TITLE NO. 74-16

Contract Strength Requirements—Cores Versus In Situ Evaluation

By V. M. MALHOTRA

The present day building codes allow acceptance of concrete on the basis of the 28-day compressive strength of test specimens cured under standard conditions. If test cylinders fail to reach the criterion specified in the codes, drilling and testing of cores is required as the codes permit no other method of evaluation. This paper discusses the problems associated with evaluation of core test data and emphasizes the contradictory nature of the available information. The effects of the variables such as length-depth ratio, embedded reinforcement, type of aggregate, strength level of concrete, direction of drilling, and curing of concrete are discussed. The unsatisfactory nature of the existing acceptance procedure is brought out and a case is made for the abandonment of the existing acceptance procedure in favor of a new approach. The suggested procedure consists of three steps: First, it is insured that concrete delivered to the site meets specification requirements. Second, accelerated strength testing is employed for acceptance testing. Third, emphasis is placed on in situ testing of hardened concrete using such methods as the pullout, penetration resistance, hardness, and pulse velocity.

Keywords: accelerated tests; **acceptability;** building codes; **compression tests; compressive strength; concrete cores;** curing; **cylinders;** field tests; fresh concretes; hardened concretes; nondestructive tests; penetration tests; pullout tests; **quality control;** reinforced concrete; reinforcing steels; **samples;** specifications; **specimens;** ultrasonic tests.

■ IN CURRENT CONCRETE PRACTICE, CONTROL of quality of concrete for acceptance purposes is based on the compressive strength of standard 6 x 12-in. (152 x 305-mm) cylinders cast, cured, and tested in accordance with standard established procedures. If test results indicate compliance with the specified strength and the concrete has been delivered, placed, consolidated, and cured in accordance with accepted practices, it is assumed that the concrete represented by the specimens and cast as part of the structure meets the design requirements. Unfortunately, in practice, the assumptions are not always correct and, more often than not, placing, vibrating, and curing conditions leave a lot to be desired. This, combined with the fact that structural units are considerably larger and more massive in size, casts doubts whether the 6 x 12-in. (152 x 305-mm) cylinders do really represent strength of concrete in structures. This is not to say that the practice of accepting concrete on the basis of 28-day compressive strength of standard-cured cylinders has not served the construction industry well. In fact it has, and thou-

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TABLE 1—COMPRESSIVE STRENGTH OF CORES AND CONTROL CYLINDERS—UNITED STATES BUREAU OF RECLAMATION DATA*

Project	Cement type	Age of testing, months	Core size, in.	Number of cores tested	Core strength, psi	Core strength, (MN/m^2)	28-day Control cylinder strength, psi	28-day Control cylinder strength, (MN/m^2)	Strength ratio,† percent
A	I and II	23	6	82	5,530	(37.9)	3,690	(25.3)	150
B	II	36	6	52	6,380	(50.7)	3,670	(25.2)	174
C	II	24	6	43	5,450	(37.4)	3,970	(27.3)	137

*From Reference 10.

$\dagger \dfrac{\text{Core strength}}{\text{Control cylinder strength}} \times 100$

sands of reinforced concrete structures in our great metropolitan cities are a monument to the acceptance of the quality of concrete on the above basis. Notwithstanding this, the problem often arises when the test cylinders cast from otherwise good concrete fail to reach the specified design strength at 28 days. When this occurs, the designers who, at times, may be hundreds of miles away from the construction site, are placed in a very awkward position of having to either rationalize the low strengths or require the cutting of cores from the structure for testing in compression in accordance with the provisions of ACI Committees 318 and 301.[1,2]

In November 1974, ACI Committees 114, Research and Development, and 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete, combined to conduct a forum at the ACI fall meeting at Atlanta, Ga., on "Contract Strength Requirements for Concrete Structures by Testing Cores and Other Field Methods." This paper is based on the presentation made at the forum and discusses the provisions of ACI Committees 301 and 318 on the subject under discussion. The parameters affecting the strength of drilled cores are discussed and a new approach involving accelerated and in situ strength testing is advocated.

