CHAPTER 16

Control Tests for Concrete

Satisfactory concrete construction and performance requires concrete with specific properties. To assure that these properties are obtained, quality control and acceptance testing are indispensable parts of the construction process. Test results provide important feedback used to base decisions regarding mix adjustments. However, past experience and sound judgment must be relied on in evaluating tests and assessing their significance in controlling the design, batching and placement processes that influence the ultimate performance of the concrete.

Specifiers are moving toward performance-based specifications (also called end-result or end-property specifications) that require the final performance of concrete be achieved independent of the process used to achieve the performance. Physical tests and concrete properties are used to measure acceptance. Such specifications may not have acceptance limits for process control tests such as slump or limits on the quantities of concrete ingredients as do prescriptive specifications. The end result of compressive strength, low permeability, documented durability, and a minimal number of cracks, for example, would be the primary measure of acceptance. Of course, even though process control tests may not be specified, the wise concrete producer would use them to guide the product to a successful end result. However, most specifications today are still a combination of prescriptive and performance requirements (Parry 2000).

CLASSES OF TESTS

Project specifications may affect (1) characteristics of the mixture, such as maximum size of aggregate, aggregate proportions, or minimum cement content; (2) characteristics of the cement, water, aggregates, and admixtures; and (3) characteristics of the freshly mixed and hardened concrete, such as temperature, slump, air content, and compressive or flexural strengths.

Cementitious materials are tested for their compliance with ASTM or AASHTO standards to avoid any abnormal performance such as early stiffening, delayed setting, or low strengths in concrete. More details regarding cementitious materials can be found in Chapters 2 and 3.

Tests of aggregates have two major purposes: (1) to determine the suitability of the material itself for use in concrete, including tests for abrasion, soundness against saturated freeze-thaw cycles, harmful materials by petrographic examination, and potential alkali-aggregate reactivity; and (2) to assure uniformity, such as tests for moisture control, relative density (specific gravity), and gradation of aggregates. Some tests are used for both purposes. Testing aggregates to determine their potential alkali-aggregate reactivity is discussed in Chapter 5, "Aggregates for Concrete." Tests of concrete to evaluate the performance of available materials, to establish mixture proportions, and to control concrete quality during construction include slump, air content, temperature, density (unit weight), and strength. Slump, air content, and strength tests are usually required in project specifications for concrete quality control, whereas density is more useful in mixture proportioning. Nevertheless, ASTM C 94 (AASHTO M 157) specifies that slump, air-content, density, and temperature tests should be made when strength specimens are made.

Following is a discussion of frequency of testing and descriptions of the major control tests to ensure uniformity of materials, desired properties of freshly mixed concrete, and required strength of hardened concrete. Special tests are also described.

ASTM (2000) and Klieger and Lamond (1994) provide extensive discussions of test methods for concrete and concrete ingredients.

Computational Software. In order to make computation of test data easier, NRMCA (2001) provides a CD with spread sheets for a variety of concrete and aggregate tests.

FREQUENCY OF TESTING

Frequency of testing is a significant factor in the effectiveness of quality control of concrete. Specified test frequencies are intended for acceptance of the material or one of its components at a random location within the quantity or time period represented by the test. Such frequencies may not occur often enough to control the material within

specified limits during production. Process control tests are nonrandom tests performed more often than specified to document trends that allow adjustments to be made before acceptance tests are performed.

The frequency of testing aggregates and concrete for typical batch-plant procedures depends largely upon the uniformity of materials, including the moisture content of aggregates, and the production process. Initially it is advisable to make process control tests several times a day, but as work progresses and the material becomes more predictable, the frequency often can be reduced. ASTM C 1451 provides a standard practice for determining the uniformity of cementitious materials, aggregates, and chemical admixtures used in concrete.

Usually, aggregate moisture tests are made once or twice a day. The first batch of fine aggregate in the morning is often overly wet since moisture will migrate overnight to the bottom of the storage bin. As fine aggregate is drawn from the bottom of the bin and additional aggregate is added, the moisture content should stabilize at a lower level and the first moisture test can be made. Obtaining moisture samples representative of the aggregates being batched is important; a one percent change in moisture content of fine aggregate will change the amount of mix water needed by approximately eight kilograms per cubic meter (13 lb / yd^3).

Slump tests should be made for the first batch of concrete each day, whenever consistency of concrete appears to vary, and whenever strength-test cylinders are made at the jobsite.

Air-content tests should be made often enough at the point of delivery to ensure proper air content, particularly if temperature and aggregate grading change. An air-content test should be performed for each sample of concrete from which cylinders are made; a record of the temperature of each sample of concrete should also be kept.

The number of strength tests made will depend on the job specifications and the occurrence of variations. The ACI 318 building code and ASTM C 94 require that strength tests of each class of concrete placed each day should be taken not less than once a day, nor less than once for each 115 cubic meters (150 cu yd) of concrete. In addition, ACI 318 recommends not less than once for each 500 square meters (5000 sq ft) of surface area for slabs or walls placed each day. The average strength of two 28-day cylinders is required for each test used for evaluating concrete. A 7-day test cylinder, along with the two 28-day test cylinders, is often made and tested to provide an early indication of strength development. As a rule of thumb, the 7-day strength is about 60% to 75% of the 28-day compressive strength, depending upon the type and amount of cementitious materials, water-cement ratio, curing temperature, and other variables. Additional specimens may be required when high-strength concrete is involved or where structural requirements are critical. Specimens should be laboratory cured when tested for acceptance or ultimate performance of the concrete. However, laboratory-cured specimens should not be used as an indication of in-place concrete strengths (ACI Committee 318, 1999).

In-place concrete strengths are typically documented by casting specimens that are field-cured (as nearly as practical) in the same manner as concrete in the structure. Field-cured specimens are commonly used to decide when forms and shores might be removed under a structural slab or to determine when traffic will be allowed on new pavement. ASTM C 31 (AASHTO T 23) contains additional instructions regarding the handling of field-cured cylinders. Although field-cured specimens may be tested at any age, 7-day tests are often made for comparison with laboratory tests at the same age; these are useful to judge if curing and protection during cold weather concreting is adequate.

TESTING AGGREGATES

Sampling Aggregates

Video

Methods for obtaining representative samples of aggregates are given in ASTM D 75 (AASHTO T 2). Accurate sampling is important. The location in the production process where samples will be obtained must be carefully planned. Sampling from a conveyor belt, stockpile, or aggregate bin may require special sampling equipment. Caution must be exercised to obtain a sample away from stockpile segregation and the sample must be large enough to meet ASTM minimum sample size requirements. In addition, samples obtained for moisture content testing should be placed in a sealed container or plastic bag as soon as possible to retain moisture until testing.

Reducing large field samples to small quantities for individual tests must be done with care so that the final samples will be truly representative ASTM C 702 (AASHTO T 248). For coarse aggregate, this is done by the quartering method: The sample, thoroughly mixed, is spread on a piece of canvas in an even layer 75 or 100 mm (3 or 4 in.) thick. It is divided into four equal parts. Two opposite parts are then discarded. This process is repeated until the desired size of sample remains. A similar procedure is sometimes used for moist, fine aggregate. Sample splitters are desirable for dry aggregate (Fig. 16-1) but should not be used for samples that are more than saturated surface dry.

Organic Impurities

Video

Organic impurities in fine aggregate should be determined in accordance with ASTM C 40 (AASHTO T 21). A sample of fine aggregate is placed in a sodium hydroxide solution and shaken. The following day the color of the sodium hydroxide solution is compared with a glass color

Fig. 16-1. Sample splitter commonly used to reduce coarse aggregate samples. (70012)

standard or standard color solution. If the color of the solution containing the sample is darker than the standard color solution or Organic Glass Plate No. 3, the fine aggregate should not be used for important concrete work without further investigation.

Video

Some fine aggregates contain small quantities of coal or lignite that give the liquid a dark color. The quantity may be insufficient to reduce the strength of the concrete appreciably. If surface appearance of the concrete is not important, ASTM C 33 (AASHTO M 6) states that fine aggregate is acceptable if the amount of coal and lignite does not exceed 1.0% of the total fine aggregate mass. A fine aggregate failing this ASTM C 33 (AASHTO M 6) limit may be used if, when tested in accordance with ASTM C 87 (AASHTO T 71), the 7-day strengths of mortar cubes made with the sand (ASTM C 109 or AASHTO T 106) are at least 95% of the 7-day strengths of mortar made with the same sand, but washed in a 3% solution of sodium hydroxide and then thoroughly rinsed in water. It should be realized that appreciable quantities of coal or lignite in aggregates can cause popouts and staining of the concrete and can reduce durability when concrete is exposed to weathering. Local experience is often the best indication of the durability of concrete made with such aggregates.

Video

Objectionable Fine Material

Large amounts of clay and silt in aggregates can adversely affect durability, increase water requirements, and increase shrinkage. Specifications usually limit the amount of material passing the 75 µm (No. 200) sieve to 2% or 3% in fine aggregate and to 1% or less in coarse aggregate. Testing for material finer than the 75 µm (No. 200) sieve should be done in accordance with ASTM C 117 (AASHTO T 11). Testing for clay lumps should be in accordance with ASTM C 142 (AASHTO T 112).

Video

Grading

Gradation of aggregates significantly affects concrete mixture proportioning and workability. Hence, gradation tests are an important element in the assurance of concrete quality. The grading or particle size distribution of an aggregate is determined by a sieve analysis test in which the particles are divided into their various sizes by standard sieves. The analysis should be made in accordance with ASTM C 136 (AASHTO T 27).

Results of sieve analyses are used in three ways: (1) to determine whether or not the materials meet specifications; (2) to select the most suitable material if several aggregates are available; and (3) to detect variations in grading that are sufficient to warrant blending selected sizes or an adjustment of concrete mix proportions.

The grading requirements for concrete aggregate are shown in Chapter 5 and ASTM C 33 (AASHTO M 6/M 80). Materials containing too much or too little of any one size should be avoided. Some specifications require that mixture proportions be adjusted if the average fineness modulus of fine aggregate changes by more than 0.20. Other specifications require an adjustment in mixture proportions if the amount retained on any two consecutive sieves changes by more than 10% by mass of the total fine-aggregate sample. A small quantity of clean particles that pass a 150 µm (No. 100) sieve but are retained on a 75 µm (No. 200) sieve is desirable for workability. For this reason, most specifications permit up to 10% of this material in fine aggregate.

