Physical Tests for Investigating Performance of Concrete

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•A THOROUGH INVESTIGATION of concrete in service usually includes some physical or analytical testing in addition to visual examination. It is true that many of the deteriorating influences that affect concrete leave characteristic marks that can be used as visual indicators of the condition of the concrete. However, when involved in a formal investigation of concrete in service, the participating investigators are not likely to be satisfied with a diagnosis based on appearance alone. Because concrete is a complicated material, any single visual feature can usually result from a number of different causes. Thus, records are assembled, samples are taken, and tests are conducted in order to provide a better basis for reconstructing the history of the concrete, for comparing concrete from different structures or from different locations of the same structure, or for judging the adequacy of the concrete to continue to fulfill its function. The test results are presented in numerical terms, and this usually makes a more convincing report than opinion or logic alone.

For the purposes of this discussion, three classes of physical tests that can be made in connection with an investigation of field concrete are considered: (a) nondestructive tests, (b) standard tests on cored or cut sections, and (c) tests of concrete constituents.

NONDESTRUCTIVE TESTS

In recent years, considerable attention has been given to the nondestructive type of test. Such tests have advantages in that they can be made directly on the concrete in situ, thus eliminating the need for coring or sawing. When desired, however, most nondestructive tests can also be applied to specimens of the usual size. In situ test results are generally free from the influence of boundary effects, which could be a factor when specimens of limited size are tested. Nondestructive tests can usually be performed rapidly, and therefore can provide a large number of readings of the property of interest in support of a statistical average for any selected mass of concrete.

Sonic Testing

Much work has been done toward determining the condition of concrete in service by measuring the velocity of pulses of sonic or ultrasonic vibrations transmitted through it. In theory, the speed of sound in a material is related to its dynamic modulus of elasticity. Thus, any condition in concrete that results in a change in this property, such as most forms of deterioration, should be reflected by changes in the velocity of sound waves.

Numerous instruments (1, 2) for measuring pulse velocity have been developed, such as the well-known soniscope, the electronic interval timer, and combinations of the two. In essence, these devices provide a means for transmitting and receiving sound pulses, and for measuring the time required for them to travel through a known thickness of the concrete, thus making it possible to calculate sound velocity.

The reliability of sonic data is largely determined by the skill and experience of the operator in choosing appropriate test points and in observing those conditions that might influence the measurements. Such factors as changes in density, moisture, aggregate-paste ratio, and the presence of voids and cracks should all be given weight in the final analysis. Properly interpreted, sonic techniques have been found useful for acquiring the following types of information regarding the condition of concrete:

1. Measure of uniformity within a structure, particularly with regard to defining the extent of observed deterioration.
2. Measure of changes in the condition of concrete with time by repetition of tests.
3. Measure of general level of quality. For example, velocities of more than 12,000 fps have been suggested as indicating a sound condition, whereas values of less than 10,000 fps generally indicate poor condition (3). Such an evaluation can be useful in determining whether specimens submitted in connection with an investigation do actually represent different levels of quality as intended.
4. Measure of depth and extent of cracks, by taking into account the fact that sound waves pass around cracks or voids and therefore travel a longer path than if the discontinuity were not there.

Sonic techniques can also be applied to determining the thickness of concrete sections such as pavement slabs. Muenow (4) has reported on a technique that requires the determination of both the wave velocity in the concrete and the longitudinal resonant frequency of the slab vibrated in the direction of its thickness. When allowances are made for surface cracks or other irregularities, thickness determinations by this method have been found to agree within 2 or 3 percent of that determined by core measurement.

Impact Testing

Many devices or techniques for determining the approximate strength of concrete by its reaction to impact have been used, particularly in European countries. These include the blow of a standard hammer, a pistol shot, use of a hydraulic jack, a steel ball and hammer, pendulum devices, and various ball impact tests. The test measurement is either the size of the indentation resulting from the impact or the rebound.

An instrument that has received a great deal of attention in this country is the Schmidt hammer, which determines the compressive strength of concrete by measuring the rebound of a spring-driven steel plunger. Because of its obvious virtues of rugged construction, simplicity, and rapidity of operation, and the fact that it seemed to fill a critical need, this device has been used extensively in the field. However, many users of the Schmidt hammer have expressed disappointment in the results obtained. Not only do individual determinations usually indicate widely varying compressive strengths, but also average strengths may not correlate well with actual strength determinations of cores or cylinders. Such results are not particularly surprising when proper consideration is given to inherent limitations of the instrument and the nonhomogeneity of concrete.

