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. Prior to the 2008 edition of the ACI 318 Standard, we relied almost exclusively on the strength of 6-by-12-inch cylinders, made on the jobsite and tested in compression at 28 days age for evaluation and acceptance of concrete. The use of 4-by-8-inch cylinders for strength evaluation was first addressed in ACI 318-08. 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 ACI 318 Standard (Section 19.2.1.1) indicates 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.

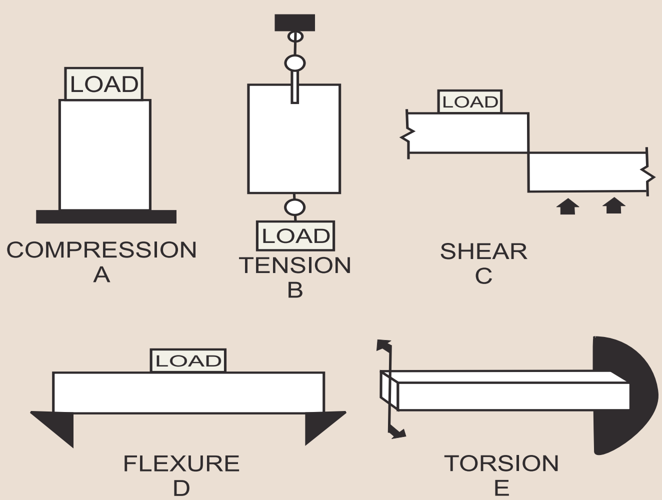


Figure 3-1: Concrete structures are subject to many kinds of loadings besides compressive. (A) Compression is a squeezing type of loading. (B) Tension is a pulling apart. (C) Shear is a cutting or sliding. (D) Flexure is a bending. (E) Torsion is a twisting.

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 C39 and ASTM C42) 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.

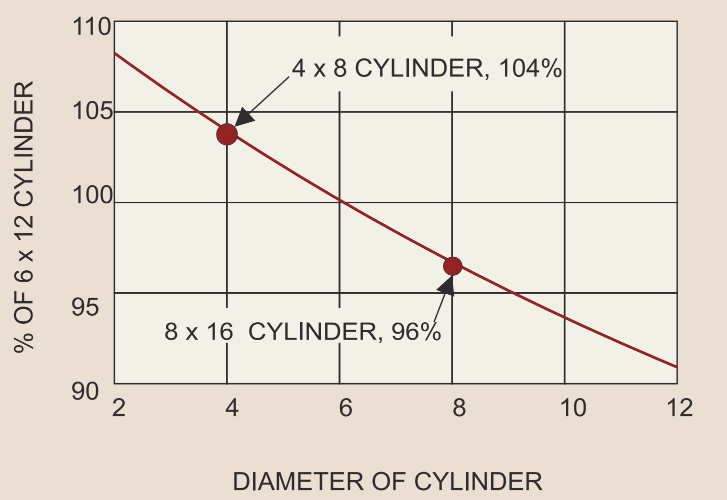


Figure 3-2: If we call the strength of a 6-by-12-inch cylinder 100 percent, then a 4-by-8-inch cylinder would indicate a strength about 4 percent higher (104 percent) for the same concrete, or an 8-by-16-inch cylinder would indicate only about 96 percent of the strength of the 6-by-12.

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.

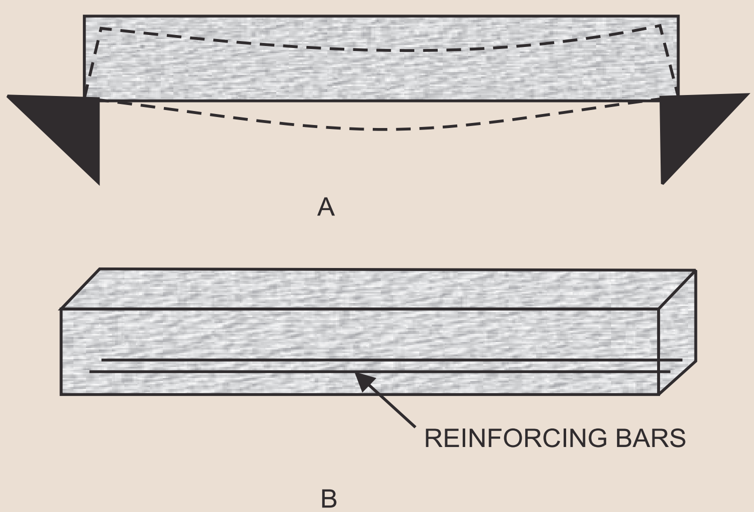


Figure 3-3: The bottom of a beam is in tension when the beam is loaded. Reinforcing bars are therefore put in the bottom of the beam to give it greater flexural strength.