CONTRADICTORY NATURE OF AVAILABLE TEST DATA

The available test data on cores are full of contradiction and confusion. Unfortunately, more often than not, the data have not been properly documented and the reported studies have not been carried out systematically, the only exception being the studies by Petersons[3,4,5] and Bhargava[6,7] in Sweden, and by Bloem[8,9] in North America.

It is known that strengths of cores are reduced due to:

(a) damage during drilling and handling,

(b) poor compaction and curing of concrete in a structure,

(c) water gain during drilling, and

(d) testing cores of smaller diameters than control cylinders.

It is also generally agreed that cores can give higher strengths than control cylinders due to:

(a) testing cores at an age later than the control cylinders,

(b) loss of entrained air during handling and compaction, and

(c) testing of cores in a dry condition instead of the saturated condition required in control tests.

Notwithstanding the above, the following remarks by Bloem[8] are of interest:

> Core tests made to check adequacy of strength in place must be interpreted with judgment. They cannot be translated to terms of standard cylinders strength with any degree of confidence, nor should they be expected necessarily to exceed the specified strength, f_c'.

Contrary to the remarks by Bloem, the United States Bureau of Reclamation (USBR) has gone on record[10] as follows:

> Tests of drill cores taken from structures almost invariably show greater strengths than those obtained from control cylinders which are standard cured for 28 days. The extent of such excess strength generally varies with the age of the cores and the conditions contributing to continued hydration of the cement.

Table 1 gives some of the USBR data. Perhaps some of the discrepancy between these two viewpoints can be explained. The cores taken by the USBR are at ages greater than 23 months, and the core strengths are then compared with the strength of control cylinders at 28 days; on the contrary, in the data reported by Bloem, 28-day strength of control cylinders is compared with the strength of cores taken at about the same age.

Thus, it is seen that strength of cores can give values lower or higher than the strength of control cylinders depending on the conditions under which cores have been drilled and tested. This has put the codifying committees in a very difficult position. To resolve this, ACI Committees 318 and 301 stipulate that concrete represented by a core test possesses adequate strength if the average strength of the cores is at least 85 percent of the specified strength f_c' and if no single core shows a strength of less than 75 percent of f_c'.

It should be emphasized that the ACI committees in formulating the above criterion have stressed the structural adequacy aspect of the problem, which obviously is more important in terms of safety.

Following the publications of the requirement by ACI Committees 318 and 301, questions have been raised as to whether the requirements are too relaxed or they establish overly stringent requirements for verification of in situ concrete quality. An attempt will be made to answer these questions later in the paper.

FACTORS AFFECTING COMPRESSIVE STRENGTH OF DRILLED CORES

As mentioned earlier, core test data as reported by various researchers are contradictory. This is so because there are a large number of factors which can affect the compressive strength of drilled cores, and unless allowance is made for the effect of these factors, the data from various sources present a dismal picture. The following discussion illustrates this contention.

Effect of length-diameter ratio on the strength of cores

In North America, the standard compression test specimens have a length to diameter (l/d) ratio of 2, with diameter being at 6 in. (152 mm). Ideally, the drilled cores should have these dimensions. In practice, this is not generally so because a large number of structural units in buildings are less than 12 in. (305 mm) thick and are often only 6 in. (152 mm) thick. For l/d, other than 2, a number of investigators[11,12,13] have reported correction factors (Table 2). In spite of the correction factors, the use of cores having diameters less than 4 in. (102 mm) should be discouraged. This is especially so when the aggregate used is 1 or 1.5 in. (25 or 37.5 mm). As the strength of cores is influenced by the maximum size of aggregate, the ratio of core diameter to maximum size of aggregate should be at least 3.[14]

TABLE 2 — STRENGTH CORRECTION FACTORS FOR DIFFERENT LENGTH/DIAMETER RATIOS

Length/diameter ratio	ASTM Standard C 42	British Standard*	Sangha and Dhir†
1.0	0.91	0.92	0.82
1.5	0.97	0.96	0.98
1.75	0.99	—	—
2.00	1.00	1.00	1.00
3.0	—	—	1.02

