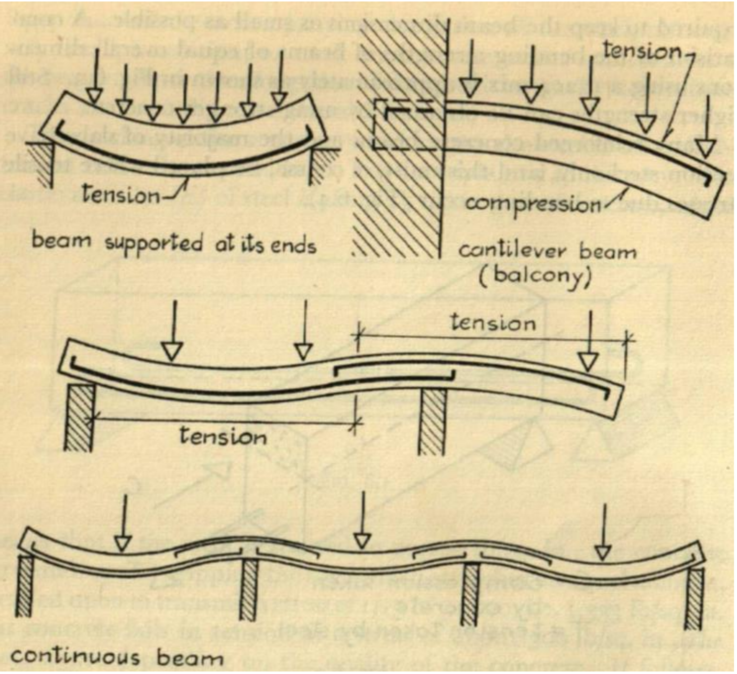


Figure 2.4-1: Reinforcement role in flexure resistance.

- Shear
  Usually additional steel bars are used to resist the inclined tension stresses that are caused by the shear force in the beams.

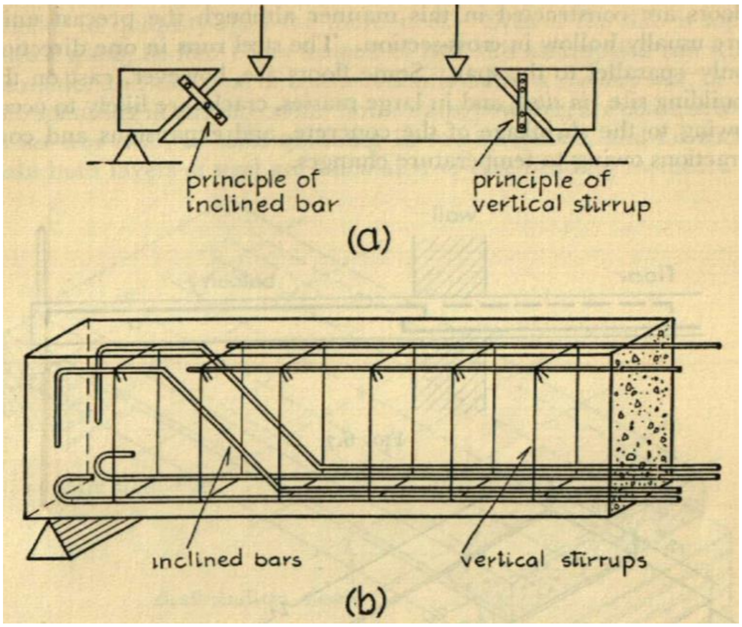


Figure 2.4-2: Reinforcement role in shear resistance.

- Columns
    - However, reinforcement is also used for ***resisting compressive forces primarily where it is desired to reduce the cross-sectional dimensions of compression members***, as in the lower-floor columns of multistory buildings.
    - Even in axially compressed member, ***a minimum amount of reinforcement is placed in all compression members to safeguard them against the effects of small accidental bending moments that might crack and even fail an unreinforced member***.