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.

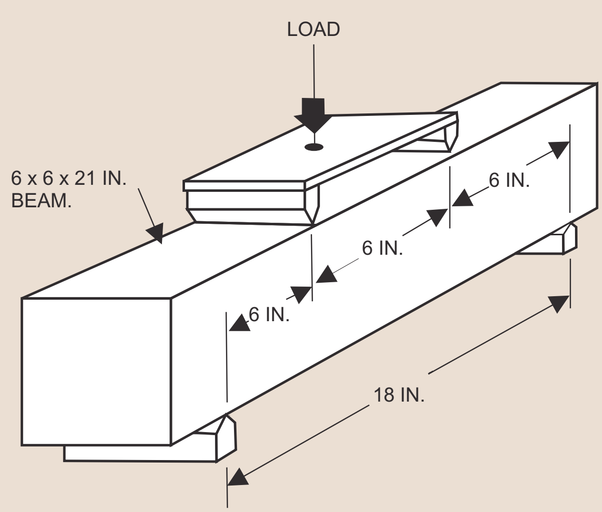
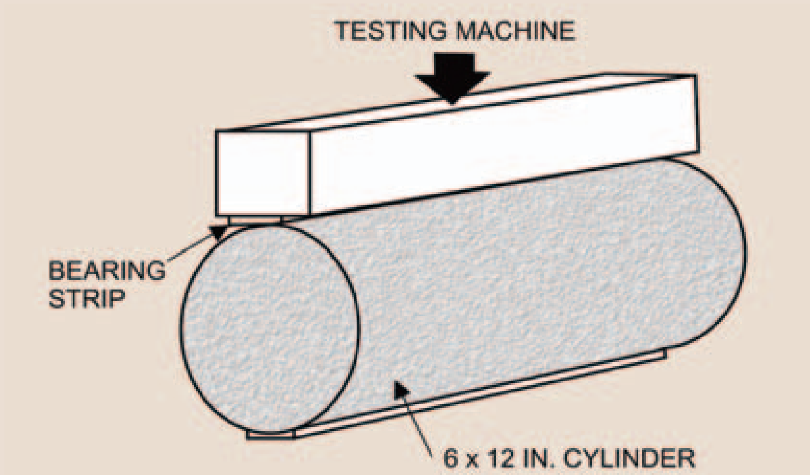


Figure 3-4: Testing a beam specimen in flexure.

3.5. Tensile Strength

There is no field test for direct determination of tension under axial loading. It is a difficult test to perform and the results are not reliable. There is, however, an indirect method called the splitting tensile test, in which a standard test cylinder is loaded in compression on its side. See Figure 3-5. By means of an equation, a value of tensile strength can be computed. Laboratory comparisons show that the tensile strength indicated by this test may be as much as 150 percent of the direct tensile strength.