*Reference 13
†Reference 12

Apart from the above, there are other unresolved issues with respect to l/d. ASTM C 42, Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete, gives correction factors for l/d when the cores are tested wet, i.e., the cores after being drilled have been soaked in water at room temperature for 40 hr immediately after drilling and tested immediately afterwards. Unfortunately, no correction factors are given when cores are tested dry, i.e., when the cores are air dried (temperature 60 to 80 F, relative humidity less than 60 percent) for 7 days before testing and tested dry as allowed in the ACI Building Code (ACI 318-71), Section 4.3.5. Thus, disputes have arisen in this regard because of the incompatibility of the requirement of ACI

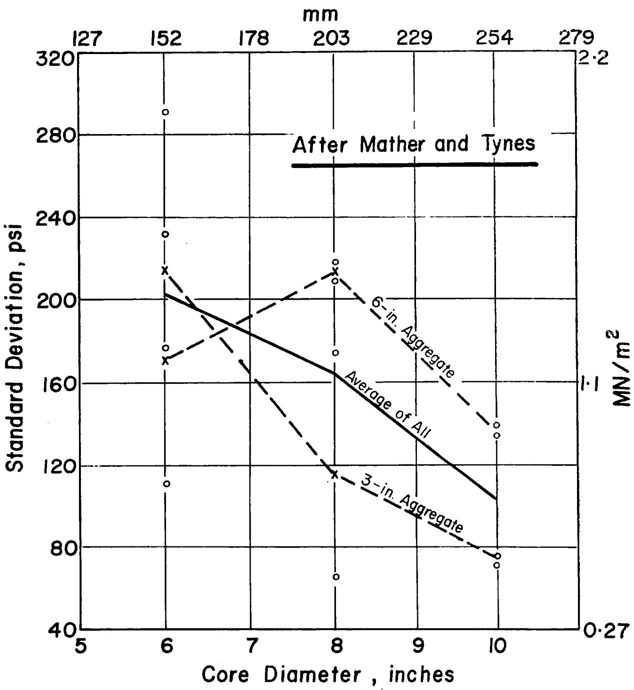

Fig. 1—Relation of standard deviation of test results to diameter of drilled cores (Reference 20)

TABLE 3—EFFECT OF REINFORCING BARS ON THE STRENGTH OF CORES

Researcher	Average reduction in strength, percent	Reference No.
Gaynor (United States, 1965)	8 to 13	21
Lewandowski (Germany, 1970)	No significant change	22
Petersons (Sweden, 1971)	No significant change	5

318-71 and ASTM C 42. It is believed that this may be resolved in the near future.

The problem of *l*/*d* and diameter of cores does not end here. Malhotra[15] has shown that if *l*/*d* is maintained at 2, the molded cylinders with smaller diameters have higher strengths than those with larger diameters. The difference can be as high as 15 percent. Similar results have been reported for cores.[16] Meininger,[17] however, has reported that core diameter did not affect the average strength level, whereas Campbell and Tobin[18] reported higher strengths for 6 in. (152 mm) cores than for 4 in. (102 mm) cores.

Effect of diameter of cores on variability of test results

Tucker[19] has tried to explain the specimen size effect on strength test results by means of the summation-strength theory. According to this theory:

(a) The strength of material is independent of the area of the specimen upon which tests are made, provided that the length of the specimens remains unchanged in tension tests and that the length-diameter ratio is constant in compression tests;

(b) The standard deviation of the compressive strength decreases with increase in cylinder diameter; however, equal information is obtained when the number of cylinders tested are such that the summation of the cross-sectional areas of the cylinders of the two sizes are equal.

The test data referred to earlier do not appear to support the first part of the theory;[15] however, Part b of the theory has been confirmed for both molded cylinders and cores.[15,20] Fig. 1 shows the trend of the standard deviation to vary inversely with core diameter.

Thus, when small diameter cores are taken it is imperative that a large number of cores be taken and tested to maintain the same within-test variation as for large diameter cores. This, of course, can become very expensive. For example, to maintain the same precision, if core diameter is reduced from 12 in. (305 mm) to 6 in. (152 mm), four times as many cores will have to be tested. It is interesting to note that a 12 in. (305 mm) core weighs about 240 lb (108 kg), whereas four 6 in. (152 mm) cores weigh only about 120 lb (54 kg), with *l*/*d* equal to 2 in each case.

