Chapter 3

The Strength of Concrete

The quality of concrete is judged largely on the strength of that concrete. Equipment and methods are continually being modernized, testing methods are improved, and means of analyzing and interpreting test data are becoming more sophisticated, yet we still rely on the strength of the same 6 by 12-inch cylinders, made on the job and tested in compression at 28 days age, as we did 90 years ago. Interestingly, the 2008 edition of the ACI 318 Standard (ACI 318-08) now specifically addresses the use of 4 by 8-inch cylinders for evaluation and acceptance of concrete (ACI 318 Section 5.6.2.4). See discussion on strength specimens in Chapter 13, Section 13.5.

3.1. The Importance of Strength

Obviously, the strength of any structure, or part of a structure, is important, the degree of importance depending on the location of the structural element under consideration. The first-floor columns in a high-rise building, for example, are more important structurally than a nonbearing wall. Loading is more critical, and a deficiency in strength can lead to expensive and difficult repairs or, at worst, a spectacular failure.

Strength is usually the basis for acceptance or rejection of the concrete in the structure. The specifications or code designate the strength (nearly always compressive) required of the concrete in the several parts of the structure. In those cases in which strength specimens fail to reach the required value, further testing of the concrete in place is usually specified. This may involve drilling cores from the structure or testing with certain nondestructive instruments that measure the hardness of the concrete.

Some specifications permit a small amount of noncompliance, provided it is not serious, and may penalize the contractor by deducting from the payments due for the faulty concrete. Statistical methods, now applied to the evaluation of tests as described in Chapter 26, lend a more realistic approach to the analysis of test results, enabling the engineer to recognize the normal variations in strength and to evaluate individual tests in their true perspective as they fit into the entire series of tests on the structure.

Strength is necessary when computing a proposed mix for concrete, as the contemplated mix proportions are based on the expected strength-making properties of the constituents.

3.2. Strength Level Required

The code and specifications state the strength that is required in the several parts of the structure. The required strength is a design consideration that is determined by the structural engineer and that must be attained and verified by properly evaluated test results as specified. Some designers specify concrete strengths of 5000 to 6000 psi, or even higher in certain structural elements. Specified strengths in the range of 15,000 to 20,000 psi have been produced for lower-floor columns in high-rise buildings. Very high strengths, understandably, require a very high level of quality control in their production and testing. Also, for economy in materials costs, the specified strength of very high-strength concrete is based on 56 or 90-day tests rather than on traditional 28-day test results. To give some idea of the strengths that might be required, Table 3.1 is included as information only. Remember that the plans and specifications govern.

Note that the *International Building Code* (IBC) (Section 1905.1.1) and the ACI 318 Standard (Section 5.1.1) indicate a minimum specified compressive strength of 2500 psi for structural concrete. Simply stated, no structural concrete can be specified with a strength less than 2500 psi.

Other properties of the concrete can be significant for concrete exposed to freeze-thaw conditions, sulfate exposure and chloride exposure (effects of chlorides on the corrosion of the reinforcing steel). Strength, however, remains the basis for judgment of the quality of concrete. Although not necessarily dependent on strength, other properties to improve concrete durability are related to the strength. Concrete that fails to develop the strength expected of it is probably deficient in other respects as well.

TABLE 3.1

STRENGTH REQUIREMENTS	
TYPE OR LOCATION OF CONCRETE CONSTRUCTION	SPECIFIED COMPRESSIVE STRENGTH, PSI
Concrete fill	Below 2000
Basement and foundation walls and slabs, walks, patios, steps and stairs	2500–3500
Driveways, garage and industrial floor slabs	3000–4000
Reinforced concrete beams, slabs, columns and walls	3000–7000
Precast and prestressed concrete	4000–7000
High-rise buildings (columns)	10,000–15,000

Note: For information purposes only; the plans and specifications give actual strength requirements for any job under consideration.

KINDS OF STRENGTH

Generally, when we speak of the strength of concrete, it is assumed that compressive strength is under consideration. There are, however, other strengths to consider besides compressive, depending on the loading applied to the concrete. Flexure or bending, tension, shear and torsion are applied under certain conditions and must be resisted by the concrete or by steel reinforcement in the concrete. Simple tests available for testing concrete in compression and in flexure are used regularly as control tests during construction. An indirect test for tension is available in the splitting tensile test, which can easily be applied to cylindrical specimens made on the job. Laboratory procedures can be used for studying shear and torsion applied to concrete; however, such tests are neither practical nor necessary for control, as the designer can evaluate such loadings in terms of compression, flexure or tension. See Figure 3-1.