Well-graded aggregates contain particles on each sieve size. Well-graded aggregates enhance numerous factors that result in greater workability and durability. The more well-graded an aggregate is, the more it will pack together efficiently, thus reducing the volume between aggregate particles that must be filled by paste. On the other hand, gap-graded aggregates—those having either a large quantity or a deficiency of one or more sieve sizes—can result in reduced workability during mixing, pumping, placing, consolidation and finishing. Durability can suffer too as a result of using more fine aggregate and water to produce a workable mix. See Chapter 5 and Galloway (1994) for additional information on aggregate grading.

Moisture Content of Aggregates

Several methods are used for determining the amount of moisture in aggregate samples. The total moisture content for fine or coarse aggregate can be tested in accordance with ASTM C 566 (AASHTO T 255). In this method a measured sample of damp aggregate is dried either in a ventilated conventional oven, microwave oven, or over an electric or gas hotplate. From the mass before and after drying, the total moisture content can be calculated as follows:

$$P = 100(M - D)/D$$

where

P = moisture content of sample, percent
M = mass of original sample
D = mass of dried sample

The surface (free) moisture can be calculated if the percentage of absorbed moisture in the aggregate is known. The surface moisture content is equal to the total moisture content minus the absorbed moisture. Historic information for an aggregate source can be used to obtain absorbed moisture content data if the mineral composition of the pit or quarry has not changed significantly. However, if recent data is not available, they can be determined using methods outlined in ASTM C 127 (AASHTO T 85) for coarse aggregate and ASTM C 128 (AASHTO T 84) for fine aggregate.

Only the surface moisture, not the absorbed moisture, becomes part of the mixing water in concrete. Surface moisture percentages are used to calculate the amount of water in the aggregates to reduce the amount of mix water used for batching. In addition, the batch weight of aggregates should be increased by the percentage of surface moisture present in each type of aggregate. If adjustments are not made during batching, surface water will replace a portion of the aggregate mass and the mix will not yield properly.

Another method to determine moisture content, which is not as accurate, is to evaporate the moisture by burning alcohol. In this method: (1) a measured sample of damp fine aggregate is placed in a shallow pan; (2) about 310 ml of alcohol for each kilogram (5 oz for each pound) is poured over the sample; (3) the mixture is stirred with a rod and spread in a thin layer over the bottom of the pan; (4) the alcohol is then ignited and allowed to burn until the sample is dry; (5) after burning, the sample is cooled for a few minutes and weighed; and (6) the percentage of moisture is then calculated.

When drying equipment is not available a field or plant determination of surface (free) moisture in fine aggregate can be made in accordance with ASTM C 70. The same procedure can be used for coarse aggregate with appropriate changes in the size of sample and dimensions of the container. This test depends on displacement of water by a known mass of moist aggregate; therefore, the relative density (specific gravity) of the aggregate must be known accurately.

Electric moisture meters are used in many concrete batching plants primarily to monitor the moisture content of fine aggregates, but some plants also use them to check coarse aggregates. They operate on the principle that the electrical resistance of damp aggregate decreases as moisture content increases, within the range of dampness normally encountered. The meters measure the electrical resistance of the aggregate between electrodes protruding into the batch hopper or bin. Moisture meters using the microwave-absorption method are gaining popularity because they are more accurate than the electric meters. However, both methods measure moisture contents accurately and rapidly, but only at the level of the probes. These meters require frequent calibration and must be maintained properly. The variable nature of moisture contents in aggregates cause difficulty in obtaining representative samples for comparison to electric moisture meters. Several oven-dried moisture content tests should be performed to verify the calibration of these meters before trends in accuracy can be established.

Table 16-1 illustrates a method of adjusting batch weights for moisture in aggregates.

Table 16-1. Example of Adjustment in Batch Weights for Moisture in Aggregates

Aggregate data	Absorption, %	Moisture content, %
Fine aggregate	1.2	5.8
Coarse aggregate	0.4	0.8

Concrete ingredients	Mix design mass (aggregates in dry BOD condition),* kg/m³ (lb/yd³)	Aggregate mass (SSD condition),** kg/m³ (lb/yd³) $BOD \cdot \frac{(Absorbed\ \%)}{100}$	Aggregate mass (in moist condition), kg/m³ (lb/yd³) $BOD \cdot \frac{(Moisture\ \%)}{100}$	Mix water correction for surface moisture in aggregates, kg/m³ (lb/yd³) $BOD \cdot \frac{(Moist\%-Absorb\%)}{100}$	Adjusted batch weight, kg/m³ (lb/yd³)
Cement	355 (598)				355 (598)
Fine aggregate	695 (1171)	703 (1185)	735 (1239)	32 (54)	735 (1239)
Coarse aggregate	1060 (1787)	1064 (1793)	1068 (1800)	4 (7)	1068 (1800)
Water	200 (337)				164 (276)
Total	2310 (3893)			36 (61)	2322 (3913)†

* An aggregate in a bulk-oven dry (BOD) condition is one with its permeable voids completely dry so that it is fully absorbent.
** An aggregate in a saturated, surface-dry (SSD) condition is one with its permeable voids filled with water and with no surface moisture on it. Concrete suppliers often request mix design proportions on a SSD basis because of batching software requirements.
† Total adjusted batch weight is higher than total mix design weight by the amount of water absorbed in the aggregate.

Video

TESTING FRESHLY MIXED CONCRETE

Sampling Freshly Mixed Concrete

The importance of obtaining truly representative samples of freshly mixed concrete for control tests must be emphasized. Unless the sample is representative, test results will be misleading. Samples should be obtained and handled in accordance with ASTM C 172 (AASHTO T 141). Except for routine slump and air-content tests performed for process control, ASTM C 172 (AASHTO T 141) requires that sample size used for acceptance purposes be at least 28 liter (1 cu ft) and be obtained within 15 minutes between the first and final portions of the sample. The composite sample, made of two or more portions, should not be taken from the very first or last portion of the batch discharge. The sample should be protected from sunlight, wind, and other sources of rapid evaporation during sampling and testing.

Consistency

The slump test, ASTM C 143 (AASHTO T 119), is the most generally accepted method used to measure the consistency of concrete (Fig. 16-2). The test equipment consists of a slump cone (a metal conical mold 300 mm [12 in.] high, with a 200-mm [8-in.] diameter base and 100-mm [4-in.] diameter top) and a steel rod 16 mm (⅝ in.) in diameter and 600 mm (24 in.) long with a hemispherically shaped tip. The dampened slump cone, placed upright on a flat, nonabsorbent rigid surface, should be filled in three layers of approximately equal volume. Therefore, the cone should be filled to a depth of about 70 mm (2½ in.) for the first layer, a depth of about 160 mm (6 in.) for the second layer, and overfilled for the third layer. Each layer is rodded 25 times. Following rodding, the last layer is struck off and the cone is slowly raised vertically 300 mm (12 in.) in 5 ± 2 seconds. As the concrete subsides or settles to a new height, the empty slump cone is then inverted and gently placed next to the settled concrete. The slump is the vertical distance the concrete settles, measured to the nearest 5 mm (¼ in.); a ruler is used to measure from the top of the slump cone (mold) to the displaced original center of the subsided concrete (see Fig. 16-2).

A higher slump value is indicative of a more fluid concrete. The entire test through removal of the cone should be completed in 2½ minutes, as concrete loses slump with time. If a falling away or shearing off occurs from a portion of the concrete, another test should be run on a different portion of the sample.

Another test method for flow of fresh concrete involves the use of the K-Slump Tester (ASTM C 1362). This is a probe-type instrument that is thrust into the concrete in any location where there is a minimum depth of 175 mm (7 in.) of concrete a 75-mm (3-in.) radius of concrete around the tester. The amount of mortar flowing into openings in the tester is reported as a measure of flow.

Additional consistency tests include: the FHWA vibrating slope apparatus (Wong and others 2001 and Saucier 1966); British compacting factor test (BS 1881); Powers remolding test (Powers 1932); German flow table test (DIN 1048-1); Vebe consistometer for roller-compacted concrete (ASTM C 1170); Kelly ball penetration test (ASTM C 360-92 now discontinued); Thaulow tester; the inverted slump cone for fiber-reinforced concrete (ASTM C 995); Powers and Wiler plastometer (Powers and Wiler 1941);

Fig. 16-2. Slump test for consistency of concrete. Figure A illustrates a lower slump, Figure B a higher slump. (69786, 69787)

Tattersall (1971) workability device; Colebrand test; BML viscometer (Wallevik 1996); BTRHEOM rheometer for fluid concrete (de Larrard, Szitkar, Hu, and Joly 1993); free-orifice rheometer (Bartos 1978); delivery chute torque meter (US patent 4,332,158 [1982]); delivery-chute vane (US patent 4,578,989 [1986]); Angles flow box (Angles 1974); ring penetration test (Teranishs and others 1994); and the Wigmore (1948) consistometer. The Vebe test and the Thaulow test are especially applicable to stiff and extremely dry mixes while the flow table is especially applicable to flowing concrete (Scanlon 1994).

Temperature Measurement

Because of the important influence concrete temperature has on the properties of freshly mixed and hardened concrete, many specifications place limits on the temperature of fresh concrete. Glass or armored thermometers are available (Figs. 16-3). The thermometer should be accurate to plus or minus 0.5°C (±1°F) and should remain in a representative sample of concrete for a minimum of 2 minutes or until the reading stabilizes. A minimum of 75 mm (3 in.) of concrete should surround the sensing portion of the thermometer. Electronic temperature meters with precise digital readouts are also available. The temperature measurement (ASTM C 1064 or AASHTO T 309) should be completed within 5 minutes after obtaining the sample.

Fig. 16-3. A thermometer is used to take the temperature of fresh concrete. (69885A)

Density and Yield

The density (unit weight) and yield of freshly mixed concrete (Fig. 16-4) are determined in accordance with ASTM C 138 (AASHTO T 121). The results should be sufficiently accurate to determine the volumetric quantity (yield) of concrete produced per batch (see Chapter 9). The test also can give indications of air content provided the relative densities of the ingredients are known. A balance or scale sensitive to 0.3% of the anticipated mass of the sample and container is required. For example, a 7-liter (0.25-ft^3) density container requires a scale sensitive to 50 g (0.1 lb). The size of the container used to determine density and yield varies with the size of aggregate; if in good condition, the 7-liter (0.25-ft^3) air meter container is commonly used with aggregates up to 25 mm (1 in.); a 14-liter (0.5-ft^3) container is used with aggregates up to 50 mm (2 in.). The container should be calibrated at least annually (ASTM C 1077). Care is needed to consolidate the concrete adequately by either rodding or internal vibration. Strike off the top surface using a flat plate so that the container is filled to a flat smooth finish. The density is expressed in kilograms per cubic meter (pounds per cubic foot) and the yield in cubic meters (cubic feet).