Effect of reinforcing bars on the strength of cores

In heavily reinforced concrete sections it is generally impossible to avoid pieces of reinforcing bars in drilled cores with resulting effects on the compressive strength. The variables associated with this aspect include:

(a) Effect of diameter of reinforcing bars,

(b) Effect of number of reinforcing bars,

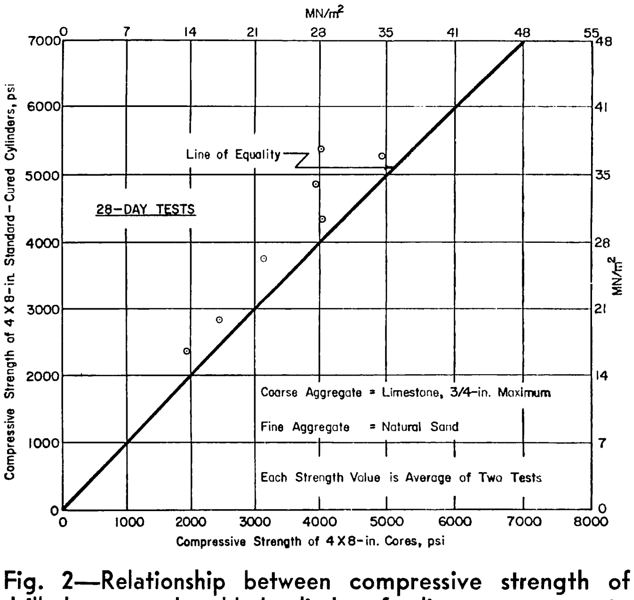

Fig. 2—Relationship between compressive strength of drilled cores and molded cylinders for limestone concrete (Reference 23)

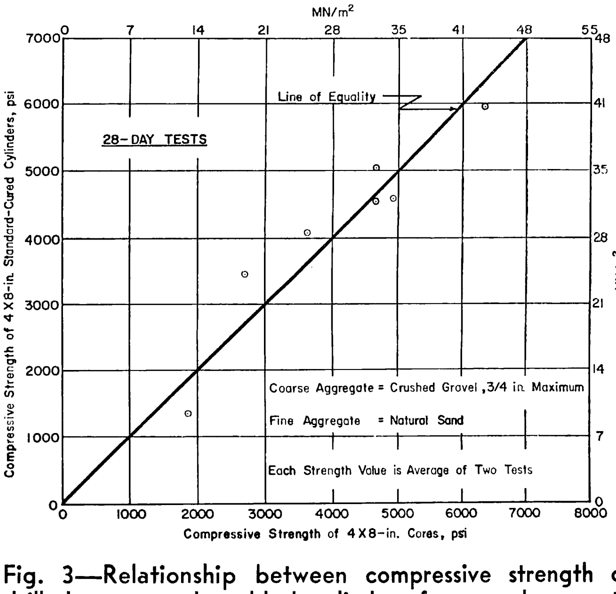

Fig. 3—Relationship between compressive strength of drilled cores and molded cylinders for gravel concrete (Reference 23)

(c) Distance of reinforcing bars from axis of cylinders, and

(d) Distance of reinforcing bars from top of cylinders.

A number of researchers[3,21,22] have investigated the effects of some or all of the above variables on the compressive strength of cores. Once again the published data are contradictory (Table 3). Where possible, efforts should be made to test cores which do not contain any reinforcing bars. If a choice has to be made between maintaining l/d of 2 and testing the cores with a reinforcing bar in a plane perpendicular to the axis of the cores, or reducing l/d and eliminating the reinforcing bars by sawing off the portion of the core containing the reinforcing bar, the latter is to be preferred.

Effect of type of aggregate on the strength of cores

The relationship between compressive strength of drilled cores and molded cylinders is shown in Fig. 2 and 3 for limestone and gravel concretes.[23] The cores were drilled from 2 x 2 x 8-in. (610 x 610 x 203-mm) concrete blocks and were tested immediately after drilling. The blocks had been moist cured for 7 days and were then left to dry in the laboratory air for 21 days; the molded cylinder specimens, 4 x 8 in. (102 x 203 mm), were also moist cured. The cores for limestone concrete (Fig. 2) test somewhat lower than molded cylinders at all strength levels whereas there is little or no difference between strength of cores and molded specimens for gravel concrete (Fig. 3). No explanation is offered for this difference in test results.