A common source of difficulty is the reluctance to calibrate the instrument for each source or type of aggregate. The practice of using the manufacturer's curve for converting impact readings to compressive strength, regardless of the aggregate involved, can lead to considerable error and frequently accounts for the difference in strengths indicated by the impact hammer and the strengths of cores. A serious limitation of the instrument is the fact that each individual test is influenced by only a very limited mass of concrete near the point where the impact is applied. Much of the variability between individual results is related to the position of large aggregate particles with respect to the point of impact. When the test is made on a formed or finished surface, it should also be recognized that the quality of the concrete near such surfaces is often different from that in the interior of the concrete. When so used, there may be difficulty in interpreting the results, but the test hammer may not be in error when it indicates strengths differing from core strengths.

To illustrate these points as well as to show how the Schmidt hammer can be used to gain information not readily obtainable by other methods, data obtained during the course of an investigation of a concrete pavement failure are shown in Figures 1 and 2. This pavement was showing surface raveling after only 2 weeks of use. Figure 1 shows the variation in impact readings in one of the cores representing concrete still in good

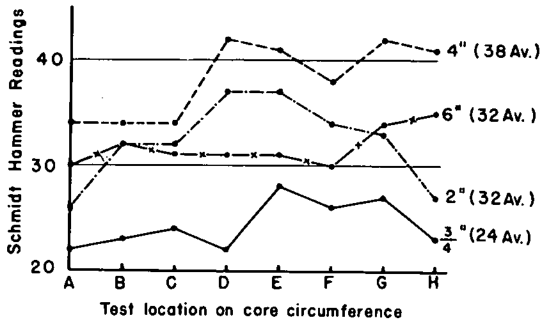

Figure 1. Variation of strength within 8½-in. pavement core.

condition. Not only did the indicated strengths vary around the core at the same depth, but the average level of strength varied greatly at various depths, being lowest near the surface of the pavement. Figure 2 shows comparison data on cores taken both from raveled and adjacent sound areas. In addition to showing variability, the several comparisons indicate that surface raveling was associated with an impact reading of 24 or less.

Locating Reinforcing Steel

Information is often desired on the location and depth of cover of reinforcing steel. At least two instruments of European manufacture have been developed to make such determinations in a nondestructive manner. The position and depth of steel are indicated by a meter deflection according to the effect of the steel on an electromagnetic field developed by the instrument. One instrument has been used extensively by the Georgia State Highway Department and is reported to provide very accurate readings for up to 1 in. of embedment and fairly close readings between 1 and 2 in. The Portland Cement Association (5) has reported on the use of another make of instrument that comes in two sizes—one for use where the cover is less than $1\frac{5}{8}$ in., and a more powerful model for cover measurements up to $4\frac{3}{4}$ in. The depth of cover could be measured to an accuracy of $\frac{1}{16}$ in. up to a 2-in. cover and to $\frac{1}{8}$ in. between a 2- and 3-in. cover.

Density by Radioactive Methods

The British have experimented with the measurement of the density of concrete by radioactive methods. When X-rays or gamma rays pass through concrete, they are partly absorbed and partly scattered, depending on the density of the concrete. When both sides of a concrete member are accessible, the density can be determined by the degree of radiation absorption through a known thickness up to thicknesses of 3 ft. When only one surface is accessible, as in the case of a pavement slab, the amount of backscatter is used as an indication of density.

Because the density of concrete is affected by many factors, such as air content, kind of aggregate, moisture content, and mix proportions, there is considerable difficulty

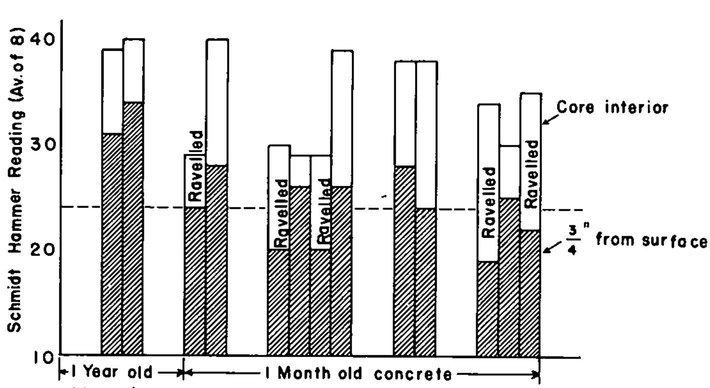

Figure 2. Strength vs raveling of pavement.