2.4.2 Additional Notes on Joint Performance of Steel and Concrete

Additional features that make for the satisfactory joint performance of steel and concrete are the following:

- The ***thermal expansion*** coefficients of the two materials, about 11.7×10^{-6} for steel vs. an average of 9.9×10^{-6} for concrete, are sufficiently close to forestall cracking and other undesirable effects of differential thermal deformations.
- While the ***corrosion resistance*** of bare steel is poor, the concrete that surrounds the steel reinforcement provides excellent corrosion protection, minimizing corrosion problems and corresponding maintenance costs.
- The ***fire resistance*** of unprotected steel is impaired by its high thermal conductivity and by the fact that its strength decreases sizably at high temperatures. Conversely, the thermal conductivity of concrete is relatively low. Thus, damage caused by even prolonged fire exposure, if any, is generally limited to the outer layer of concrete, and a moderate amount of concrete cover provides sufficient thermal insulation for the embedded reinforcement.

2.4.3 Reinforcing Bars

- Typical Bars[1]:
  The most common type of reinforcing steel (as distinct from prestressing steel) is in the form of round bars, often called ***rebars***, available in a large range of diameters from about 10 to 36 mm for ordinary applications and in two heavy bar sizes of about 43 and 57mm, see Table 2.4-1.
- Bar Deformed Surface:
    - These bars are furnished with surface deformations for the purpose of ***increasing resistance to slip between steel and concrete***.
    - Minimum requirements for these deformations (spacing, projection, etc.) have been developed in experimental research.
    - Different bar producers use different patterns, all of which satisfy these requirements. Figure 2.4-3 shows a variety of current types of deformations.
- Designation by Number:
    - For many years, bar sizes have been designated by numbers, Nos. 10 to 36 being commonly used and Nos. 43 and 57 representing the two special large-sized bars previously mentioned.
    - Designation by number, instead of by diameter, ***was introduced because the surface deformations make it impossible to define a single easily measured value of the diameter***.

---

[1] A "***soft conversion***" involves changing a measurement from inch-pound units to equivalent metric units within what the DoD calls "***acceptable measurement tolerances***." This is done to merely convert the imperial measurements to metric without physically changing the item, and it is typically used to specify a requirement. For example, a ½-in. rebar diameter would be converted to either 12.7 or 13 mm using soft conversion. Although this is not a standard metric rebar size, it expresses the requirement.

A "***hard conversion***" involves a change in measurement units that results in a "physical configuration change." Using the rebar example, this would be analogous to changing the diameter of the rebar from ½ in. to an M12 (12-mm) or M14 (14-mm) rebar diameter. Either one of the two new metric rebar diameters would be outside an "***acceptable measurement tolerance***". The new rebar would be considered a "***hard metric***" item. This is size substitution, which is one method of using hard conversion; the other method is adaptive conversion, where imperial and metric units are reasonably equivalent, but not exact conversions of each other.

Table 2.4-1: ASTM STANDARD REINFORCING BARS

Bar size, no.*	Nominal diameter, mm	Nominal area, mm^2	Nominal mass, kg/m
10	9.5	71	0.560
13	12.7	129	0.994
16	15.9	199	1.552
19	19.1	284	2.235
22	22.2	387	3.042
25	25.4	510	3.973
29	28.7	645	5.060
32	32.3	819	6.404
36	35.8	1006	7.907
43	43.0	1452	11.38
57	57.3	2581	20.24

*Bar numbers approximate the number of millimeters of the nominal diameter of the bar.

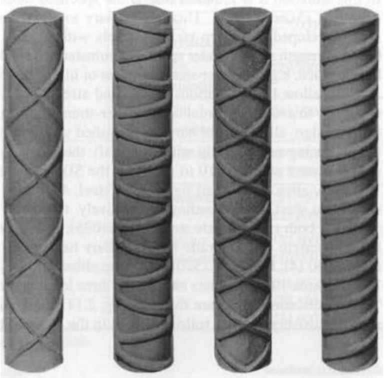


Figure 2.4-3: Types of deformed reinforcing bars.

2.4.4 Grades and Strengths

- Trend toward higher-strength materials:
  In reinforced concrete, a long-term trend is evident toward the use of higher-strength materials, both steel and concrete. Reinforcing bars with 280 MPa yield stress, Grade 40, once standard, have largely been replaced by bars with 420 MPa yield stress, Grade 60, both because:
  - They are more economical,
  - Their use tends to reduce steel congestion in the forms.
- Grads proposed for columns:
  - Bars with a yield stress of 520 MPa are often used in columns,
  - Bars with a yield stress of 690 MPa are allowed to be used as confining reinforcement.
- Table 2.4-2 lists all presently available reinforcing steels, their grade designations, the ASTM specifications that define their properties (including deformations) in detail, and their two main minimum specified strength values.
- Conversion between from US Customary to SI Unit System:

US Customary Unit System	SI Unit System
Grade 40	Grade 280
Grade 60	Grade 420
Grade 75	Grade 520
Grade 100	Grade 690

- Weldability of Rebars:
  - Welding of reinforcing bars;
    - In making splices,
    - Or for convenience in ***fabricating reinforcing cages*** for placement in the forms,

may result in ***metallurgical changes*** that ***reduce both strength and ductility***, and special restrictions must be placed both on the type of steel used and the welding procedures.