Bloem[8] has shown that the cores drilled from structural lightweight concrete give somewhat higher strength than the cores drilled from concrete made with normal weight aggregates. Bloem explains that this strength difference is caused by the moisture absorbed inside the lightweight aggregate.

Effect of strength level of concrete on the strength of cores

The effect of strength level on the compressive strength of drilled cores as reported by Petersons[5] is shown in Table 4. It is seen that the percentage reduction in strength of the drilled cores from concrete in a structure increases with the increase in strength level of concrete. At strength levels of 7000 psi (49 MN/m²), the percentage reduction reaches as high as 15 percent. Data by Petersons are the only reliable data available in this regard.

TABLE 4—EFFECT OF STRENGTH LEVEL OF CONCRETE ON THE STRENGTH OF CORES*

Strength level of cast specimens, psi	(MN/m²)	Reduction in strength of concrete in a structure as measured by cores, percent
3000	(21)	5
4000	(28)	10
6000	(42)	12.5
7000	(49)	15

*From Reference 5.

The reasons for increased percentage reduction in strength with increase in strength levels of concrete are not clear but it is believed that stronger concrete offers more resistance to drilling and, in the process, may introduce microcracks or other damages to the cores.

Effect of direction of drilling on strength of cores

Petersons[3] has shown that, in columns, cores drilled horizontally developed lower strengths than similarly located cores drilled vertically. The difference in strength is in the order of 12 percent. Meininger[17] has reported that cores drilled horizontally from a wall were about 7 percent weaker than cores drilled from a slab of similar dimensions and, of course, cast from the same concrete. The difference between the results of these investigators is probably due to the size of the structures or the blocks of concrete from which the cores were drilled. It is worth reporting that Bloem[8] found no difference in the strength of cores whether these were drilled vertically or horizontally.

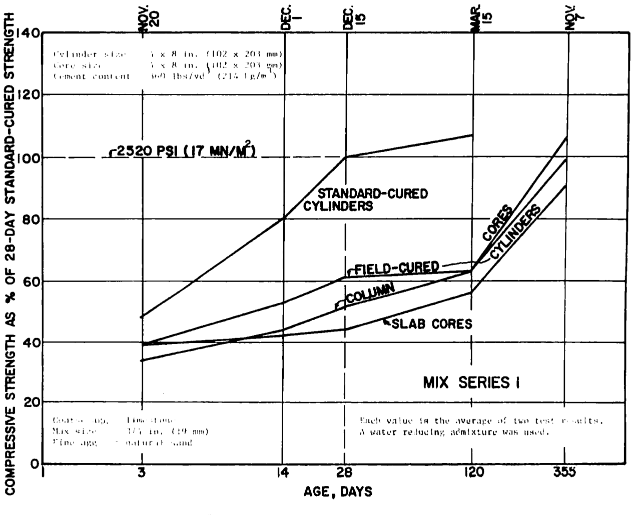

Fig. 4—Relationship between age and compressive strength of both laboratory-cured test specimens and drilled cores (Reference 25)

Effect of initial curing of concrete on the strength of cores

Malhotra and Berwanger[24,25] reported the relationship between compressive strength of drilled cores and molded cylinders for concrete cast and cured under winter concreting conditions. In one investigation, 2 x 2 x 6 ft (610 x 610 x 1830 mm) high columns, and 4 ft x 4 ft x 8 in. (1220 x 1220 x 203 mm) thick slabs were cast in the field and a large number of companion 4 x 8-in. (102 x 203-mm) cylinders were also cast for standard curing. For the first 3 days the specimens were maintained at about 50 F (10 C) by artificial heating following which the specimens were exposed to the elements. For the first 4 months the ambient temperatures were generally well below 32 F (0 C) and later, during the summer months, the temperatures reached up to 80 F (26.7 C). Fig. 4 shows the relationship for strength of cores and molded cylinders.