to be expected in using this property of concrete as in indicator of deterioration. Preiss (6) states that an accuracy of 0.5 percent is possible by the transmission method and suggests that no greater accuracy is necessary in view of the heterogeneity of concrete. He indicates that the method can be useful for location of steel reinforcement, voids in grout, segregated zones, and poorly consolidated concrete.

STANDARD TESTS ON CORED OR CUT SECTIONS

The tests that are made on cores or beams taken from a structure are in many cases the same tests that are made on molded specimens. When interpreting test results, however, there are differences between molded and cut specimens and between both the types of specimen and the concrete in the structure to be considered. One important feature of specimens taken from a structure is that they have the same curing history as that of the structure. In this respect, at least, tests on such specimens are more truly indicative of the condition of the concrete in the structure than are tests of specimens molded from the same concrete, because it is virtually impossible to provide curing equivalent to that provided by the large mass of concrete. On the other hand, both molded and cut specimens of concrete are subject to boundary effects that may cause them to act differently from the concrete in the structure. This is even more true of cut specimens than molded specimens because many aggregate particles in cut specimens are not completely surrounded by cement paste and therefore may tend to act as discrete particles rather than as an integral part of the concrete.

Strength

Strength tests are usually performed in accordance with the ASTM Method C 42, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete, and are particularly useful for determining relative strengths in different parts of a structure. However, when such tests are used to indicate the actual strength of the concrete in situ, or are compared with the strengths of standard molded specimens, certain limitations should be recognized. For example, Method C 42 requires specimens to be immersed in water for at least 40 hours prior to the test or in a moisture condition other than 40 hours as directed by the testing agency. Such condition is desirable for the purpose of standardizing the test procedure, but it also has the effect of lowering the determined strength below the strength that would be obtained if specimens were tested in a drier condition, such as would be likely to exist in a structure. The drilling or sawing of a specimen, as opposed to molding, can have a sizable effect on the strength of the specimen, as can variation in size and shape of specimen.

Compressive Strength—The relationship between the compressive strength of 6-in. drilled cores and molded cylinders made with the same concrete (3/4-in. aggregate) and similarly cured is shown in Figure 3 (7). It is observed that the ratio of strengths varies with the strength of the concrete. However, it is fortunate that at the lower strength levels, which would be of greatest concern in an investigation, the strengths of the two types of specimen are not greatly different. The method provides for the use of cores of different sizes and length-diameter ratios. But if the provisions regarding these factors are observed, the differences in strength as a result of these variables are also not large enough to require special consideration when interpreting test results.

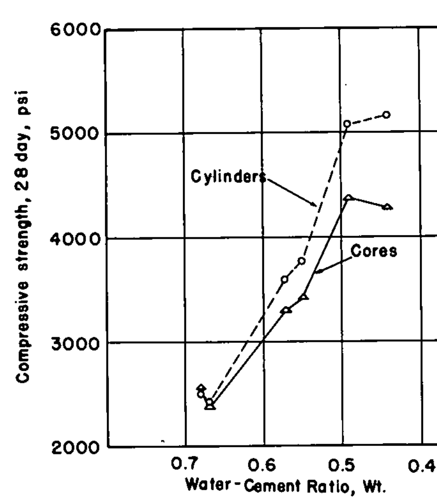

Figure 3. Relation of compressive strength of 6 by 12-in. cylinders and cores similarly cured.