- The provisions of ***ASTM A 706*** relate specifically to welding.

Table 2.4-2: Summary of minimum ASTM strength requirements.

Product	ASTM Specification	Designation	Minimum Yield Strength, psi (MPa)	Minimum Tensile Strength, psi (MPa)
Reinforcing bars	A615	Grade 40 Grade 60 Grade 75	40,000 (280) 60,000 (420) 75,000 (520)	60,000 (420) 90,000 (620) 100,000 (690)
	A706	Grade 60	60,000 (420) [78,000 (540) maximum]	80,000 (550)[a]
	A996	Grade 40 Grade 50 Grade 60	40,000 (280) 50,000 (350) 60,000 (420)	60,000 (420) 80,000 (550) 90,000 (620)
	A1035	Grade 100	100,000 (690)	150,000 (1030)
Deformed bar mats	A184	Same as reinforcing bars		
Zinc-coated bars	A767	Same as reinforcing bars		
Epoxy-coated bars	A775, A934	Same as reinforcing bars		
Stainless-steel bars[b]	A955	Same as reinforcing bars		
Wire Plain	A82		70,000 (480)	80,000 (550)
Deformed	A496		75,000 (515)	85,000 (585)
Welded wire reinforcement Plain W1.2 and larger Smaller than W1.2	A185		 65,000 (450) 56,000 (385)	 75,000 (515) 70,000 (485)
Deformed	A497		70,000 (480)	80,000 (550)
Prestressing tendons Seven-wire strand	A416	Grade 250 (stress-relieved)	212,500 (1465)	250,000 (1725)
		Grade 250 (low-relaxation)	225,000 (1555)	250,000 (1725)
		Grade 270 (stress-relieved)	229,500 (1580)	270,000 (1860)
		Grade 270 (low-relaxation)	243,000 (1675)	270,000 (1860)
Wire	A421	Stress-relieved	199,750 (1375) to 212,500 (1465)[c]	235,000 (1620) to 250,000 (1725)[c]
		Low-relaxation	211,500 (1455) to 225,000 (1550)[c]	235,000 (1620) to 250,000 (1725)[c]
Bars	A722	Type I (plain) Type II (deformed)	127,500 (800) 120,000 (825)	150,000 (1035) 150,000 (1035)
Compacted strand[b]	A779	Type 245 Type 260 Type 270	241,900 (1480) 228,800 (1575) 234,900 (1620)	247,000 (1700) 263,000 (1810) 270,000 (1860)

[a] But not less than 1.25 times the actual yield strength.
[b] Not listed in ACI 318.
[c] Minimum strength depends on wire size.

- Rebar Marking System:
  - To allow bars of various grades and sizes ***to be easily distinguished***, which is necessary ***to avoid accidental use*** of lower-strength or smaller-size bars than called for in the design, all deformed bars are furnished with rolled-in markings.
  - These identify:
    - The producing mill (usually with an initial),
    - The bar size (Nos. 3 to 18 under the inch-pound system and Nos. 10 to 57 under the SI),
    - The type of steel:
      - "S" for carbon steel, (A615)
      - "W" for low-alloy steel, (A706)

- A rail sign for rail steel, (A996)
- "A" for axle steel, (A996)
- "CS" for low-carbon chromium steel, (A1035)

▪ An additional marking to identify higher-strength steels:

- Grade 60 (420) bars have either one longitudinal line or the number 60 (4);
- Grade 75 (520) bars have either two longitudinal lines or the number 75 (5);
- Grade 100 (690) bars have either three longitudinal bars or the number 100 (6).

o The identification marks are shown in Figure 2.4-4.