It is seen that drilled cores reach or exceed the compressive strength of corresponding standard cured specimens at later ages. The high compressive strength of cores at later ages is probably due to the low initial curing temperature of cast concrete.

Meininger[17] in his studies found that cores drilled at the ages of 35 to 91 days from 18 in. (456 mm) thick slabs and walls which were moist-cured for the duration of the investigation were 69 to 85 percent of the 28-day compressive strength of reference moist-cured cylinders.

Effect of type and dimensions of the structure on the strength of cores

The strength of the drilled cores is affected by the type and dimensions of the structures from which these cores are drilled. These effects are due to the higher temperature rise inside large masses of concrete than at locations near the edges and top surfaces. Thus, cores taken from thin slabs can give different results than those taken from deep inside thick retaining walls. Lapinas* has shown that cores drilled from central portions of large blocks [(minimum dimension = 8 ft (2.4 m)] where temperature rise was higher gave lower strengths than cores drilled from near the edges of the blocks where the temperature rise was lower.

From the foregoing discussion it can be safely stated that the relations between the strength of control cylinders cured under standard laboratory conditions and the strength of cores from a structure are dubious at best. Further, the ACI 318-71 stipulation that drilled cores from structures reach 0.85 f_c' may be unrealistic in some cases because of the inherent difficulties in drilling and testing of cores.

It cannot be overemphasized that unless extra caution is exercised during drilling and testing, and care is taken to allow for the effect of various variables discussed earlier in analyzing the core test results, the evaluation of the core test data presents a rather hazardous situation. In general, many testing laboratories and consulting engineering firms neither have the expertise nor the resources to properly go into all the ramifications that evaluation of core test results involves. Notwithstanding the fact that testing of drilled cores is one of the valid means of determining the adequacy of structural concrete, it has been shown that, more often than not, the drilling and testing of cores can create more problems than they solve if an attempt is made to relate the strength of cores to the strength of control cylinders.

Murphy,[26] in his review of the relationships between the strengths of cores and standard cubes, concluded:

> The inferred cube strength will be subject to a considerable margin of error, which to a large extent, will reflect the limitations in the knowledge of the effects of various parameters influencing the relationship between the strength of cores and the potential quality. The precision with which the potential quality can be inferred might be increased by research directed towards areas where current information is inadequate.

SUGGESTED NEW APPROACH TO THE DETERMINATION OF COMPRESSIVE STRENGTH OF CONCRETE

Where do we go from here then? The answer is not simple. Unless we are prepared to make fundamental changes in our approach to the determination of strength of concrete in structures, it is doubtful that we can make much progress in the foreseeable future. One suggested approach, radical as it may seem, is as follows:

Step 1—Carry out sufficient inspection and control to insure that the quality of fresh concrete as delivered to the site meets specification requirements as regards water-cement ratio, cement content, air content, and slump. Insure that transporting, placing, consolidation, and curing of concrete is done according to standard established procedures.

Step 2—Eliminate 28-day compressive strength of control cylinders as the acceptance criterion for structural concrete; instead, institute accelerated strength tests for both quality control and acceptance testing.

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*Lapinas, R. A., "Strength Development of High Cement Content Concrete Cast in Large Sections," paper presented at the fall meeting, American Concrete Institute, Toronto, Ont., Canada, 1963.

Step 3—Standardize in situ nondestructive tests to estimate/determine strength of concrete in a structure.

The steps outlined above will now be discussed in some depth.

Step. 1: Determination of quality of concrete as delivered

The quality of concrete as delivered to the site can be insured by providing more inspection at the batch plant and increasing the frequency of determination of unit weight, air content, and slump tests at the site. The cement content of fresh concrete can be determined by chemical means.[27,28] Unfortunately, this procedure is rather difficult because of the requirement for a highly trained technician at the site and, furthermore, the procedure can take up to one-half hour. Recently, the Cement and Concrete Association of England[29] has developed a rapid cement analyzer machine which can determine the cement content of fresh concrete by an elutriation process in 6 min. This method looks promising although the equipment may be beyond the reach of small contractors and testing laboratories because of high cost.* Even though it may not be possible to determine the cement content by the available methods, the other available conventional methods are satisfactory to insure that the quality of concrete as delivered to the site meets the specification requirements.