ASTM Method C 42 also mentions the determination of compressive strength by testing

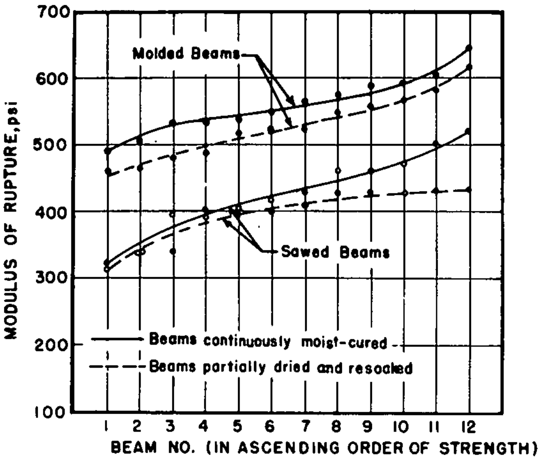

Figure 4. Relationship between flexural strengths of sawed and molded beams of same concrete.

portions of beams as modified cubes in accordance with ASTM Method C 116, Test for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure. Strength values obtained by this method differ significantly from those obtained on the standard 6 by 12-in. cylinder according to the strength of the concrete. Kesler (8) developed a statistical relationship between results on the two types of specimen that indicated that in general the cube strengths exceeded the cylinder strengths by more than 10 percent. Although Kesler's work was based on molded specimens, it is assumed here that the same relationship would apply to sawed beams.

Flexural Strength—Unlike the approximate equivalency found to exist between the compressive strengths of cores and cylinders at certain strength levels, it has been found that sawing significantly reduces the flexural strength of beams below that obtained on the same size of molded specimens at all strength levels. Figure 4 shows data developed by Walker and Bloem (9) on beams having a 3 by 4-in. cross section and containing a quartz gravel aggregate. For similar curing conditions, the modulus of rupture of the sawed specimens averaged about 25 percent less than the molded beams. It is further shown that intermittent drying, such as might be experienced by specimens from a structure, is more damaging to sawed specimens than to molded specimens. Further studies by Bloem (10) showed that the effect of sawing was not related to type of aggregate or size of beam but was related to the location of the sawed surface with respect to the tension side, the strength reduction being greatest when a sawed surface was in tension.

The use of the splitting tensile test apparently has not been proposed for determining the tensile strength of drilled cores. However, certain aspects of this test appear to recommend it over the flexural test for determining tensile strength of concrete where cut specimens are involved. Because the zone of maximum stress in the splitting tensile test does not occur at the surface of the specimen, it is unlikely that there would be any effect on strength as a result of the cutting of aggregate particles during drilling. However, because the bearing edges of such a specimen would be along a cut surface, the effect of such an edge, or the need for special leveling treatment of the specimen in this regard, would have to be determined.

Elasticity

Although concrete cannot be considered a perfectly elastic material, it is enough so that the theory of elasticity can be applied to it within limits of stress and time. Thus, ASTM Method C 469 outlines a procedure for determining the static Young's modulus of elasticity of cores or cylinders in compression as a chord modulus where the maximum stress does not exceed 40 percent of the ultimate load. By this limitation on stress and the prescribed rate of stress application, the conditions under which creep can come into play during the test are standardized. The modulus of elasticity can also be determined from data obtained dynamically. ASTM Method C 215 describes the procedure for determining the fundamental transverse, longitudinal, and torsional frequencies of concrete specimens from which the dynamic moduli can be calculated. Because the specimen is essentially in an unstressed state during the test, the influence of creep is not a factor and, as a result, the modulus of elasticity determined dynamically tends to be higher than that determined statically.

Static determinations of the modulus of elasticity provide values that are useful for design purposes, such as determining deformation and stress distribution between concrete and steel in reinforced or prestressed concrete members. The static modulus of elasticity is also useful for calculating the stresses resulting from shrinkage, settlement, or other distortions. Thus, for investigative purposes, the elastic constants determined statically will be of interest primarily where some aspect of structural performance is in question.

Dynamic elasticity tests, on the other hand, yield values that are widely used as an index of concrete quality. Although there is no generally applicable relationship between the strength and elastic properties of concrete, these properties are affected by the same factors in the same manner; that is, a deteriorating influence that lowers strength will also lower the modulus of elasticity. The dynamic modulus of elasticity by resonant frequency, therefore, is useful for investigating the quality of concrete in specimens of known size and weight in the same way that sonic tests are useful in studying concrete in situ.

Air Content

An investigation of the performance of concrete, particularly where durability with respect to freezing and thawing is a factor, often requires information on the air-void system of the concrete. Determination of all the important air-void parameters of hardened concrete requires analysis by optical methods, but if only the total air content is required the so-called high-pressure method can be used (11).