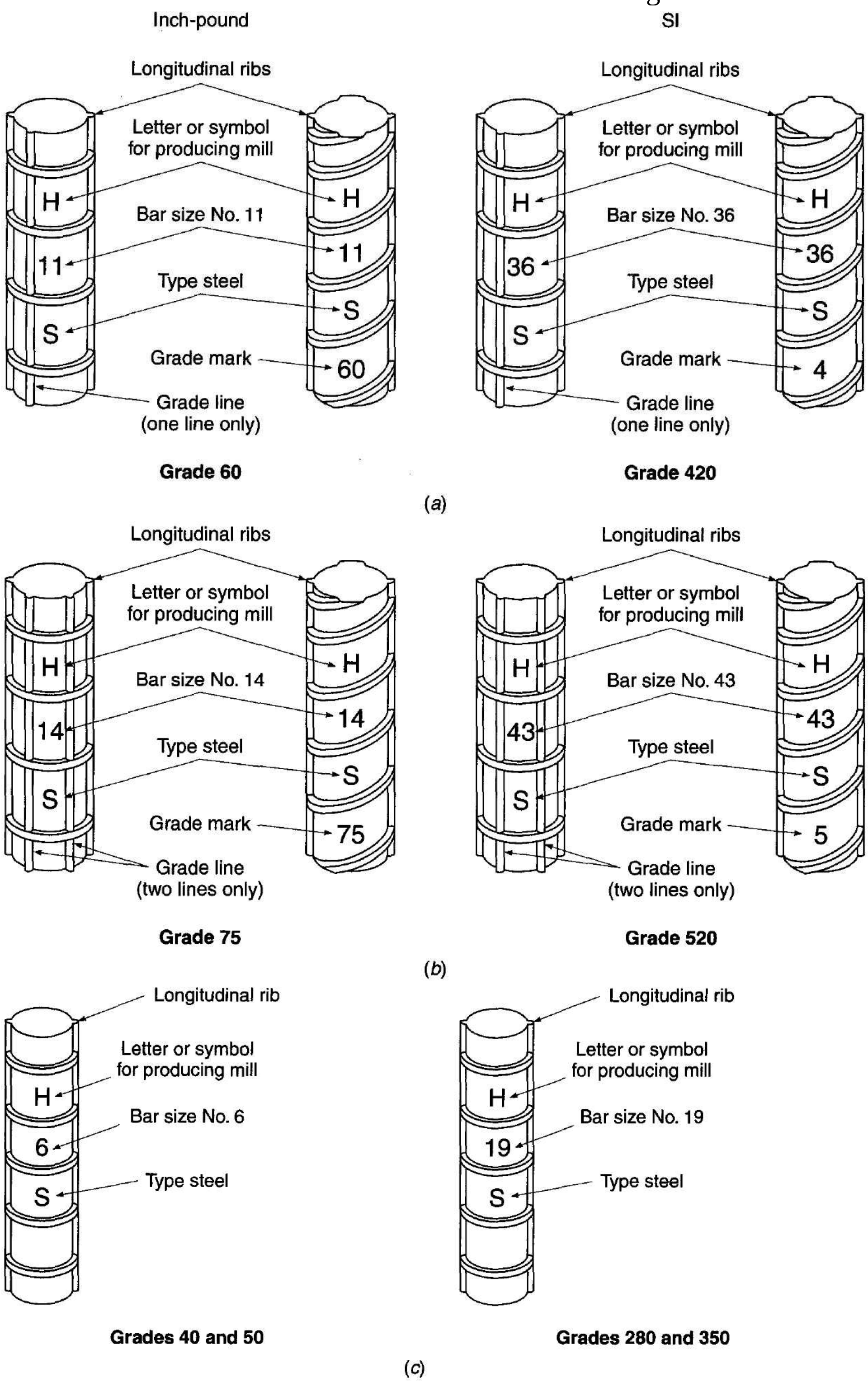


Figure 2.4-4: Marking system for reinforcing bars meeting ASTM Specifications A615, A706, and A996: (a) Grades 60 and 420; (b) Grades 75 and 520; (c) Grades 40, 50, 280, and 350.