Fig. 16-4. Fresh concrete is measured in a container of known volume to determine density (unit weight). (69785)

The density of unhardened as well as hardened concrete can also be determined by nuclear methods, ASTM C 1040 (AASHTO T 271).

Air Content

A number of methods for measuring air content of freshly mixed concrete can be used. ASTM standards include the pressure method (C 231) (AASHTO T 152), the volumetric method (C 173) (AASHTO T 196), and the gravimetric method (C 138) (AASHTO T 121).

The pressure method (Fig. 16-5) is based on Boyle's law, which relates pressure to volume. Many commercial air meters of this type are calibrated to read air content directly when a predetermined pressure is applied. The applied pressure compresses the air within the concrete sample, including the air in the pores of aggregates. For this reason, tests by this method are not suitable for determining the air content of concretes made with some lightweight aggregates or other very porous materials. Aggregate correction factors that compensate for air trapped in

Fig. 16-5. Pressure-type meter for determining air content. (69766)

Fig. 16-6. Volumetric air meter. (69886)

normal-weight aggregates are relatively constant and, though small, should be subtracted from the pressure meter gauge reading to obtain the correct air content. The instrument should be calibrated for various elevations above sea level if it is to be used in localities having considerable differences in elevation. Some meters utilize change in pressure of a known volume of air and are not affected by changes in elevation. Pressure meters are widely used because the mix proportions and specific gravities of the concrete ingredients need not be known. Also, a test can be conducted in less time than is required for other methods.

The volumetric method (Fig. 16-6) outlined in ASTM C 173 (AASHTO T 196) requires removal of air from a known volume of concrete by agitating the concrete in an excess of water. This method can be used for concrete containing any type of aggregate, including lightweight or porous materials. An aggregate correction factor is not necessary with this test. The volumetric test is not affected by atmospheric pressure, and specific gravity of the concrete ingredients need not be known. Care must be taken to agitate the sample sufficiently to remove all air. The addition of 500 mL (1 pt) of alcohol accelerates the removal of air, thus shortening test times; it also dispels most of the foam and increases the precision of the test, including those performed on high-air-content or high-cement-content concretes.

The gravimetric method utilizes the same test equipment used for determining the density (unit weight) of concrete. The measured density of concrete is subtracted from the theoretical density as determined from the absolute volumes of the ingredients, assuming no air is present (see ASTM C 138 or AASHTO T 121). This difference, expressed as a percentage of the theoretical density, is the air content. Mixture proportions and specific gravities of the ingredients must be accurately known; otherwise results may be in error. Consequently, this method is suitable only where laboratory-type control is exercised. Significant changes in density can be a convenient way to detect variability in air content.

A pocket-size air indicator (AASHTO T 199) can be used as a quick check for the presence of low, medium, or high levels of air in concrete, but it is not a substitute for the other more accurate methods. A representative sample of mortar from the concrete is placed in the container. The container is then filled with alcohol and rolled with the thumb over the open end to remove the air from the mortar. The indicated air content is determined by comparing the drop in the level of the alcohol with a calibration chart. The test can be performed in a few minutes. It is especially useful in checking for the presence of air in concrete near the surface that may have suffered reductions in air because of faulty finishing procedures.

With any of the above methods, air-content tests should be started within 5 minutes after the final portion of the composite sample has been obtained.

Studies into the effect of fly ash on the air-void stability of concrete have resulted in the development of the foam-index test. The test can be used to measure the relative air-entraining admixture requirements for concrete mixtures containing fly ash. The fly ash to be tested is placed in a wide mouth jar along with the air-entraining admixture and shaken vigorously. Following a waiting period of 45 seconds, a visual determination of the stability of the foam or bubbles is made (Gebler and Klieger 1983).

Fig. 16-7. Preparing standard test specimens for compressive strength of concrete. (69790)

Strength Specimens

Specimens molded for strength tests should be made and cured in accordance with ASTM C 31 or AASHTO T 23 (field-molded specimens) or ASTM C 192 or AASHTO T 126 (laboratory-molded specimens). Molding of strength specimens should be started within 15 minutes after the composite sample is obtained.

The standard test specimen for compressive strength of concrete with a maximum aggregate size of 50 mm (2 in.) or smaller is a cylinder 150 mm (6 in.) in diameter by 300 mm (12 in.) high (Fig. 16-7). For larger aggregates, the diameter of the cylinder should be at least three times the maximum-size aggregate, and the height should be twice the diameter. While rigid metal molds are preferred, parafined cardboard, plastic, or other types of disposable molds conforming to ASTM C 470 can be used. They should be placed on a smooth, level, rigid surface and filled carefully to avoid distortion of their shape.

A 100-mm (4-in.) diameter by 200-mm (8-in.) high cylinder mold has been commonly used with high strength concrete containing up to 19 mm (¾ in.) maximum-size aggregate (Burg and Ost 1994, Forstie and Schnormeier 1981, and Date and Schnormeier 1984). The 100 x 200-mm cylinder is easier to cast, requires less sample, weighs considerably less than a 150 x 300-mm (6 x 12-in.) concrete cylinder; it is therefore easier to handle and requires less moist-curing storage space. In addition, the smaller cross-sectional area allows higher compressive strengths to be reached by a testing machine that has a smaller load capacity. The difference in indicated strength between the two cylinder sizes is insignificant as illustrated in Fig. 16-8. The standard deviation and coefficient of variation of 100-mm cylinders is slightly higher or similar to that for 150-mm cylinders (Burg and others 1999 and Pistilli and Willems 1993). The predominant size used in Canada is the 100-mm diameter cylinder. Consult job specifications for allowable cylinder sizes.

Beams for the flexural strength test should be 150 x 150 mm (6 x 6 in.) in cross section for aggregates up to 50 mm (2 in.). For larger aggregates, the minimum cross-sectional dimension should be not less than three times the maximum size of aggregate. The length of beams should be at least three times the depth of the beam plus 50 mm (2 in.), or a total length of not less than 500 mm (20 in.) for a 6 x 6-in. beam.

Test cylinders to be rodded (slump of 25 mm [1 in.] or more) should be filled in three approximately equal layers with each

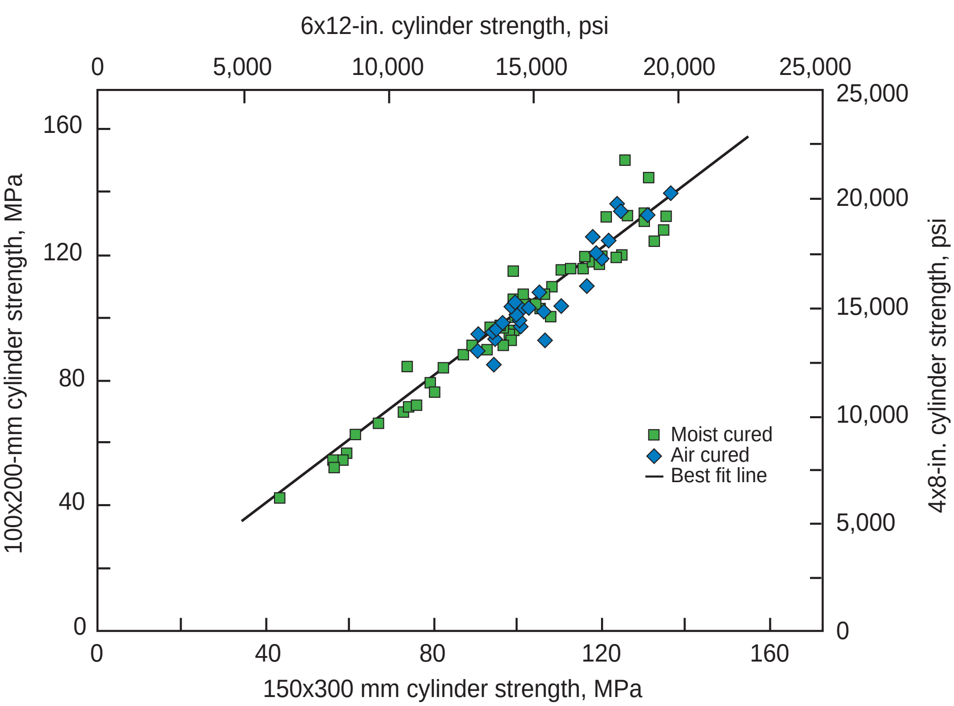

Fig. 16-8. Comparison of 100 x 200-mm (4 x 8-in.) and 150 x 300-mm (6 x 12-in.) cylinder strengths (Burg and Ost 1994).

layer rodded 25 times for 150-mm (6-in.) diameter cylinders; beam specimens up to 200 mm (8 in.) deep should be filled in two equal layers with each layer rodded once with a 16-mm (⅝-in.) rod for each 1400 mm² (2 in.²) of the specimen's top surface area. If the rodding leaves holes, the sides of the mold should be lightly tapped with a mallet or open hand. Cylinders to be vibrated should be filled in two layers with one insertion per layer for 100-mm (4-in.) diameter cylinders and two insertions per layer for 150-mm (6-in.) cylinders.

Beams over 200 mm (8 in.) deep and cylinders 300 to 450 mm (12 to 18 in.) deep to be vibrated (slump of 75mm [3 in.] or less) should be filled in two layers; beams 150 to 200 mm (6 to 8 in.) deep to be vibrated can be filled in one layer. Internal vibrators should have a maximum width of no more than ⅓ the width of beams or ¼ the diameter of cylinders. Immediately after casting, the tops of the specimens should be (1) covered with an oiled glass or steel plate, (2) sealed with a plastic bag, or (3) sealed with a plastic cap.

The strength of a test specimen can be greatly affected by jostling, changes in temperature, and exposure to drying, particularly within the first 24 hours after casting. Thus, test specimens should be cast in locations where subsequent movement is unnecessary and where protection is possible. Cylinders and test beams should be protected from rough handling at all ages. Remember to identify specimens on the exterior of the mold to prevent confusion and errors in reporting. Do not etch identification numbers into the surface of fresh concrete test specimens. Use tape or identification tags that do not damage the sample.

Standard testing procedures require that specimens be cured under controlled conditions, either in the laboratory (Fig. 16-9) or in the field. Controlled laboratory curing in a moist room or in a limewater storage tank gives an accurate indication of the quality of the concrete as delivered. Limewater must be saturated with hydrated lime, not agricultural lime, in accordance with ASTM C 511 (AASHTO M 201) to prevent leaching of lime from concrete specimens.