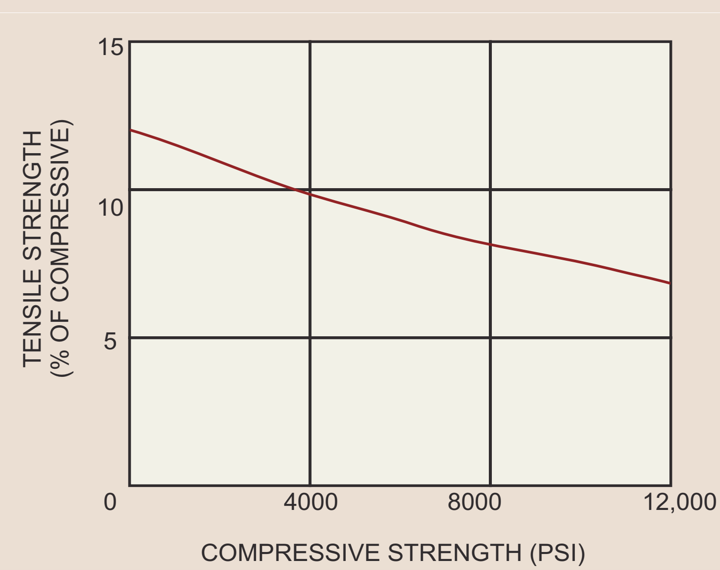
Figure 3-5: The splitting tensile test gives a good indication of the tensile strength of the concrete.



Concrete in the structure is rarely loaded in pure tension, the tensile stresses being in connection with flexure, torsion or a combination of loadings.

Awareness of the importance of tensile strength has increased, however, because of the significance of tension on the control of cracking. Research indicates that direct tension averages about 10 percent of the compressive, being about 7 or 8 percent for high-strength concrete (8000 to 10,000 psi compressive) and going as high as 11 or 12 percent for low-strength concrete in the range of 1000 psi compressive. See Figure 3-6.

Figure 3-6: Tensile strength of concrete is about 12 percent of the compressive for low-strength concrete, going down to about 7 percent for high-strength concrete.



3.6. Shear, Torsion and Combined Stresses

Shear is a loading in which a part of a member attempts to slide or shear along another part. See Figure 3-1. Because of the complexity of the action of forces in the concrete, it is not possible to make a direct determination of shear. Torsion, which is a twisting, is also complex and difficult to evaluate. When concrete fails, a combination of stresses causes the failure. Even a standard cylinder test, in which an axial compressive load is applied to the specimen, imposes shear and tension in parts of the specimen. Concrete in a structure is nearly always subjected to more than one type of stress—compressive, tensile, shearing—resulting from the application of various loads and moments on the members.

Theoretical and experimental relationships have been established that enable the engineer to relate forces and loads acting on members to compressive, flexural and splitting tensile values. By application of a suitable factor of safety, strength requirements for construction can then be specified.

3.7. Relationship of Test Strength to the Structure

In a later section of this book we will discuss how to test concrete and how to analyze test results. This analysis is necessary because of the natural variation of test results. This brings up two important questions: What is the relationship between the strength indicated by the test cylinders compared with the strength of the concrete in the structure? How are the variations in cylinder strengths reflected in the structure?

Consider the first question. Test specimens are made, cured and tested under certain standard conditions that are usually appreciably different from the conditions existing in the structure. Temperature and curing conditions can be vastly different. The value of the test specimens is that they give a measure of the strength potential and other properties of the concrete; they evaluate the materials and mix under certain standard conditions. If they indicate a low strength, then something is wrong with the materials or proportions. Actual strength of the concrete in the structure can be appreciably different. Besides temperature and curing, other variables are moisture content, size, shape, quality of consolidation, possible presence of defects such as rock pockets, restraint, and combinations of loading in the structure. It is because of these unknowns that a factor of safety must be considered by the structural engineer when the structure is designed.

In answer to the second question, the variations in cylinder strengths are not always reflected in the structure. If three specimens are made from one batch of concrete, under identical conditions throughout the test, there is no assurance that they will all fail at the same strength. In fact, the probability is that they will each break at a different strength. These are normal variations.

We do know that there are variations in the structure that are not caused by basic variations in the concrete itself. For example, when cores are taken from a column, the cores from the upper portion of the column invariably indicate lower strength than the cores from the bottom portion of the column. The reason for this is that the concrete near the bottom was compacted by the static hydraulic head of the concrete being worked above, yet there was no change in mix or materials.

MEASUREMENT OF STRENGTH

The strength of concrete can be determined by any one of four methods: by molding specimens from the fresh concrete on the job, by testing cores removed from the hardened concrete, by applying certain impact and rebound instruments to the hardened concrete and by sonic and electronic measurements applied to the hardened concrete in place. Specimens molded from fresh concrete on the job are universally used for control and acceptance testing. Tests by other methods are used for checking the results of molded specimens, especially in case of low strength indications or dispute, and for research involving existing structures.