2.4.5 Stress-Strain Curves

- Main Characteristics:
  The two chief numerical characteristics that determine the character of bar reinforcement are
  - Its yield point (generally identical in tension and compression)
  - Its modulus of elasticity E_s. It is practically the same for all reinforcing steels (but not for prestressing steels) and is taken as $E_s = 200000\ MPa,$ (ACI318M, 2014) ***Article 20.2.2.2***.
- Shape of Stress-strain Curves:
  - Typical stress-strain curves for U.S. reinforcing steels are shown in Figure 2.4-5.
  - The complete stress-strain curves are shown in the left part of the figure; the right part gives the initial portions of the curves magnified 10 times.
  - Low-carbon steels, typified by the Grade 40 curve, show:
    - ***An elastic portion.***
    - ***Yield plateau***, i.e., a horizontal portion of the curve where strain continues to increase at constant stress. For such steels, the ***yield point is that stress at which the yield plateau establishes itself***.
    - ***Strain hardening***, with further strains, the stress begins to increase again, though at a slower rate, a process that is known as ***strain hardening***.
  - Higher-strength carbon steels, e.g., those with 420 MPa (60 ksi) yield stress or higher, have,
    - ***A yield plateau of much shorter length***
    - ***Or enter strain-hardening immediately without any continued yielding at constant stress***.
    - In the latter case, the ACI Code specifies that ***the yield stress*** f_y ***be the stress corresponding to a strain of 0.0035***, as shown in Figure 2.4-5.
  - Low-alloy, high-strength steels rarely show any yield plateau and usually enter strain-hardening immediately upon beginning to yield.

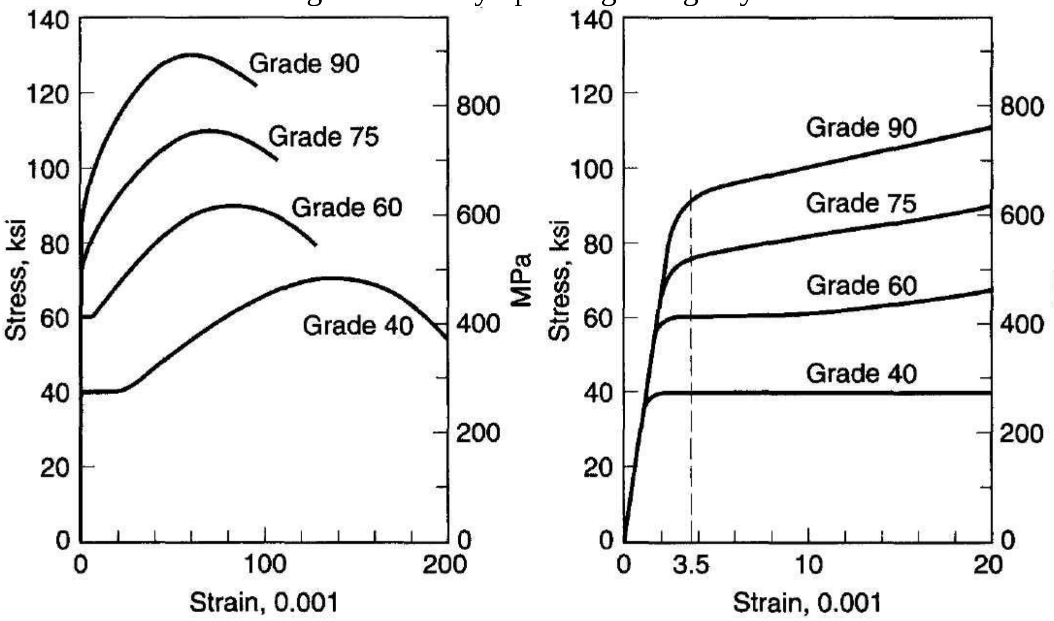


Figure 2.4-5: Typical stress-strain curves for reinforcing bars.

2.4.6 Welded Wire Reinforcement

- Welded wire reinforcement, also described as welded wire fabric, consists of sets of longitudinal and transverse cold-drawn steel wires at right angles to each other and welded together at all points of intersection.

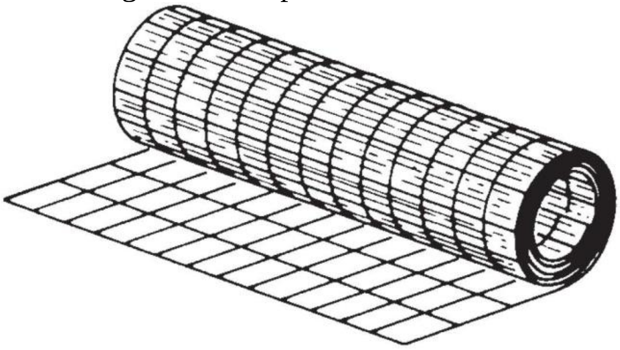


Figure 2.4-6: Welded wire reinforcement.