Fig. 16-9. Controlled moist curing in the laboratory for standard test specimens at a relative humidity of 95% to 100% and temperature of 23±2°C (73±3°F) (ASTM C 511 or AASHTO M 201). (8974)

Specimens cured in the field in the same manner as the structure more closely represent the actual strength of concrete in the structure at the time of testing; however, they give little indication of whether a deficiency is due to the quality of the concrete as delivered or to improper handling and curing. On some projects, field-cured specimens are made in addition to those destined for controlled laboratory curing; these are especially useful when the weather is unfavorable, to determine when forms can be removed, or when the structure can be put into use. For more information see "Strength Tests of Hardened Concrete" in this chapter and ASTM (2000).

In-place concrete strength development can also be evaluated by maturity testing (ACI Committee 306 and ASTM C 1074), which was discussed in Chapter 14.

Time of Setting

Test method ASTM C 403 (AASHTO T 197) is used to determine the time of setting of concrete by means of penetration resistance measurements made at regular time intervals on mortar sieved from the concrete mixture (Fig.

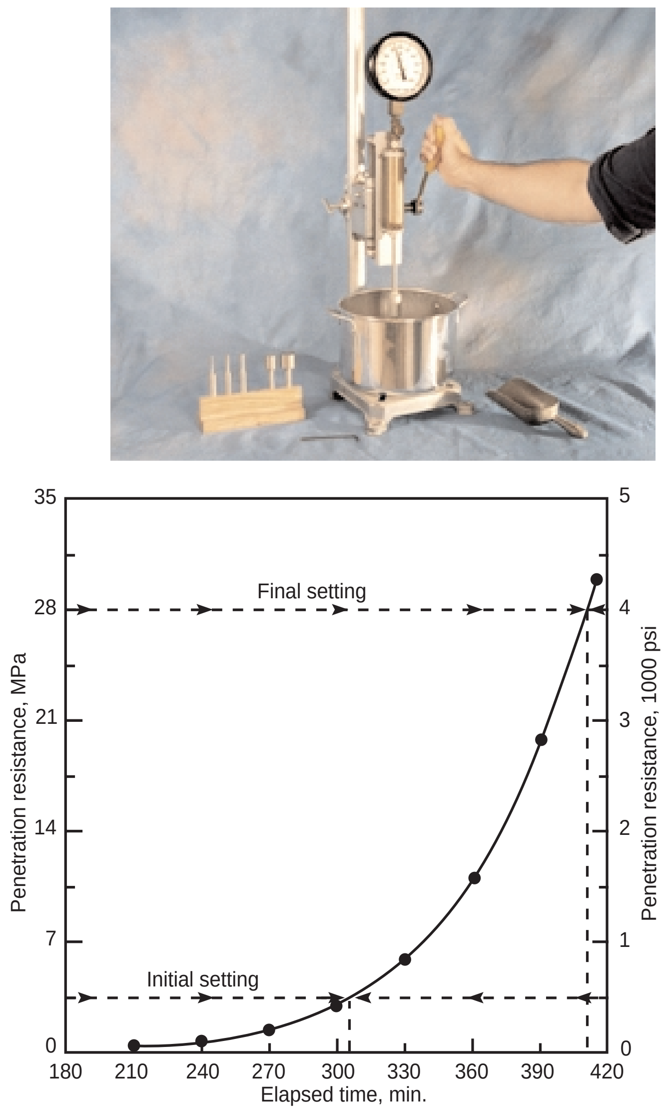

Fig. 16-10. (top) Time of setting equipment. (bottom) Plot of test results. (69788)

16-10). The initial and final time of setting is determined as the time when the penetration resistance equals 3.4 MPa (500 psi) and 27.6 MPa (4000 psi), respectively. Typically, initial set occurs between 2 and 6 hours after batching and final set occurs between 4 and 12 hours. The rate of hardening of concrete greatly influences the rate of which construction progresses. Temperature, water-cementing materials ratio, and admixtures all affect setting time.

Accelerated Compression Tests to Project Later-Age Strength

The need to assess the quality of concrete at early ages in comparison to traditional 28-day tests has received much attention due to the quickening pace of today's construction. ASTM has developed two methods for estimating later-age strengths of concrete specimens based upon early-age tests.

ASTM C 684 uses accelerated strength tests to expedite quality control of concrete. Cylinder strength tests are accelerated using one of four curing procedures: warm water at 35°C ± 3°C (95°F ± 5°F), boiling water, autogenous (insulated), and high temperature at 150°C ± 3°C (300°F ± 5°F). Accelerated strength tests are performed at ages ranging between 5 and 49 hours, depending on the curing procedure used. Later-age strengths are estimated using previously established relationships between accelerated strength and standard 28-day compressive strength tests.

ASTM C 918 uses the maturity method of monitoring temperature of cylinders cured in accordance with standard methods outlined in ASTM C 31 (AASHTO T 23). Cylinders are tested at early ages beyond 24 hours, and the concrete temperature history is used to compute the maturity index at the time of test. Using historic data, a prediction equation is developed to project the strength at later ages based on the maturity index and early-age strength tests. See Carino (1994).

Chloride Content

The chloride content of concrete and its ingredients should be checked to make sure it is below the limit necessary to avoid corrosion of reinforcing steel. An approximation of the water-soluble chloride content of freshly mixed concrete, aggregates, and admixtures can be made using a method initiated by the National Ready Mixed Concrete Association (NRMCA 1986). A determination of the total chloride content of freshly mixed concrete may be made by summing up the chloride contents of all of the individual constituents of the mix. The NRMCA method gives a quick approximation and should not be used to determine compliance. See Chapter 9 for chloride-ion limitations for concrete.

Portland Cement Content, Water Content, and Water-Cement Ratio

Test methods are available for estimating the portland cement and water content of freshly mixed concrete. These test results can assist in determining the strength and durability potential of concrete prior to setting and hardening and can indicate whether or not the desired cement and water contents were obtained. ASTM test methods C 1078-87 and C 1079-87 (discontinued in 1998), based on the Kelly-Vail method, can be used to determine cement content and water content, respectively. Experimental methods using microwave absorption have been developed to estimate water to cement ratio. The disadvantage of these test methods is they require sophisticated equipment and special operator skills, which may not be readily available.

Other tests for determining cement or water contents can be classified into four categories: chemical determination, separation by settling and decanting, nuclear related, and electrical. The Rapid Analysis Machine and nuclear cement gage have been used to measure cement contents (Forester, Black, and Lees 1974 and PCA 1983). The microwave oven (AASHTO T 23) and neutron-scattering methods have been used to measure water contents. For an overview of these and other tests from all four categories, see Lawrence (1994). A combination of these tests can be run independently of each other to determine either cement content or water content to calculate the water-cement ratio.

Supplementary Cementitious Materials Content

Standard test methods are not available for determining the supplementary cementitious materials content of freshly mixed concrete. However, the presence of certain supplementary cementitious materials, such as fly ash, can be determined by washing a sample of the concrete's mortar over a 45 µm (No. 325) sieve and viewing the residue retained with a stereo microscope (150 to 250X) (Fig. 16-11). Fly ash particles appear as spheres of various colors. Sieving the mortar through a 150 or 75 µm (No. 100 or 200) sieve is helpful in removing sand grains.

Bleeding of Concrete

The bleeding properties of fresh concrete can be determined by two methods described in ASTM C 232 (AASHTO T 158). One method consolidates the specimen by tamping without further disturbance; the other method consolidates the specimen by vibration after which the specimen is vibrated intermittently throughout the test. The amount of bleed water at the surface is expressed as the volume of bleed water per unit area of exposed concrete, or as a percentage of the net mixing water in the test specimen. Typical values range from 0.01 to 0.08

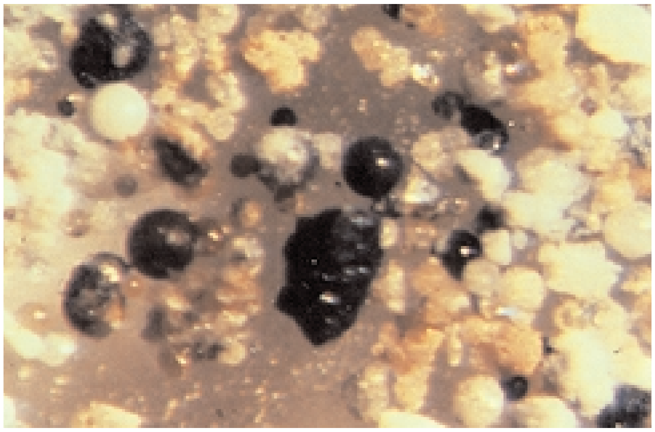

Fig. 16-11. Fly ash particles retained on a 45 µm sieve after washing, as viewed through a microscope at 200X. (58949)

Fig. 16-12. ASTM C 232 (AASHTO T 158) test for bleeding of concrete; Method A without vibration. The container has an inside diameter of about 255 mm (10 in.) and height of about 280 mm (11 in.). The container is filled to a height of about 255 mm and covered to prevent evaporation of the bleed water. (69780)

mL / cm^2 or 0.1% to 2.5% of mix water. The bleeding test is rarely used in the field (Fig. 16-12). Bleeding was also discussed in Chapter 1.

TESTING HARDENED CONCRETE

Premolded specimens described in the previous section "Strength Specimens" (ASTM C 31 [AASHTO T 23], ASTM C 192 [AASHTO T 126], or ASTM C 873), or samples of hardened concrete obtained from construction or laboratory work (ASTM C 42 [AASHTO T 24], ASTM C 823, or ASTM C 873) can be used in tests on hardened concrete. Separate specimens should be obtained for each test performed because specimen preconditioning for certain tests can make the specimen unusable for other tests.

Strength Tests of Hardened Concrete

Strength tests of hardened concrete can be performed on the following: (1) cured specimens molded in accordance with ASTM C 31 or C 192 (AASHTO T 23 and T 126) from samples of freshly mixed concrete; (2) in-situ specimens cored or sawed from hardened concrete in accordance with ASTM C 42 (AASHTO T 24); or (3) specimens made from cast-in-place cylinder molds, ASTM C 873 (Fig. 16-13).