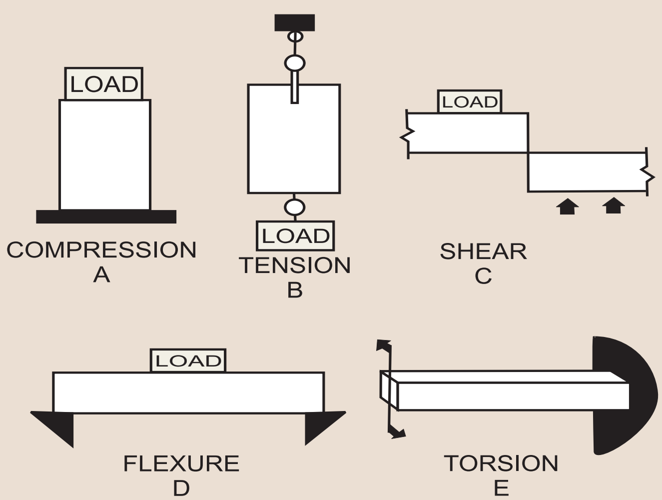


Figure 3-1: Concrete structures are subject to many kinds of loadings besides compressive. (A) Compression is a squeezing type of loading. (B) Tension is a pulling apart. (C) Shear is a cutting or sliding. (D) Flexure is a bending. (E) Torsion is a twisting.

3.3. Compressive Strength

Because concrete is an excellent material for resisting compressive loading, it is used in dams, foundations, columns, arches and tunnel linings where the principal loading is in compression.

Strength is usually determined by means of test cylinders made of fresh concrete on the job and tested in compression at various ages. The requirement is a certain strength at an age of 28 days or such earlier age as the concrete is to receive its full service load or maximum stress. Additional tests are frequently conducted at earlier ages to obtain advance information on the adequacy of strength development where age-strength relationships have been established for the materials and proportions used.

The size and shape of the strength test specimen affect the indicated strength. If we assume that 100 percent represents the compressive strength indicated by a standard 6- by 12-inch cylinder with a length/diameter (L/D) ratio of 2.0, then a 6-inch-diameter specimen 9 inches long will indicate 104 percent of the strength of the standard. Correction factors for test specimens with an L/D ratio less than 2.0 are given in the test methods for compressive strength (ASTM C 39 and ASTM C 42) for direct comparison with the standard specimen (Table 3.2.) For cylinders of different size but with the same L/D ratio, tests show that the apparent strength decreases as the diameter increases. See Figure 3-2. See also Chapter 13, Section 13.5.

TABLE 3.2

LENGTH DIVIDED BY DIAMETER	CORRECTION FACTOR
2.00	none
1.75	0.98
1.50	0.96
1.25	0.93
1.00	0.87

Example: A 6-inch core $8^{1}/_{4}$ inches long broke at 4020 psi

L/D = 8.25/6 = 1.375

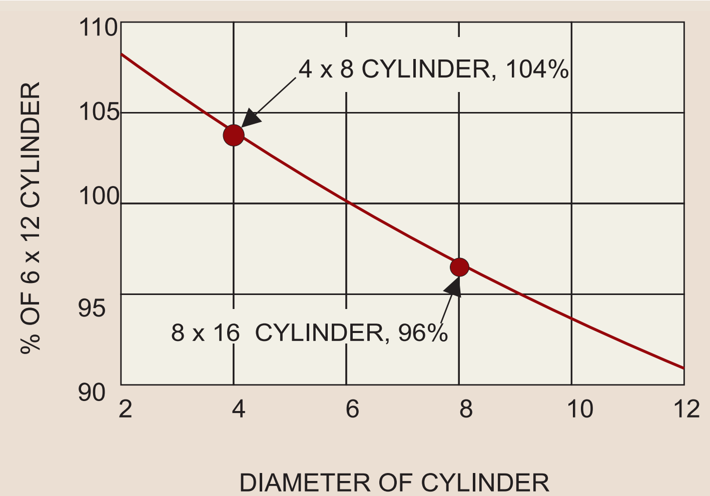
For: L/D of 1.375, the factor is 0.945.* Corrected strength is then: 4020 × 0.945 = 3800 psi.