In this method, a known volume of concrete in a saturated condition is subjected to hydraulic pressure of 5,000 psi. The apparatus measures the change in volume of the entrapped and entrained air in accordance with the principles of Boyle's law as the pressure is increased from atmospheric pressure to 5,000 psi. The method is convenient in that any size or shape of specimen can be used that will fit into the pressure chamber, no special treatment of the specimen is required other than moisture conditioning, only about 15 minutes are required for the actual air determination, and the procedure is relatively free from the effects of personal technique.

Air contents of hardened concrete by the high-pressure method have been found to be in approximate agreement with air contents determined on the same batches of concrete plastic, within the range of air content normally specified for air-entrained concrete. For air contents of less than 3 percent, the high-pressure method generally indicates a slightly higher value than that determined on the same concrete in a plastic state. The high-pressure method has also been compared with optical techniques by several investigators. Table 1 (12) gives data developed by the Corps of Engineers that indicate reasonably good agreement between the two methods. Comparisons by other investigators have not shown such good agreement, variously indicating both lower and higher values by the high-pressure method. Conceivably, these different findings may be related to the poor reproducibility of the optical method itself when the work of different operators is being compared. The Corps of Engineers data also point to one of the limitations of the high-pressure method—that it indicates total air and does not distinguish between air present as small beneficial voids, that present as entrapped

TABLE 1

AIR CONTENT—HIGH PRESSURE VS POINT COUNT

Batch	Percent Air Content Plastic	Percent Air Content, Hardened[a]			
		High Pressure	Point Count		
			Entrained	Accidental	Total
1	3.9	4.2	3.0	1.1	4.1
2	7.5	8.0	7.0	1.2	8.2
3	11.5	13.2	12.2	1.2	13.4

[a]Each value is an average of three tests (Corps of Engineers data).

air, or that present in aggregate particles. Even with this limitation, the high-pressure method is generally adequate for quickly answering the question of whether concrete in service has insufficient or excessive air content. Because the high-pressure method tends to indicate too high a value at low levels of air content, it is reasonably certain that a low air content by the high-pressure method indicates that the concrete is not adequately protected against freezing and thawing damage.

Effect of Environment

Many investigations of concrete are initiated because the concrete has evidenced deterioration as a result of some environmental influence, such as frost action, temperature or moisture changes, or chemical attack. In such cases, it may be desired to demonstrate that concrete from the structure is affected by one or more of these factors under controlled conditions. Tests for this purpose are difficult to interpret at best, but if attempted should be made on specimens that have not yet begun to deteriorate. The ideal specimen would be one containing sound aggregate, free from cracks, and usually taken from an interior location that has been protected from the suspected environmental influence. The significance of the tests is often greatly enhanced if concrete from another structure of proven good performance under the same conditions of exposure is included in the test program as a reference.

Deterioration of concrete from environmental effects usually results from internal pressures occurring in cycles, such as from freezing and thawing, or as a constant buildup, as in the case of alkali-silica reaction. The test procedure used, therefore, should consist of a series of cycles or a constant condition, depending on which is most conducive to producing the observed deterioration. The condition of specimens may be evaluated during the test by visual observation for evidence of deterioration, weight loss, length change, change in resonant frequency, or loss of strength.

Freezing and Thawing—Freezing and thawing tests, even when performed on carefully fabricated specimens, are recognized as being difficult to interpret in terms of probable performance under specific conditions of service. The difficulty of interpreting such tests performed on cut specimens is even greater, because the exposure of aggregate particles to absorption of water without the protection of cement paste can be expected to increase the severity of the test to an unknown degree, and thus to remove even further the conditions of the test from the reality of performance in a structure. The consideration that should be given to this factor in interpreting results is probably dependent on the pore characteristics of the aggregate. An aggregate of very low absorption, for example, would not be expected to be affected, and therefore specimens containing such an aggregate logically could be evaluated by the same criteria as molded specimens. Where aggregates with an appreciable absorption are involved, it may be impossible to determine the extent to which exposure of the aggregate particles may have increased damage to the specimen above the damage that would have occurred had they been surrounded by cement paste.