Cast-in-place cylinders can be used in concrete that is 125 to 300 mm (5 to 12 in.) in depth. The mold is filled in the normal course of concrete placement. The specimen is then cured in place and in the same manner as the rest of the concrete section. The specimen is removed from the concrete and mold immediately prior to testing to determine the in-place concrete strength. This method is particularly applicable in cold-weather concreting, post-tensioning work, slabs, or any concrete work where a minimum in-place strength must be achieved before construction can continue.

For all methods, cylindrical samples should have a diameter at least three times the maximum size of coarse aggregate in the concrete and a length as close to twice the diameter as possible. Correction factors are available in ASTM C 42 (AASHTO T 24) for samples with lengths of 1 to 2 times the diameter. Cores and cylinders with a height of less than 95% of the diameter before or after capping should not be tested. Use of a minimum core diameter of 95 mm (3.75 in.) is suggested where a length to diameter (L / D) ratio greater than one is possible.

Drilled cores should not be taken until the concrete can be sampled without disturbing the bond between the mortar and the coarse aggregate. For horizontal surfaces, cores should be taken vertically and not near formed joints or edges. For vertical or sloped faces, cores should be taken perpendicular to the central portion of the concrete element. Although diamond-studded coring bits can cut through reinforcing steel, it should be avoided if possible

Fig. 16-13. Concrete cylinders cast in place in cylindrical molds provide a means for determining the in-place compressive strength of concrete. (69781)

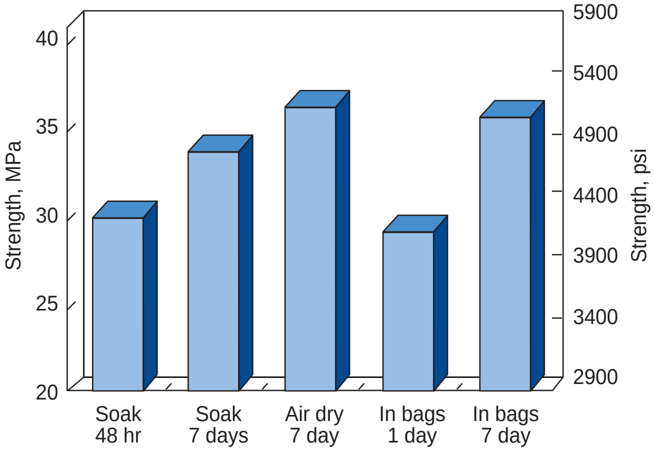

Fig. 16-14. Effect of core conditioning on strength of drilled cores (Fiorato, Burg and Gaynor 2000).

Fig. 16-15. Testing hardened concrete specimens: (left) cylinder, (right) beam (44178, 69684).

when obtaining compression test specimens. A covermeter (electromagnetic device) or a surveyor's magnetic locator can be used to locate reinforcing steel. Cores taken from structures should be tested in a moisture condition as near as that of the in-place concrete as possible. Conditioning options for preparing specimens are described in ASTM C 42 (AASHTO T 24) and ACI 318.

Fig. 16-14 shows the effects of core conditioning on the strength of drilled core samples. Forty-eight hour water immersion of the specimens prior to testing yields significantly lower test results than air-drying specimens for seven days prior to testing. Measured strengths varied by up to 25%, depending upon the time and type of conditioning prior to testing.

Flexure test specimens that are saw-cut from in-place concrete are always immersed in lime-saturated water at 23.0°C ± 2.0°C (73.5°F ± 3.5°F) for at least 40 hours immediately prior to testing.

Test results are greatly influenced by the condition of the ends of cylinders and cores. For compression testing, specimens should be ground or capped in accordance with the requirements of ASTM C 617 (AASHTO T 231) or ASTM C 1231. Various commercially available materials can be used to cap compressive test specimens. ASTM C 617 (AASHTO T 231) outlines methods for using sulfur mortar capping. Caps must be allowed to harden at least two hours before the specimens are tested. Unbonded neoprene caps can be used to test molded cylinders if quick results are needed. Sulfur mortar caps should be made as thin as is practical to avoid a cap failure that might reduce test results.

ASTM C 1231 describes the use of unbonded neoprene caps that are not adhered or bonded to the ends of the specimen. This method of capping uses a disk-shaped 13 ± 2-mm (½ ± 1⁄16-in.) thick neoprene pad that is approximately the diameter of the specimen. The pad is placed in a cylindrical steel retainer with a cavity approximately 25 mm (1 in.) deep and slightly smaller than the diameter of the pad. A cap is placed on one or both ends of the cylinder; the specimen is then tested in accordance with ASTM C 39 (AASHTO T 22) with the added step to stop the test at 10% of the anticipated load to check that the axis of the cylinder is vertical within a tolerance of 0.5°. If either the perpendicularity of the cylinder end, or the vertical alignment during loading are not met, the load applied to the cylinder may be concentrated on one side of the specimen. This can cause a short shear fracture in which the failure plane intersects the end of the cylinder. This type of fracture usually indicates the cylinder failed prematurely, yielding results lower than the actual strength of the concrete. If perpendicularity requirements are not met, the cylinder can be saw-cut, ground, or capped with a sulfur mortar compound in accordance with ASTM C 617 (AASHTO T 231).

Short shear fractures can also be reduced by: dusting the pad and end of cylinder with corn starch or talcum powder, preventing excess water from cylinders or burlap from draining into the retainer and below the pad, and checking bearing surfaces of retainers for planeness and indentations. In addition, annually clean and lubricate the spherically seated block and adjacent socket on the compression machine.

Testing of specimens (Fig. 16-15) should be done in accordance with (1) ASTM C 39 (AASHTO T 22) for compressive strength, (2) ASTM C 78 (AASHTO T 97) for flexural strength using third-point loading, (3) ASTM C 293 (AASHTO T 177) for flexural strength using center-point loading, and (4) ASTM C 496 (AASHTO T 198) for splitting tensile strength. Fig. 16-16 shows the correlation between compressive strength and flexural strength test results.

For both pavement thickness design and pavement mixture proportioning, the modulus of rupture (flexural strength) should be determined by the third-point loading test (ASTM C 78 or AASHTO T 97). However, modulus of rupture by center-point loading (ASTM C 293 or AASHTO T 177) or cantilever loading can be used for job control if empirical relationships to third-point loading test results are determined before construction starts.

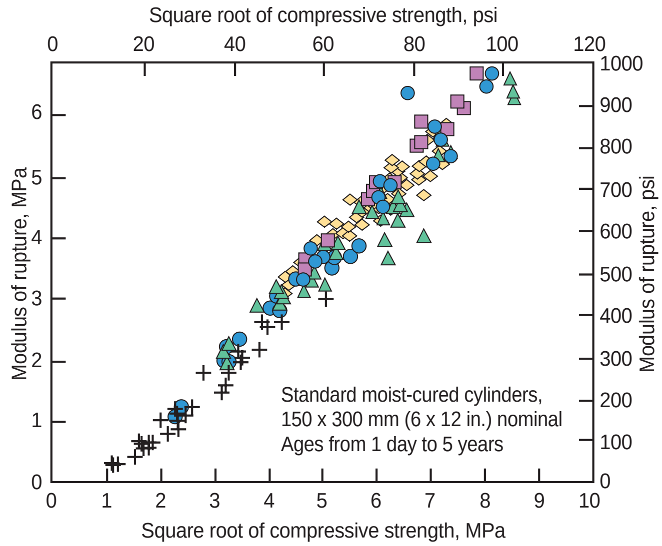

Fig. 16-16. Long-term data show that compressive strength is proportional to the square root of flexural strength (measured by third-point loading) over a wide range of strength levels (Wood 1992).

The moisture content of the specimen has considerable effect on the resulting strength (Fig. 16-15). Beams for flexural tests are especially vulnerable to moisture gradient effects. A saturated specimen will show lower compressive strength and higher flexural strength than those for companion specimens tested dry. This is important to consider when cores taken from hardened concrete in service are compared with molded specimens tested as taken from the moist-curing room or water storage tank. Cylinders used for acceptance testing for a specified strength must be cured in accordance with ASTM C 31 and C 511 (AASHTO T 23 and M 201) to accurately represent the quality of the concrete. However, cores are subject to workmanship, variable environmental site conditions, and variable conditioning after extraction. Cores are tested in either a dry or moist condition, but rarely in a saturated condition similar to lab-cured cylinders. Because cores and cylinders are handled in very different ways, they cannot be expected to yield the same results.

The amount of variation in compressive-strength testing is far less than for flexural-strength testing. To avoid the extreme care needed in field flexural-strength testing, compressive-strength tests can be used to monitor concrete quality; however, a laboratory-determined empirical relationship (Fig. 16-16) must be developed between the compressive and flexural strength of the concrete used (Kosmatka 1985a). Because of this empirical relationship and the economics of testing cylinders instead of beams, most state departments of transportation are now utilizing compression tests of cylinders to monitor concrete quality for their pavement and bridge projects.

Evaluation of Compression Test Results. The ACI 318 building code states that the compressive strength of concrete can be considered satisfactory if the following conditions are met: the averages of all sets of three consecutive strength tests equal or exceed the specified 28-day strength f'_c and no individual strength test (average of two cylinders) is more than 3.5 MPa (500 psi) below the specified strength. If the results of the cylinder tests do not meet this criteria, the strength of the in-place concrete should be evaluated by drilled cores.

In addition to the two 28-day cylinders, job specifications often require one or two 7-day cylinders and one or more “hold” cylinders. The 7-day cylinders monitor early strength gain. Hold cylinders are commonly used to provide additional information in case the 28-day cylinders are damaged or do not meet the required compressive strength. For low 28-day test results, the hold cylinders are typically tested at 56 days in age.

Protection and curing procedures should also be evaluated to judge if they are adequate when field-cured cylinders have a strength of less than 85% of that of companion laboratory-cured cylinders. The 85% requirement may be waived if the field-cured strength exceeds f'_c by more than 3.5 MPa (500 psi).

When necessary, the in-place concrete strength should be determined by testing three cores for each strength test taken in the portion of the structure where the laboratory-cured cylinders did not meet acceptance criteria. Moisture conditioning of cores prior to compression testing should follow the guidelines in ASTM C 42 (AASHTO T 24) or ACI 318.

Nondestructive test methods are not a substitute for core tests (ASTM C 42 or AASHTO T 24). If the average strength of three cores is at least 85% of f'_c, and if no single core is less than 75% of f'_c, the concrete in the area represented by the cores is considered structurally adequate. If the results of properly made core tests are so low as to leave structural integrity in doubt, load tests as outlined in Chapter 20 of ACI 318 may be performed. Refer to Chapter 9 and NRMCA (1979), ACI Committee 214 (1997), and ACI Committee 318 (1999).