- Welded wire reinforcement is often used:
  - For reinforcing slabs:

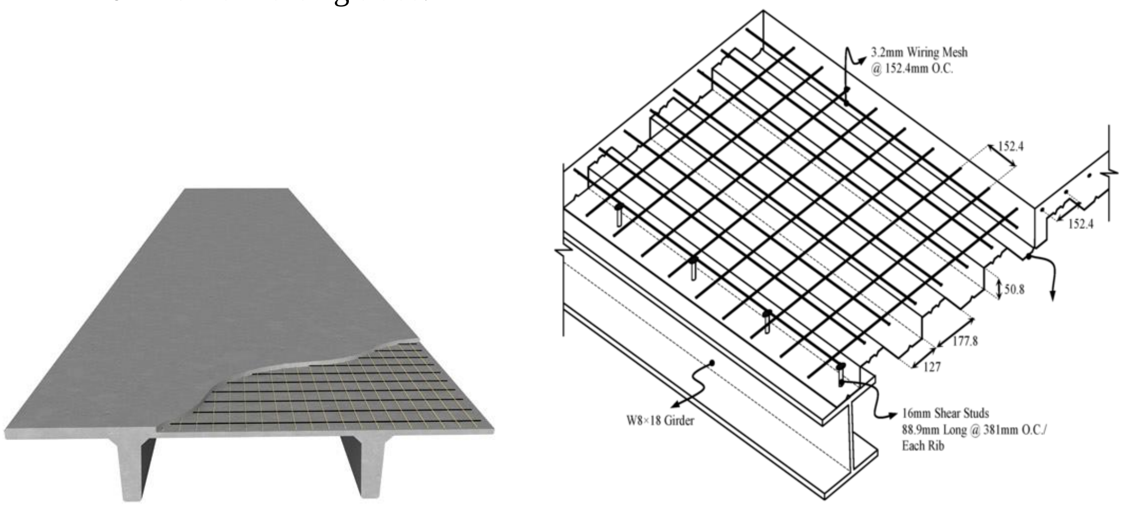


Figure 2.4-7: Slabs reinforced with welded wire reinforcement.

  - For reinforcing slabs on grade:

Figure 2.4-8: Slabs on grade reinforced with welded wire reinforcement.

  - For shear reinforcement in thin beam webs, particularly in prestressed beams.

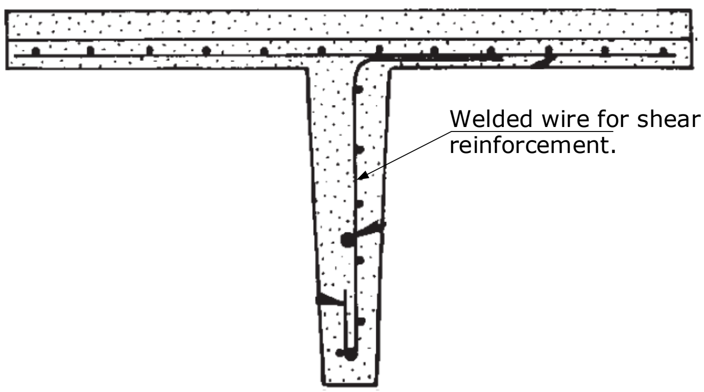


Figure 2.4-9: Welded wire for shear reinforcement.

- Standard wire reinforcement according to ASTM are presented in Table 2.4-3 below. The letter "W" to designate smooth wire while the letter "D" to describe deformed wire.