Two methods for rapid freezing and thawing of concrete specimens are presently available as ASTM Standards. As indicated in the scope of these methods, they are not intended to answer the question of how a particular concrete will perform in a structure, but rather to make possible a comparison of the freezing-thawing resistance of different concretes. For the purposes of an investigation, these procedures can be used to determine if concrete in the subject structure is more or less durable than concrete in another structure, or does or does not meet some arbitrary standard used to judge concrete for similar structures in the area.

In any case, the quantitative measure of the test can be in terms of changes in resonant frequency or length changes. Weight loss is sometimes used but can be very unreliable because even obviously deteriorated specimens may show a gain in weight due to increased absorption. Resonant frequency is generally not as sensitive an indicator of deterioration as length change. Total length change after a specified number of cycles, however, may be unreliable because it is strongly influenced by temperature and moisture conditions. Dilation of specimens during a single cooling cycle has been proposed by Powers (13) as a theoretically more appropriate measure of frost action, and has been used as a basis for accepting aggregates for concrete (14). For this work, a dilation of more than 50 millionths in. per in. above the length at the freezing point was considered as being indicative of unsatisfactory durability under the conditions of the test.

Wetting-Drying, Heating-Cooling—Some concretes may be subject to deterioration as a result of excessive volume change caused by temperature and moisture fluctuations. Excessive volume changes of this type are usually related to thermal or compositional properties of the aggregates. Although the effects of moisture and temperature changes might be studied separately, the maximum volume change, and therefore the maximum effect, will usually be produced by a cycle such as wetting at an elevated temperature, drying, and then cooling. The extremes of temperature used should bear some relationship to those temperatures expected in structures.

Both resonant frequency and length-change measurements can be used to measure the effect of the treatment. Total length change is probably more useful for this type of test than for freezing and thawing tests because the specimens can be evaluated in a dry condition without disturbing the testing routine.

Chemical Action—Deterioration from chemical or physicochemical action may occur from reactions between constituents of the concrete, such as between cement and aggregates, or between a constituent of the concrete and an outside agent, such as sulfate solution. In either case, the course of the reaction can proceed under constant conditions and does not depend on a cycling treatment to cause damage. The test conditions should be selected so as to best promote the suspected type of reaction, such as the use of 100 F moist storage for the alkali-silica reaction. Length change is usually the best type of measurement for indicating the effect of the treatment on the specimens. Like freezing and thawing tests, a positive reaction of specimens to a particular test may only indicate that the concrete is susceptible to damage from a specific cause. The damage may not actually take place under the environmental conditions in the structure. One actual case history (15) of a structure that had remained sound for over 30 years showed that concrete specimens taken from the structure gave quick evidence of alkali-silica reactivity in 100 F moist storage as indicated by profuse formation of silica gel.

Absorption

The absorption of concrete is considered to be related to its overall quality and for this reason is frequently included as one of the properties to be determined on concrete whose performance is being studied. Of primary interest is the absorption that takes place rather rapidly when concrete is immersed in water at normal pressure and temperatures. Except where highly absorptive aggregates are involved, such absorption is primarily a filling of capillary pores of the paste and is known to vary inversely as the cement content and directly as the water-cement ratio and mixing water content of the concrete. Absorption also decreases as curing proceeds. Although each of these factors has an influence on the quality of concrete, it has not been found feasible to use absorption, per se, as an index of durability. The property of absorption is of value primarily for comparing different concretes, particularly with regard to their original water-cement ratio.

The absorption value, as well as its interpretation, will depend on the conditions of the test. A common procedure is to dry the concrete to constant weight at 105 C and immerse it for 24 to 72 hours at room temperature. Absorption of structural concrete on this basis is not particularly useful unless other background information is available on concretes being compared. For example, before it can be inferred that the higher absorption of two concretes indicates a higher mixing water content, it should be known that the curing histories and cement contents are the same. On the other hand, if one has evidence that the cement and original water contents of two concretes were essentially the same, then large differences in absorption should be indicative of different curing treatment.

Axon (16) has proposed a procedure for determining the original water-cement ratio of hardened concrete that utilizes an absorption value based on vacuum saturation. Under this condition of test, absorption is considered to represent total porosity, including air voids and aggregate pore space, and is used in conjunction with linear traverse measurements of aggregate, paste, and air content to determine the relative volumes of the various components of the concrete.