This is followed by insuring that transporting, placing, consolidation, and curing of concrete, and storage and handling of test specimens, is done in accordance with the specifications.

Step 2: Accelerated strength tests

Having insured that concrete as delivered meets the specification requirements, the second step is to perform accelerated strength tests to actually determine the strength of concrete at an early age. These tests can insure that if the strength of concrete is considerably lower than the designed value, there is still a good chance of getting it removed from the structure. Three accelerated strength tests have been standardized (ASTM C 684-74). These are the hot water method, the boiling method, and the autogenous curing procedure.

It has been shown that all these methods can predict strength at which standard cured cylinders will break with a satisfactory degree of accuracy and that the test results are available within 24 to 48 hr depending on the method employed.[30] There are sufficient available data to suggest that the modified boiling method and the autogenous curing procedure can be used with confidence for acceptance testing of concrete.[31,32]

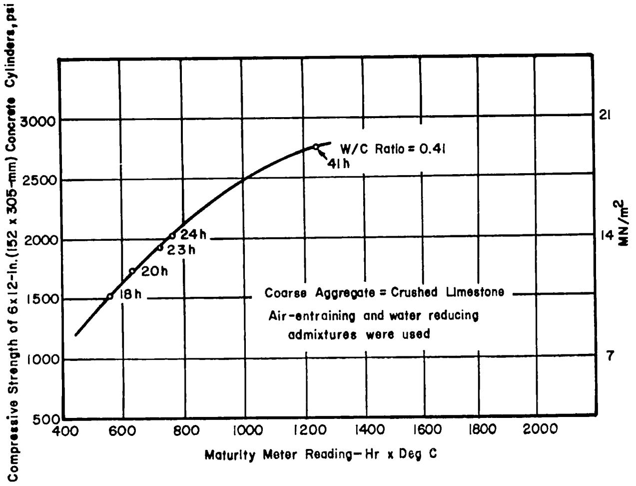

Fig. 5—Relationship between maturity of concrete and its compressive strength (Reference 34)

Step 3: In situ strength estimation/determination of concrete

Having performed tests specified in Steps 1 and 2, the next step is to carry out in situ testing of concrete to estimate/determine quality and strength of concrete. There are a number of methods available to an engineer to achieve this, and the more promising of these methods are: (1) maturity concept, (2) determination of pulse velocity through concrete, (3) determination of penetration resistance and hardness of concrete, and (4) pullout tests.

Of all these techniques, the pullout tests are the only ones which actually determine in situ "strength" of concrete. The other tests determine some other properties of concrete from which an estimate of strength can be obtained. Sometimes a combination of two or more tests can yield more meaningful information.

1. *Maturity concept* — The basic principle of the maturity concept is that the increase in strength varies as the product of time and temperature minus 10 C (plus 14 F). It has been shown[33,34] that within narrow limits of time (3 to 28 days) and temperature (60 to 80 F) the maturity concept can be used with advantage to estimate strength of concrete. The maturity of in situ concrete can be monitored by thermocouples or by instruments called maturity meters. A relationship between maturity and compressive strength of 6 x 12-in. (152 x 305-mm) cylinders is shown in Fig. 5.[34]

2. *Determination of pulse velocity through concrete* — The use of ultrasonic pulse to measure

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Currently the machine retails at about $8000 in Toronto, Ont., and is available from Canadian Consociates Ltd., Brampton, Ont., Canada. See also the January 1977 ACI JOURNAL, p. N7, for a brief description.