Air Content

The air-content and air-void-system parameters of hardened concrete can be determined by ASTM C 457. The hardened air-content test is performed to assure that the air-void system is adequate to resist damage from a freeze-thaw environment. The test is also used to determine the effect different admixtures and methods of placement and consolidation have on the air-void system. The test can be performed on premolded specimens or samples removed from the structure. Using a polished section of a concrete sample, the air-void system is documented by making measurements using a microscope. The information obtained from this test includes the volume of entrained and entrapped air, its specific surface (surface area of the air voids), the spacing factor, and the number of voids per

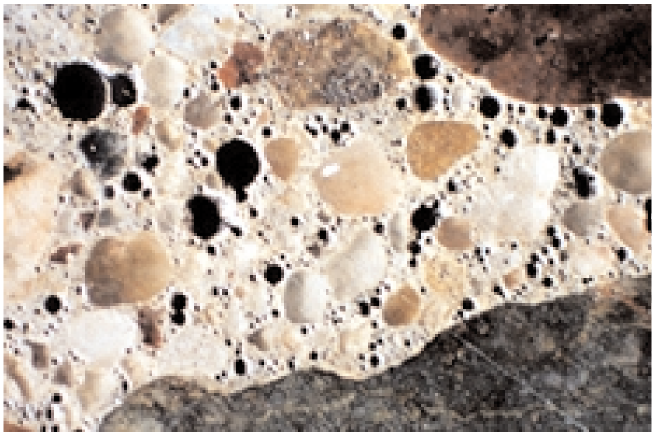

Fig. 16-17. View of concrete air-void system under a microscope. (67840)

lineal distance (Fig. 16-17). See Chapter 8 "Air-Entrained Concrete," for more information.

Density, Relative Density (Specific Gravity), Absorption, and Voids

The density, relative density (specific gravity), absorption, and voids content of hardened concrete can be determined in accordance with ASTM C 642 procedures (Table 16-2). It should be noted that the boiling procedure in ASTM C 642 can render the specimens useless for certain additional tests, especially strength tests. The density can be obtained by multiplying the relative density (specific gravity) by the density of water (1000 kg / m^3 or 62.4 lb / ft^3).

Saturated, surface-dry density (SSD) is often required for specimens to be used in other tests. In this case, the density can be determined by soaking the specimen in water for 48 hours and then determining its weight in air (when SSD) and immersed in water. The SSD density is then calculated as follows:

$$D_{SSD} = \frac{M_1 \rho}{M_1 - M_2}$$

where

D_{SSD} is density in the SSD condition

M_1 is the SSD mass in air, kg (lb)

M_2 is the apparent mass immersed in water, kg (lb)

ρ is the density of water, 1000 kg / m^3 (62.4 lb / ft^3)

The SSD density provides a close indication of the freshly mixed density of concrete. The density of hardened concrete can also be determined by nuclear methods (ASTM C 1040 or AASHTO T 271).

Table 16-2. Permeability and Absorption of Concretes Moist Cured 7 Days and Tested After 90 Days.

Mix No.	Cement, kg/m^3 (lb/yd^3)	w/cm	Compressive strength at 90 days, MPa (psi)	Permeability				Por-osity, %†	Vol. of permeable voids, %	Absorption after im-mersion, %	Absorption after im-mersion and boiling, %
				RCPT, coulombs	90 days ponding, % Cl	Water, m/s**	Air, m/s**				
			ASTM C 39 (AASHTO T 22)	ASTM C 1202 (AASHTO T 277)	AASHTO T 259	API RP 27	API RP 27		ASTM C 642	ASTM C 642	ASTM C 642
1	445 (750)	0.26*	104.1 (15100)	65	0.013	—	2.81×10^{-10}	7.5	6.2	2.43	2.56
2	445 (750)	0.29*	76.7 (11130)	852	0.022	—	3.19×10^{-10}	8.8	8.0	3.13	3.27
3	381 (642)	0.40*	46.1 (6690)	3242	0.058	2.61×10^{-13}	1.16×10^{-9}	11.3	12.2	4.96	5.19
4	327 (550)	0.50	38.2 (5540)	4315	0.076	1.94×10^{-12}	1.65×10^{-9}	12.5	12.7	5.45	5.56
5	297 (500)	0.60	39.0 (5660)	4526	0.077	2.23×10^{-12}	1.45×10^{-9}	12.7	12.5	5.37	5.49
6	245 (413)	0.75	28.4 (4120)	5915	0.085	8.32×10^{-12}	1.45×10^{-9}	13.0	13.3	5.81	5.90

* Admixtures: 59.4 kg / m^3 (100 lb / yd^3) silica fume and 25.4 ml / kg of cement (30 fl.oz / cwt) HRWR (Mix 1); 13.0 ml / kg (20 fl.oz / cwt) HRWR (Mix 2); 2.2 ml / kg (3.4 fl. oz / cwt) WR (Mix 3).
** To convert from m / s to Darcy, multiply by 1.03×10^5, from m / s to m^2, multiply by 1.02×10^{-7}.
† Measured with helium porosimetrie.
Adapted from Whiting (1988).

Portland Cement Content

The portland cement content of hardened concrete can be determined by ASTM C 1084 (AASHTO T 178) standard methods. Although not frequently performed, the cement content tests are valuable in determining the cause of lack of strength gain or poor durability of concrete. Aggregate content can also be determined by these tests. However, the user of these test methods should be aware of certain admixtures and aggregate types that can alter test results. The presence of supplementary cementitious materials would be reflected in the test results.

Supplementary Cementitious Material and Organic Admixture Content

The presence and amount of certain supplementary cementitious materials, such as fly ash, can be determined by petrographic techniques (ASTM C 856). A sample of the supplementary cementitious material used in the concrete is usually necessary as a reference to determine the type and amount of the supplementary cementitious material present. The presence and possibly the amount of an organic admixture (such as a water reducer) can be determined by infrared spectrophotometry (Hime, Mivelaz, and Connolly 1966).

Chloride Content

Concern with chloride-induced corrosion of reinforcing steel has led to the need to monitor and limit the chloride content of reinforced concrete. Limits on the water-soluble chloride-ion content of hardened reinforced concrete are given in ACI 318. The water-soluble chloride-ion content of hardened concrete can be determined in accordance with procedures outlined in ASTM C 1218. In addition, ASTM C 1152 can be used to determine the acid-soluble chloride content of concrete which in most cases is equivalent to total chloride.

Many of the above tests for chloride-ion content also extract chloride-ions from the fine and coarse aggregates that generally do not contribute to corrosion of reinforcing steel. ASTM PS 118 (to be redesignated as ASTM C 1500) is a standard for the analysis of aggregate for water-extractable chloride (Soxhlet method). It is used when chloride contents have been found to be significantly high in aggregates, concretes, or mortars when tested by either ASTM C 1152 or C 1218. Because ASTM PS 118 does not pulverize the aggregates as other tests do, it theoretically measures more closely the chloride-ions available for corrosion. ACI 222.1 is also a Soxhlet procedure that tests chunks of concrete for water-extractable chloride. The true meaning of results from the Soxhlet procedures is still being debated.

Petrographic Analysis

Petrographic analysis uses microscopic techniques described in ASTM C 856 to determine the constituents of concrete, concrete quality, and the causes of inferior performance, distress, or deterioration. Estimating future performance and structural safety of concrete elements can be facilitated. Some of the items that can be reviewed by a petrographic examination include paste, aggregate, fly ash, and air content; frost and sulfate attack; alkali-aggregate reactivity; degree of hydration and carbonation; water-cement ratio; bleeding characteristics; fire damage; scaling; popouts; effect of admixture; and several other aspects. Almost any kind of concrete failure can be analyzed by petrography (St. John, Poole, and Sims 1998). However, a standard petrographic analysis is sometimes accompanied by "wet" chemical analyses, infrared spectroscopy, X-ray diffractometry, scanning electron microscopy with attendant elemental analysis, differential thermal analysis, and other analytical tools.

The Annex to ASTM C 856 (AASHTO T 299) describes a technique for field and laboratory detection of alkali-silica gel. Using this method, a uranyl-acetate solution is applied to a broken or roughened concrete surface that has been dampened with distilled or deionized water. After one minute, the solution is rinsed off and the treated surface is viewed under ultraviolet light. Areas of gel fluoresce bright yellow-green. It must be recognized, however, that several materials not related to ASR in concrete can fluoresce and interfere with an accurate indication of ASR gel. Materials that fluoresce like gel include: naturally fluorescent minerals, carbonated paste, opal, and some other rock ingredients, and reactions from fly ash, silica fume, and other pozzolans. ASTM C 856 includes a prescreening procedure that gives a visual impression to compensate for the effects of these materials. However, this test is considered ancillary to more definitive petrographic examinations and other tests. In addition, the toxicity and radioactivity of uranyl acetate warrants special handling and disposal procedures regarding the solution and treated concrete. Caution regarding potential eye damage from ultraviolet light also merits attention.

The Los Alamos method is a staining technique that does not require ultraviolet light or uranyl-acetate solution. Instead, solutions of sodium cobaltinitrite and rhodamine B are used to condition the specimen and produce a dark pink stain that corresponds to calcium-rich ASR gel. It should be noted that these methods can produce evidence of ASR gel without causing damage to concrete. ASR gel can be present when other mechanisms such as freeze-thaw action, sulfate attack, and other deterioration mechanisms have caused the damage. These rapid methods for detecting the presence of ASR gel are useful but their limitations must be understood. Neither of the rapid procedures is a viable substitute for petrographic examination coupled with proper field inspection (Powers 1999).

Volume and Length Change

Volume or length change limits are sometimes specified for certain concrete applications. Volume change is also of concern when a new ingredient is added to concrete to make sure there are no significant adverse effects. ASTM C 157 (AASHTO T 160) (water and air storage methods) determines length change in concrete due to drying shrinkage, chemical reactivity, and forces other than those intentionally applied. Determination of early volume change of concrete before hardening can be performed using ASTM C 827. Creep can be determined in accordance with ASTM C 512. The static modulus of elasticity and Poisson's ratio of concrete in compression can be determined by methods outlined in ASTM C 469 and dynamic values of these parameters can be determined by using ASTM C 215.