Permeability

Permeability refers to the movement of water through concrete under pressure. This property is primarily of interest in connection with hydraulic structures or other structures, such as basement walls or storage vats, that might be subjected to percolation of liquids under head. Because permeability occurs primarily in the paste portion, it is a function of the paste pore structure and is influenced greatly by the water-cement ratio and by curing.

The usual method of testing concrete for permeability utilizes equipment such as that described by Cook (17), which provides a means of forcing water through a specimen under a known head. Results are usually expressed as permeability coefficients in terms of cubic feet per second across 1 sq ft of area under 1 ft of head through 1 ft of thickness. Data developed by the U.S. Bureau of Reclamation (18) show that permeability increases rapidly for water-cement ratios higher than 0.55 by weight. Permeability may also vary according to the direction in which it is measured. Thus, permeability measured in the vertical direction, as originally cast, would be expected to differ from that measured in the horizontal direction through the same specimen of concrete.

Thermal Expansion

The properties of thermal conductivity, specific heat, thermal diffusivity, and coefficient of thermal expansion may each have significance to specific engineering uses of concrete. The property considered here as having greatest significance to outdoor structures is the coefficient of thermal expansion.

The thermal expansion of most structural concrete lies between 3.5 and 6.5 $\times 10^{-6}$ in. per in. per deg F, and for all practical purposes can be considered a weighted average of the thermal coefficients of the paste and aggregate portions. However, the coefficient of the paste portion, and therefore of the concrete also, varies according to its moisture content, being a minimum when either oven-dry or saturated.

Because of the difficulties of closely controlling temperature and moisture conditions when concrete is supposedly in an oven-dry state, tests for thermal expansion are usually made when the concrete is in a saturated condition even though this does not yield as high a coefficient as would be obtained at intermediate conditions of moisture. An attempt to develop a standardized procedure for determining coefficient of thermal expansion on a saturated basis is being made by an ASTM subcommittee. Tests to date demonstrate that the coefficient varies according to the particular temperature range over which it is determined. For example, a typical set of data obtained in the Bureau of Public Roads laboratory gave these results on the same specimen:

Temperature Range, F	Thermal Coefficient, $\times 10^{-6}$
40 to 70	3.0
70 to 100	3.3
100 to 130	3.6

Thus, a suitable procedure must define the temperature range and, as a minimum, should provide for temperature control within 0.2 F. A further requirement is that specimens must be given an opportunity to reach volume equilibrium at each temperature point.

Shrinkage

The shrinkage of concrete from a structure may be of interest for explaining observed cracking, warping, or movement of structural members. The term shrinkage usually refers to the change in volume of concrete that takes place as it loses moisture from its initial wet condition to some specific condition of dryness. The investigator of concrete in service cannot make this determination because the concrete has already experienced some drying. Thus, he can only determine the shrinkage taking place from some subsequent condition of wetness, such as that obtained by immersion in water. This is normally less than the original shrinkage. Nevertheless, shrinkage determined in this manner can be used to compare different concretes or to determine whether a concrete shows excessive shrinkage characteristics, such as that caused by the use of aggregates having a low modulus of elasticity or exhibiting high dimensional changes within themselves.

ASTM Method C 341, Length Change of Drilled or Sawed Specimens of Cement Mortar or Concrete, was revised to cover only the determination of volume change of concrete specimens taken from a structure as opposed to formed concrete products. Length changes are measured between gage points set into the specimen. Because the easiest condition of wetness to standardize is immersion in water, this treatment is prescribed for 7 days. The drying condition is at 50 percent relative humidity and 23 C. Under these conditions, concrete having normal shrinkage characteristics would not be expected to show greater than about 0.05 percent contraction even if allowed to reach equilibrium.

Unit Weight

The unit weight of hardened concrete varies according to the density of aggregates, mix proportions, and air content. Within a structure, it is unlikely that any of these factors other than air content will vary sufficiently to cause significant variations in density. Thus, the unit weight of concrete in a structure usually varies directly as its air content and is therefore a good indicator of the uniformity of this important property. Density can be used to estimate the actual air content of hardened concrete only with a great deal of difficulty, because the density of the aggregates, proportions, and water contents must be determined.