Table 2.4-3: Standard wire reinforcement

MW & MD size		Nominal diameter, mm	Nominal mass, kg/m	Area, mm^2/m of width for various spacings						
				Center-to-center spacing, mm						
Plain	Deformed			50	75	100	150	200	250	300
MW290	MD290	19.22	2.27	5800	3900	2900	1900	1450	1160	970
MW200	MD200	15.95	1.5700	4000	2700	2000	1300	1000	800	670
MW130	MD130	12.90	1.0204	2600	1700	1300	870	650	520	430
MW120	MD120	12.40	0.9419	2400	1600	1200	800	600	480	400
MW100	MD100	11.30	0.7849	2000	1300	1000	670	500	400	330
MW90	MD90	10.70	0.7064	1800	1200	900	600	450	360	300
MW80	MD80	10.10	0.6279	1600	1100	800	530	400	320	270
MW70	MD70	9.40	0.5494	1400	930	700	470	350	280	230
MW65	MD65	9.10	0.5102	1300	870	650	430	325	260	220
MW60	MD60	8.70	0.4709	1200	800	600	400	300	240	200
MW55	MD55	8.40	0.4317	1100	730	550	370	275	220	180
MW50	MD50	8.00	0.3925	1000	670	500	330	250	200	170
MW45	MD45	7.60	0.3532	900	600	450	300	225	180	150
MW40	MD40	7.10	0.3140	800	530	400	270	200	160	130
MW35	MD35	6.70	0.2747	700	470	350	230	175	140	120
MW30	MD30	6.20	0.2355	600	400	300	200	150	120	100
MW25	MD25	5.60	0.1962	500	330	250	170	125	100	83
MW20		5.00	0.1570	400	270	200	130	100	80	67
MW15		4.40	0.1177	300	200	150	100	75	60	50
MW10		3.60	0.0785	200	130	100	70	50	40	33
MW5		2.50	0.0392	100	67	50	33	25	20	17

2.5 PROBLEMS FOR SOLUTION

Problem 1

Transform the following empirical equations from the SI unit system (where strength and modulus of elasticity are expressed in MPa) to the U.S. customary unit system (where strength and modulus of elasticity are expressed in psi).

$$E_c = 4700\sqrt{f_c'}\ (\text{MPa}) \quad \text{and} \quad f_r = 0.62\sqrt{f_c'}\ (\text{MPa})$$

Hint for Solution:

It is useful to note that:

1MPa = 145 psi

Notes on Problem 1:

- Relations in engineering and sciences can be classified into ***Rational Relations*** and ***Empirical Relations***.
- ***Rational Relation*** is derived analytically and it represents a cause and effect relation. It must be valid regardless of the system of units used and must be dimensionally homogenous, e.g.:
$$y'' = \frac{M(x)}{EI}$$
is a rational equation that shows the relation between the cause (the bending moment $M(x)$) and effect (the beam curvature y''). This relation has unique form regardless it has been written in SI System or in Imperial System.
- On the other hand, ***Empirical Relation*** is the equation that used to express a quantity that is difficult, or costly to be measured directly, in terms of a quantity that can be measured directly with simple procedure and reasonable cost. For example, it is costly to measure (E_c) for concrete directly, then it is usually computed based on an experimental correlation with the concrete compressive strength f_c' that can be measured simply from direct compression test with reasonable cost.
- ***Empirical Relation*** not necessarily represents a cause and effect relation, but usually describe that relation between two quantities that depend on the same agent. For example increasing of f_c' is not a reason for increasing of E_c of concrete, but since both quantities depend on the water cement ratio, then the increasing in f_c' can be taken as an indication on increasing of E_c of concrete and vice versa.
- Above concepts have been used widely in reinforced concrete design. ***ACI code had been used the concrete compressive strength as an index on nearly all concrete properties***. All these relations are empirical in nature.

Answers:

$$E_{\text{Concrete in psi}} = 56\,595\sqrt{f_c'(\text{psi})} \quad \text{and} \quad f_{r\text{ in psi}} = 7.46\sqrt{f_c'(\text{psi})}$$

Problem 2

The specified concrete strength f_c' for a new building is 42 MPa. Calculate the required average strength f_{cr}'; for the concrete:

(a) If there are no prior test results for concrete with a compressive strength within 7 MPa of f_c' made with similar materials,

(b) If 20 test results for concrete with $f_c' = 35\ MPa$ made with similar materials produce a sample standard deviation s_s of 4.0 MPa,

(c) If 30 tests with $f_c' = 38\ MPa$ made with similar materials produce a sample standard deviation s_s of 4.1 MPa.

Problem 3

Ten consecutive strength tests are available for a new concrete mixture with $f_c' = 28\ MPa$: $31.7. 32.8, 36.4, 29.0, 30.8, 28.8, 25.9, 35.2, 32.0,\ and\ 28.8\ MPa$

(a) Do the strength results represent concrete of satisfactory quality? Explain your reasoning.

(b) If f_{cr}' has been selected based on 30 consecutive test results from an earlier project with a sample standard deviation s_s of 3.5 MPa, must the mixture proportions be adjusted? Explain.

Contents