*An example of interpolation.

	L/D RATIO FROM TABLE ABOVE	DIFFERENCE	CORRECTION FACTOR
Given value	1.50		0.96
		0.125	
Value to be determined	1.375	0.25	0.945
		0.125	
Given value	1.25		0.93

Note that the value to be determined lies halfway between given values; therefore, the correction factor is assumed to be halfway between values given.

Figure 3-2: If we call the strength of a 6 by 12-inch cylinder 100 percent, then a 4 by 8-inch cylinder would indicate a strength about 4 percent higher (104 percent) for the same concrete, or an 8 by 16-inch cylinder would indicate only about 96 percent of the strength of the 6 by 12.



3.4. Flexural Strength

Many structural components are subject to flexure, or bending. Pavements, slabs and beams are examples of elements that are loaded in flexure. An elementary example is a simple beam loaded at the center and supported at the ends. When this beam is loaded, the bottom fibers (below the neutral axis) are in tension and the upper fibers are in compression. Failure of the beam, if it is made of concrete, will be a tensile failure in the lower fibers, as concrete is much weaker in tension than in compression. Now, if we insert some steel bars in the lower part of the beam (reinforced concrete), it will be able to support a much greater load because the steel bars, called reinforcing steel, have a high tensile strength. See Figure 3-3. Carrying this one step further, if the reinforcing steel is prestressed in tension (prestressed concrete), the beam can carry a still greater load.

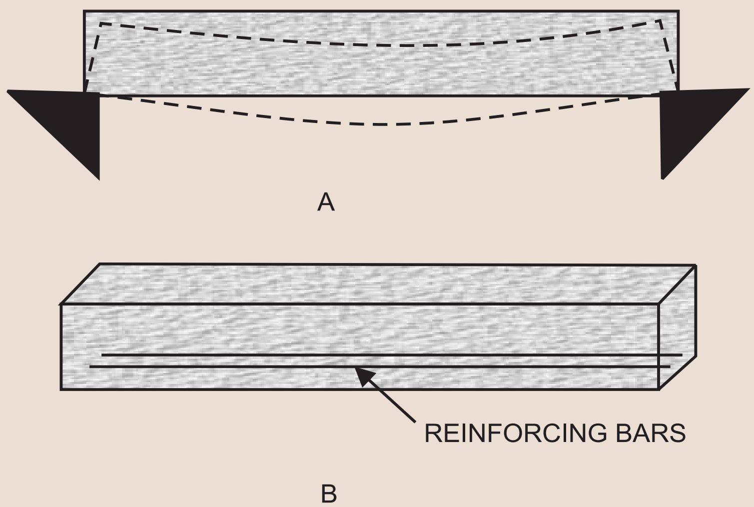


Figure 3-3: The bottom of a beam is in tension when the beam is loaded. Reinforcing bars are therefore put in the bottom of the beam to give it greater flexural strength.

The modulus of rupture is a measure of the flexural strength and is determined by testing a small beam, usually 6 by 6 inches in cross section, in bending. Usual practice is to test a simple beam by applying a concentrated load at each of the third points. See Figure 3-4. Some agencies test the beams under one load at the center point, which usually indicates a higher strength than the third-point loading. Center-point loading is not usually used for 6-inch beams but is confined to smaller specimens.

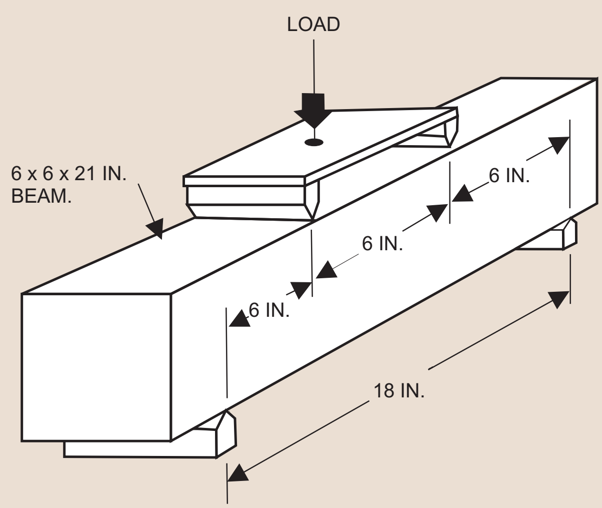


Figure 3-4: Testing a beam specimen in flexure.