TESTS OF MOLDED SPECIMENS

In addition to visually examining and testing the concrete in a structure, it may be desirable to fabricate and test molded specimens in connection with an investigation of performance. The need for such tests may arise either because it has not been possible to determine the cause of the observed performance, or it is desired to demonstrate that the condition of the concrete resulted from a suspected cause by reproducing the same condition under controlled conditions.

Depending on the specific situation, it may be desirable to use samples of the original constituents if they are available, to use samples from the same sources from which the original constituents were obtained, or at least to use materials having similar properties as the original constituents. The comparisons that are necessary to develop the desired information usually fall into one or a combination of the following categories:

1. Comparison of the same or similar constituents with other constituents of known performance;
2. Comparison of various percentages of the same or similar constituents; and
3. Influence of exposure by subjecting similar specimens to a range of environmental conditions.

A prime example of this type of approach to understanding the performance of concrete in service was the manner in which the alkali-silica phenomenon was discovered and proved. Having observed that the particular type of deterioration in question could not be explained by any known factor, and that it occurred only with certain aggregates, but not necessarily always with those aggregates, specimens were fabricated using the suspected aggregates with different cements. It was finally observed that an expansion occurred only when cements of high alkali content were used, thus leading to the cause of the deterioration.

As in the case of the alkali-aggregate reaction, tests of this type are of the nature of research and, in fact, do often lead to extensive research investigations when the specific performance cannot be fully understood or explained by any known theory.

REFERENCES

1. Kesler, C. E., and Change, T. S. A Review of Sonic Methods for the Determination of Mechanical Properties of Solid Materials. ASTM Bull., Oct. 1957, p. 40.
2. Effects of Concrete Characteristics on the Pulse Velocity—A Symposium. HRB Bull. 206, 1959.
3. Whitehurst, E. A. Soniscope Tests Concrete Structures. PCA Bull. 36, Feb. 1951.
4. Muenow, Richard. A Sonic Method to Determine Pavement Thickness. Jour. PCA Research and Development Laboratories, Vol. 5, No. 3, Sept. 1963, p. 8.
5. Locating Reinforcing Steel in Concrete. Jour. PCA Research and Development Laboratories, May 1965, p. 76.
6. Preiss, K. Measuring Concrete Density by Gamma Ray Transmission. ASTM Materials and Research Standards, June 1965, p. 285.
7. Investigation of Compressive Strength of Molded Cylinders and Drilled Cores of Concrete. U.S. Army Engineer Waterways Experiment Station, Tech. Rept. 6-5222, Aug. 1959.
8. Kesler, C. E. Statistical Relation Between Cylinder, Modified Cube, and Beam Strength of Plain Concrete. Proc. ASTM, Vol. 54, 1954, pp. 1178-1187.
9. Walker, S., and Bloem, D. L. Studies of Flexural Strength of Concrete—Part 3: Effects of Variations in Testing Procedures. Proc. ASTM, Vol. 57, 1957, pp. 1122-1139.
10. Bloem, D. L. Effects of Sawing Specimens From Hardened Concrete on Measured Flexural Strength. Distributed with NSGA Technical Information Letter 145.
11. Lindsay, J. D. Illinois Develops High Pressure Air Meter for Determining Air-Content of Hardened Concrete. HRB Proc., Vol. 35, 1956, pp. 424-435.
12. High Pressure Test for Determining Air Content of Hardened Concrete. U.S. Army Engineer Waterways Experiment Station, Misc. Paper 6-286, Oct. 1958.
13. Powers, T. C. Basic Considerations Pertaining to Freezing-and-Thawing Tests. Proc. ASTM, Vol. 55, 1955, pp. 1132-1155.
14. Tremper, B., and Spellman, D. L. Tests for Freeze-Thaw Durability of Concrete Aggregates. HRB Bull. 305, 1961, pp. 28-50.
15. Memorandum from H. Allen to A. C. Swain, Bureau of Public Roads, Feb. 20, 1957.
16. Axon, E. O. A Method of Estimating the Original Mix Composition of Hardened Concrete Using Physical Tests. Proc. ASTM, Vol. 62, 1962, pp. 1068-1080.
17. Cook, H. K. Permeability Tests of Lean Mass Concrete. Proc. ASTM, Vol. 51, 1951, pp. 1156-1165.
18. Concrete Manual. U.S. Bureau of Reclamation, 7th Edition, 1963, p. 38.