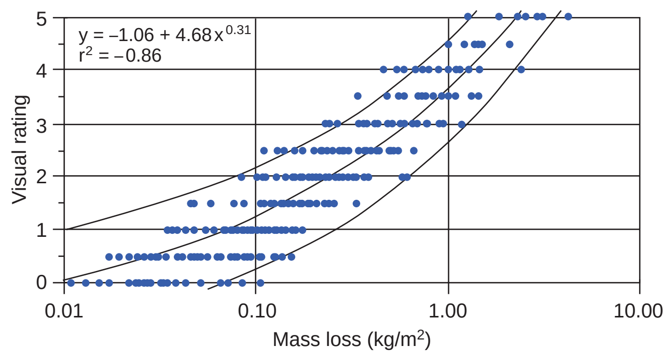

Fig. 16-18. Correlation between mass loss and visual rating for each specimen tested according to ASTM C 672 (Pinto and Hover 2001).

Durability

Durability refers to the ability of concrete to resist deterioration from the environment or from the service in which it is placed. Properly designed concrete should endure without significant distress throughout its service life. In addition to tests for air content and chloride content described previously, the following tests are used to measure the durability of concrete:

Frost Resistance. The freeze-thaw resistance of concrete is usually determined in accordance with ASTM C 666 (AASHTO T 161). Samples are monitored for changes in dynamic modulus, mass, and volume over a period of 300 or more cycles of freezing and thawing. ASTM C 617 (AASHTO T 231) and ASTM C 682 are also available to evaluate frost resistance. Concrete that will be exposed to deicers as well as saturated freezing should be tested according to ASTM C 672 for deicer-scaling resistance. Although ASTM C 672 requires that only surface scaling be monitored, many practitioners also measure mass loss, as is done in Canada (Fig. 16-18). Concrete mixtures that perform well in ASTM C 666 (AASHTO T 161) do not always perform well in ASTM C 672. ASTM C 666 (AASHTO T 161) and ASTM C 672 are often used to evaluate innovative mix designs, or new materials such as chemical admixtures, supplementary cementitious materials, and aggregates to determine their effect on frost and deicer resistance.

Sulfate Resistance. The sulfate resistance of concrete materials can be evaluated by using a saturated mortar bar test, ASTM C 1012. This test is valuable in assessing the sulfate resistance of concrete that will be continuously wet, but it does not evaluate the more aggressive wet-dry cycling environment. The test can be modified to include wet-dry cycling or the U.S. Bureau of Reclamation's wet-dry concrete prism test for sulfate attack can be used. ASTM D 516 (AASHTO T 290) or the Bureau's method (U.S. Bureau of Reclamation 1975) can be used to test soil and water for sulfate ion content to determine the severity of the sulfate exposure (ASTM is currently developing a new test).

Alkali-Silica Reactivity. Alkali-silica reaction is best controlled at the design stage when selecting materials for use in a specific concrete mixture. Aggregate can be tested for potential alkali-silica reactivity by using the ASTM C 227 mortar bar test (for moderate to highly reactive aggregate), ASTM C 289 chemical method (for highly reactive aggregate), ASTM C 295 (petrographic analysis), ASTM C 1260 (AASHTO T 303) rapid mortar bar, and ASTM C 1263 concrete prism test. Materials, such as fly ash and slag, are often used to control alkali-silica reaction; they should be evaluated by tests such as ASTM C 227, ASTM C 441, modified C 1260 (PCA 1998), or C 1293 to determine their effectiveness. An alternate to testing aggregate separately for potential reactivity is to test the concrete mixture to be used on the job; here one would use ASTM C 1260 (modified) or C 1293. A rapid 13-week version of ASTM C 1293 is being developed by the University of Texas at Austin through the International Center for Aggregate Research (Touma, Fowler, Folliard, and Nelson 2001). Existing concrete structures can be evaluated for alkali-silica reaction using ASTM C 856.

Alkali-Carbonate Reactivity. Alkali-carbonate reactivity is more rare than alkali-silica reactivity. Potential reactivity of aggregates can be evaluated by using ASTM C 295, ASTM C 586 rock cylinder, and ASTM C 1105. Existing concrete structures can be evaluated for alkali-carbonate reaction using ASTM C 856.

Corrosion Resistance. The corrosion resistance of reinforced concrete is rarely tested unless unusual materials are used, concrete will be used in a very severe environment, or there is a need to evaluate the potential for in-place corrosion. Corrosion activity can be evaluated using ASTM C 876.

Abrasion Resistance. Abrasion resistance can be determined by using ASTM C 418 (sandblasting), ASTM C 779 (revolving disk, dressing wheel, and ball bearing methods), ASTM C 944 (rotating cutter), and ASTM C 1138 (underwater test).

Moisture Testing

The in-place moisture content, water vapor emission rate, and relative humidity of hardened concrete are useful indicators in determining if concrete is dry enough for application of floor-covering materials and coatings. The moisture content of concrete should be low enough to avoid spalling when exposed to temperatures above the boiling point of water. Moisture related test methods fall into two general categories: either qualitative or quantitative. Qualitative tests provide an indication of the presence or absence of moisture while quantitative tests measure the amount of moisture. Qualitative tests may give a strong indication that excessive moisture is present and the floor is not ready for floor-covering materials. Quantitative tests are performed to assure that the floor is dry enough for these materials.

Qualitative moisture tests include: plastic sheet, mat bond, electrical resistance, electrical impedance, and nuclear moisture gauge tests. The plastic sheet test (ASTM D 4263) uses a square sheet of clear plastic film that is taped to the slab surface and left for 24 hours to see if moisture develops under it. The plastic sheet test is unreliable. In the mat bond test, a 1-m^2 (9-ft^2) sheet of floor covering is glued to the floor with the edges taped to the concrete for 72 hours. The force needed to remove the flooring is an indication of the slab moisture condition. Electrical resistance is measured using a moisture meter through two probes placed in contact with the concrete. Electrical impedance uses an electronic signal that is influenced by the moisture in the concrete. Nuclear moisture gauges contain high-speed neutrons that are slowed by the hydrogen atoms in water. The affect of these encounters is a measure of the moisture content of the concrete. Although the last three tests each yield a numeric test result, their value is quite limited. Experience and skill are needed to judge the trustworthiness of the devices and the test results produced by them.

Quantitative test methods include: gravimetric moisture content, moisture vapor emission rate, and relative humidity probe tests. The most direct method for determining moisture content is to dry cut a specimen from the concrete element in question, place it in a moisture proof container, and transport it to a laboratory for testing. After obtaining the specimen's initial mass, dry the specimen in an oven at about 105°C (220°F) for 24 hours or until constant mass is achieved. The difference between the two masses divided by the dry mass, times 100, is the moisture content in percent. The moisture vapor emission rate (ASTM F 1869) is the most commonly used test in the United States for measuring the readiness of concrete for application of floor coverings. The emission rate is expressed as kilograms (pounds) of moisture emitted from 93 m^2 (1000 ft^2) in 24 hours. See Kosmatka (1985), and PCA (2000) for more information.

Relative humidity tests are used in several countries outside the United States for measuring moisture in concrete slabs. Two British standards, BS 5325: 1996 and BS 8203: 1996 use a hygrometer or relative humidity probe sealed under an insulated, impermeable box to trap moisture in an air pocket above the floor. The probe is allowed to equilibrate for at least 72 hours or until two consecutive readings at 24 hours intervals are within the precision of the instrument (typically ± 3% RH). Acceptable relative humidity limits for the installation of floor coverings range from a maximum of 60% to 90%. It can require several months of air-drying to achieve the desired relative humidity. A method for estimating drying time to reach a specified relative humidity based on water-cement ratio, thickness of structure, number of exposed sides, relative humidity, temperature and curing conditions can be found in Hedenblad (1997), Hedenblad (1998), and Farny (2001).

Carbonation

The depth or degree of carbonation can be determined by petrographic techniques (ASTM C 856) through the observation of calcium carbonate—the primary chemical product of carbonation. In addition, a phenolphthalein color test can be used to estimate the depth of carbonation by testing the pH of concrete (carbonation reduces pH). Upon application of the phenolphthalein solution to a freshly fractured or freshly cut surface of concrete, noncarbonated areas turn red or purple while carbonated areas remain colorless. (Fig. 16-19). The phenolphthalein indicator when observed against hardened paste changes color at a pH of 9.0 to 9.5. The pH of good quality noncarbonated concrete without admixtures is usually greater than 12.5. For more information, see "pH Testing Methods" below, and see Verbeck (1958), Steinour (1964), and Campbell, Sturm, and Kosmatka (1991).

Fig. 16-19. The depth of carbonation is determined by spraying phenolphthalein solution on a freshly broken concrete surface. Noncarbonated areas turn red or purple, carbonated areas stay colorless. (69804)

pH Testing Methods

There are three practical methods for measuring the pH of hardened concrete in the field. The first uses litmus paper designed for the alkaline range of pH readings. Place a few drops of distilled water on the concrete, wait 60 ± 5 seconds and immerse an indicator strip (litmus paper) in the water for 2 to 3 seconds. After removing the strip, compare it to the standard pH color scale supplied with the indicator strips. A second method uses a pH "pencil." The pencil is used to make a 25 mm (1 in.) long mark after which 2 to 3 drops of distilled water are placed on the mark. After waiting 20 seconds, the color is compared to a standard color chart to judge the pH of the concrete. Finally, the third method uses a wide-range liquid pH indicator on a freshly fractured surface of the concrete or a core obtained from the concrete. After several minutes, the resulting color is compared to a color chart to determine the pH of the concrete. This method is also effective for measuring the depth of carbonation present on the concrete surface. See PCA (2000) for more information.

Permeability

Both direct and indirect methods of determining permeability are used. Table 16-2 shows typical concrete permeabilities. Resistance to chloride-ion penetration, for example, can be determined by ponding chloride solution on a concrete surface and, at a later age, determining the chloride content of the concrete at particular depths (AASHTO T 259). The rapid chloride permeability test (RCPT) (ASTM C 1202 and AASHTO T 277), also called the Coulomb or electrical resistance test, is often specified for concrete bridge decks. Various absorption methods, including ASTM C 642, are used. Direct water permeability data can be obtained by using the Army Corp of Engineers CRC C 163-92 test method for water permeability of concrete using a triaxial cell. A test method recommended by the American Petroleum Institute for determining the permeability of rock is also available. ASTM is in the process of developing a standard method for hydraulic permeability of concrete. All the above test methods have limitations. For more information, see American Petroleum Institute (1956), Tyler and Erlin (1961), Whiting (1981), Pfeifer and Scali (1981), and Whiting (1988).