Procedures for all strength tests are explained in detail in Chapter 13.

3.8. Job-Molded Specimens

For all concrete other than pavements, job-molded specimens are cylinders. The number of test cylinders required is given in ACI 318 Section 26.12.2, or in the project specifications. Test cylinders made to determine compliance with the specifications are made and cured under controlled conditions of temperature and humidity (ACI 318 Section 26.12.3). Test cylinders are sometimes made for curing under job or field conditions to determine time for removal of shoring or forms or when the structure can be put in service (ACI 318 Section 26.5.3.2).

3.9. Testing of Hardened Concrete

Samples sawed or cored from hardened concrete are not normally required, their use being confined to those cases in which some question or dispute has developed regarding the quality of the concrete as revealed by tests of molded specimens. Number, location, size and type of specimens are determined at the time sampling becomes necessary.

Coring and sawing specimens from hardened concrete are expensive expedients and should be adopted only as a last resort. Both procedures leave scars on the surface of the concrete that are difficult to eradicate, a condition that must be considered if the concrete is exposed to view. The possibility of structural damage, especially damage to reinforcement, cannot be ignored. If an approximation of the strength will suffice, one of the following described instruments can be used.

There are two simple instruments available for determining the strength of concrete in place. One of these, called a Swiss hammer (ASTM C805), operates on the principle that the rebound of a spring-loaded steel plunger striking the surface of concrete is proportional to the strength of that concrete. It is a quick, nondestructive test that can be used for the determination of the approximate compressive strength of concrete in place, but it cannot be used to replace properly conducted cylinder or core tests. Testing is described in Chapter 13.

The second instrument is based on the principle that the penetration of a probe gauge into the concrete is inversely proportional to the compressive strength of the concrete. Called a Windsor probe (ASTM C803), it uses a power-actuated device to drive the probe into the concrete. Accuracy is about the same as that of the Swiss hammer, but small indentations are left in the surface of the concrete, which might be unsightly in some exposed concrete.

In-place tests of concrete can be made with instruments that measure the velocity of a small mechanical pulse through the concrete. Known as the pulse velocity method, the apparatus consists of two vibration pickups (phonograph pickups), a hammer device to apply a blow to the concrete and an electronic circuit to measure the velocity of the sound generated by the hammer blow as the sound travels through the concrete from one pickup to the next. Considerable experience and expertise are required to interpret results correctly.

FACTORS AFFECTING STRENGTH

3.10. General Comments

When we ask what affects the strength of concrete, the answer is—just about everything. Among the factors are type, quality and amount of cement; quality, cleanness and grading of the aggregate; quality and amount of water; presence or lack of admixtures; methods followed in handling and placing the concrete; age of the concrete when placed in the forms; temperature; curing conditions; and age of the concrete when tested. Foreign materials may find their way into the concrete, thereby affecting the strength. Finally, the indicated strength of the test specimens may or may not actually represent the strength of the concrete in the structure. Table 3.3 shows some of the variables and their effects.

In using a table of this type, the first step is to eliminate the items that obviously do not apply, then to consider those that might be significant. In many cases, it will be found that there was more than one factor acting at the time. There may be one or more factors of high significance, or there may be several of minor significance that when acting together become highly significant.

In the following discussion we will assume that test specimens truly represent the concrete from which they had been sampled. One problem with strength tests is the time lapse between making the concrete and testing specimens. By the time strength results become available, it is too late to do anything about the concrete already placed, but the information at least provides a warning to avoid the troublesome materials or practices in future work.

Appreciable variations in strength of concrete result from the use of different brands intermittently or can even be caused by variations between shipments of cement from the same mill. Variations in raw materials, processing, age, fineness and temperature contribute to these variations. Undetected differences in cement types will affect strength, especially at early ages. If a batching plant has facilities for more than one type of cement, there is always the danger of using the wrong cement. There have been cases of accidental substitution of Type I for Type III. Also, accidental use of pozzolan instead of cement has occurred. Adequate inspection will minimize these incidents.