Nondestructive Test Methods

Nondestructive tests (NDT) can be used to evaluate the relative strength and other properties of hardened concrete. The most widely used are the rebound hammer, penetration, pullout, and dynamic or vibration tests. Other techniques for testing the strength and other properties of hardened concrete include X-rays, gamma radiography, neutron moisture gages, magnetic cover meters, electricity, microwave absorption, and acoustic emissions. Each method has limitations and caution should be exercised against acceptance of nondestructive test results as having a constant correlation to the traditional compression test; for example, empirical correlations must be developed prior to use (Malhotra 1976, NRMCA 1979, Malhotra 1984, Clifton 1985, Malhotra and Carino 1991).

An NDT program may be undertaken for a variety of purposes regarding the strength or condition of hardened concrete, including:

- Determination of in-place concrete strength
- Monitoring rate of concrete strength gain
- Location of nonhomogeneity, such as voids or honeycombing in concrete
- Determination of relative strength of comparable members
- Evaluation of concrete cracking and delaminations
- Evaluation of damage from mechanical or chemical forces
- Steel reinforcement location, size, and corrosion activity
- Member dimensions

Irrespective of the type of NDT test used, adequate and reliable correlation data with standard 28-day compressive strength data is usually necessary to evaluate the accuracy of the NDT method. In addition, correlation to in-place compressive strengths using drilled cores from one or two locations can provide guidance in interpreting NDT test results; these can then be used to survey larger portions of the structure. Care should be taken to consider the influence that varying sizes and locations of structural elements can have on the NDT test being used.

Rebound Hammer Tests. The Schmidt rebound hammer (Fig. 16-20) is essentially a surface-hardness tester that provides a quick, simple means of checking concrete uniformity. It measures the rebound of a spring-loaded

Fig. 16-20. The rebound hammer gives an indication of the compressive strength of concrete. (69782)

plunger after it has struck a smooth concrete surface. The rebound number reading gives an indication of the compressive strength and stiffness of the concrete. Two different concrete mixtures having the same strength but different stiffnesses will yield different readings. In view of this, an understanding of the factors influencing the accuracy of the test is required.

The results of a Schmidt rebound hammer test (ASTM C 805) are affected by surface smoothness, size, shape, and rigidity of the specimen; age and moisture condition of the concrete; type of coarse aggregate; and degree of carbonation of the concrete surface. When these limitations are recognized; and the hammer is calibrated for the particular materials used in the concrete (Fig. 16-21) by comparison with cores or cast specimens, then this instrument can be useful for determining the relative compressive strength and uniformity of concrete in the structure.

Penetration Tests. The Windsor probe (ASTM C 803), like the rebound hammer, is basically a hardness tester that provides a quick means of determining the relative strength of the concrete. The equipment consists of a powder-actuated gun that drives a hardened alloy probe into the concrete (Fig. 16-22). The exposed length of the probe is measured and related by a calibration table to the compressive strength of the concrete.

The results of the Windsor-probe test will be influenced by surface smoothness of the concrete and the type and hardness of aggregate used. Therefore, to improve accuracy, a calibration table or curve for the particular concrete to be tested should be made, usually from cores or cast specimens.

Both the rebound hammer and the probe damage the concrete surface to some extent. The rebound hammer leaves a small indentation on the surface; the probe leaves a small hole and may cause minor cracking and small craters similar to popouts.

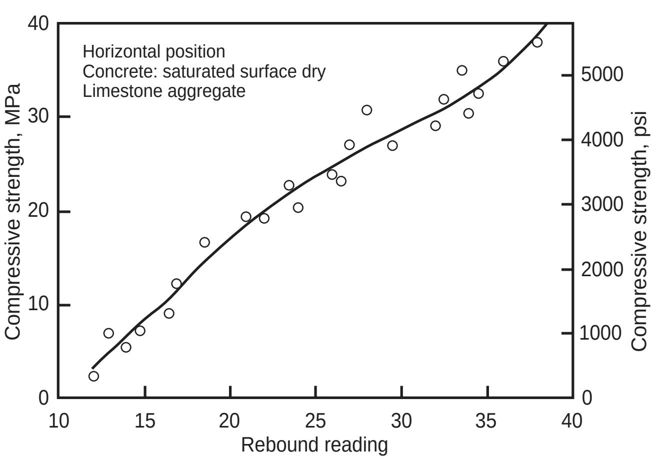

Fig. 16-21. Example of a calibration chart for an impact (rebound) test hammer.

Fig. 16-22. The Windsor-probe technique for determining the relative compressive strength of concrete.
(top) Powder-actuated gun drives hardened alloy probe into concrete. (69783)
(left) Exposed length of probe is measured and relative compressive strength of the concrete then determined from a calibration table. (69784)

Maturity Tests. The maturity principle is that strength gain is a function of time and temperature. ASTM C 1074 generates a maturity index that is based on temperature and time factors. The estimated strength depends on properly determining the strength-maturity function for a particular concrete mixture. The device uses thermocouples or thermistors placed in the concrete and connected to strip-chart recorders or digital data-loggers that record concrete temperature as a function of time. The temperature in relation to time data is correlated to compression tests performed on cylindrical specimens to generate a temperature-time versus strength curve that is used to estimate in-place concrete strength.

Pullout Tests. A pullout test (ASTM C 900) involves casting the enlarged end of a steel rod in the concrete to be tested and then measuring the force required to pull it out (Fig. 16-23). The test measures the direct shear strength of the concrete. This in turn is correlated with the compressive strength; thus a measurement of the in-place compressive strength is made.

Break-Off Tests. The break-off test (ASTM C 1150) determines the in-place strength of the concrete by breaking off an in situ cylindrical concrete specimen at a failure plane parallel to the finished surface of the concrete element. A break-off number is generated and assessed in relation to the strength of the concrete. Similar to pullout tests, the relationship between break-off test numbers and compres-

Fig. 16-23. Pullout test equipment being used to measure the in-place strength of concrete. (44217)

sion tests must also be developed prior to obtaining final test results.

For more information on test methods used to estimate in-place concrete strengths, see ACI Committee 228 (1995).

Dynamic or Vibration Tests. A dynamic or vibration (ultrasonic pulse velocity) test (ASTM C 597) is based on the principle that velocity of sound in a solid can be measured by (1) determining the resonant frequency of a specimen, or (2) recording the travel time of short pulses of vibrations through a sample. High velocities are indicative of good concrete and low velocities are indicative of poor concrete.

Resonant frequency methods employ low-frequency vibration to impart mechanical energy used to detect, locate, and record discontinuities within solids. Resonant frequency is a function of the dynamic modulus of elasticity, poisson ratio, density, and geometry of the structural element. The presence and orientation of surface and internal cracking can be determined. In addition, fundamental transverse, longitudinal, and torsional frequencies of concrete specimens can also be determined by ASTM C 215, a method frequently used in laboratory durability tests such as freezing and thawing (ASTM C 666 or AASHTO T 161).

Stress wave propagation methods using impact-echo tests are employed in ASTM C 1383 to measure P-wave speeds and the thickness of concrete elements such as slabs, pavements, bridge decks and walls. The advantage of the test is that its not only nondestructive, but also access is only required to one side of the structure. Other stress-wave methods not yet mentioned include: ultrasonic-echo and spectral analysis of surface waves.

Other Tests. The use of X-rays for testing concrete properties is limited due to the costly and dangerous high-voltage equipment required as well as radiation hazards.

Gamma-radiography equipment can be used in the field to determine the location of reinforcement, density, and perhaps honeycombing in structural concrete units. ASTM C 1040 (AASHTO T 271) procedures use gamma radiation to determine the density of unhardened and hardened concrete in place.

Battery-operated magnetic detection devices, like the pachometer or covermeter, are available to measure the depth of reinforcement in concrete and to detect the position of rebars. Electrical-resistivity equipment is being developed to estimate the thickness of concrete pavement slabs.

A microwave-absorption method has been developed to determine the moisture content of porous building materials such as concrete. Acoustic-emission techniques show promise for studying load levels in structures and for locating the origin of cracking.

Ground-penetrating (short-pulse) radar is a rapid technique for nondestructive detection of delaminations and other types of defects in overlaid reinforced concrete decks. It also shows potential for monitoring strength development in concrete, measuring the thickness of concrete members, and locating reinforcement.

Infrared thermographic techniques are used to detect and show, both large and small, internal voids, delaminations and cracks in bridges, highway pavements, garage decks, buildings and other structural elements exposed to direct sunlight. For more information, see Malhotra and Carino (1991). ACI Committee 228 (1998) presents additional information on these and other nondestructive test methods.

Finally, acoustic impact methods also employ simple hammer and chain drag soundings that are low-cost accurate tests used to identify delaminated areas of concrete. Hammer soundings can be used on either vertical or horizontal surfaces, but are usually limited to small areas of delaminations. These areas are identified by striking the surface of the concrete with a hammer while listening for either a ringing or hollow sound. Dragging either a single chain, in small areas, or for larger areas, a T-bar with or without wheels having four or more chains attached are also used to identify delaminated concrete (ASTM D 4580). Approximately one meter (3 ft) of chain is in contact with the concrete during chain drag soundings. The sound emitted indicates whether the concrete is delaminated or not. Chain drag soundings are usually limited to horizontal surfaces that have a relatively rough texture. Smooth concrete may not bounce the chain links enough to generate adequate sound to detect delaminated areas. Note that corrosion of reinforcing bars in the area of delaminated concrete will probably extend beyond the boundary identified as delaminated.

Table 16-3 lists several nondestructive test methods along with main applications.

Table 16-3. Nondestructive Test Methods for Concrete

Concrete properties	Recommended NDT methods	Possible NDT methods
Strength	Penetration probe Rebound hammer Pullout methods Break off	
General quality and uniformity	Penetration probe Rebound hammer Ultrasonic pulse velocity Gamma radiography	Ultrasonic pulse echo Visual examination
Thickness		Radar Gamma radiography Ultrasonic pulse echo
Stiffness	Ultrasonic pulse velocity	Proof loading (load-deflection)
Density	Gamma radiography Ultrasonic pulse velocity	Neutron density gage
Rebar size and location	Covermeter (pachometer) Gamma radiography	X-ray radiography Ultrasonic pulse echo Radar
Corrosion state of reinforcing steel	Electrical potential measurement	
Presence of subsurface voids	Acoustic impact Gamma radiography Ultrasonic pulse velocity	Infrared thermography X-ray radiography Ultrasonic pulse echo Radar Resonant frequency testing
Structural integrity of concrete structures	Proof loading (load-deflection)	Proof testing using acoustic emission

Adapted from ACI Subcommittee 364 (1994) and Clifton (1985).

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