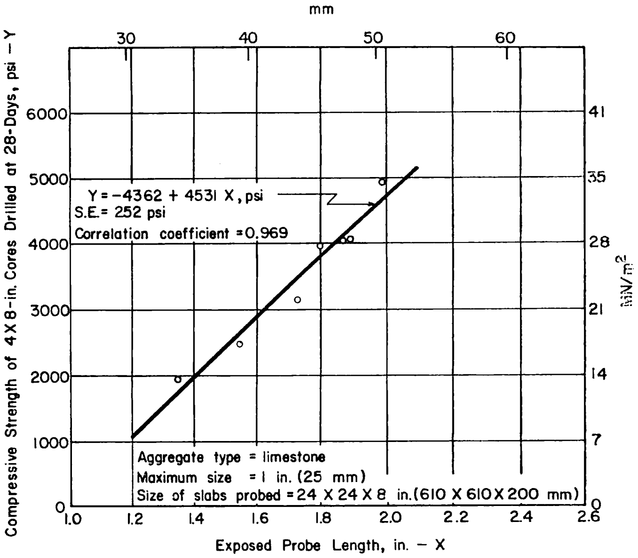

Fig. 6—Relationship between the exposed probe length and the compressive strength of drilled cores (Reference 23)

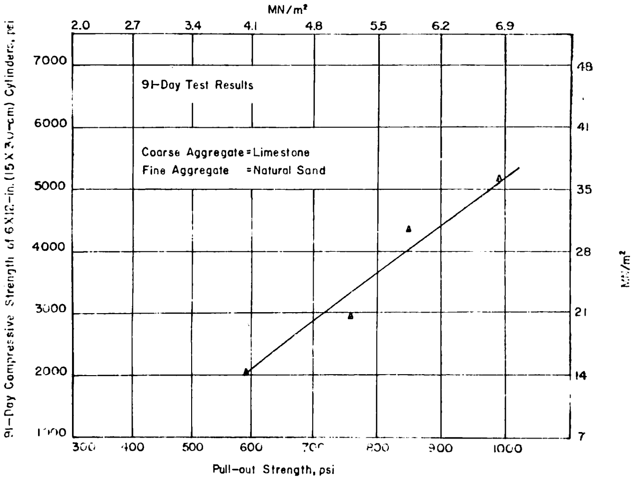

Fig. 7—Relationship between the pullout strength and the 91-day compressive strength of drilled cores (Reference 42)

properties of hardened concrete is well known.[35] The pulse velocity methods are excellent in measuring uniformity of concrete and have been used successfully to isolate areas of poor quality. Unfortunately, the velocity measurements are greatly affected by the moisture condition of the specimen, reinforcement, and by a number of other factors. Until recently, the available equipment was relatively cumbersome to use in the field and generally required skilled operators. However, recently in Holland[36] and in the United Kingdom[37] portable digitized apparatus have been developed.

In general, pulse velocity measurement cannot be used to determine in situ strength of concrete because of a large number of variables involved; however, if careful calibration charts have been prepared correlating the compressive strength of concrete and the pulse velocity through it, some estimate of in situ strength may be possible. However, calibration charts should take note of statistical uncertainty involved. The accuracy of the estimate is increased if the pulse velocity measurement and hardness values of concrete as determined by the rebound hammer (to be described later) are combined to estimate the strength.[38]

3. *Determination of penetration resistance and hardness of concrete* — The penetration resistance and hardness of concrete can be measured by the Windsor probe and the Schmidt hammer, respectively. Both these tests are not expected to yield absolute values of strength of concrete in a structure. However, they do provide an excellent means for determining relative strengths of concrete in different parts of the same structure or relative strengths in different structures.[23,35,39,40,41]

The Windsor probe consists of a powder-activated gun or driver, hardened-alloy probes, loaded cartridges, a depth gage for measuring penetration, and related equipment.[39] The probe is 0.25 in. (6.3 mm) in diameter, 3.125 in. (79.5 mm) long and has a frusto-conical point.

A powder-activated driver is used to fire a probe into the concrete; the exposed length of the probe, measured by a calibrated gage, is a measure of the penetration resistance of concrete. Fig. 6 shows the relationship between the exposed probe length and the compressive strength of 4 x 8 in. (102 x 203 mm) drilled cores from 2 ft x 2 ft x 8 in. (610 x 610 x 203 mm) thick concrete block.[23]

The hardness of concrete is measured by indentation and rebound methods, the most commonly used method being the rebound hammer by Schmidt.[35] Like the Windsor probe, the Schmidt rebound hammer should not be used for determining absolute values of in situ strength of concrete, but when its test results have been combined with pulse velocity measurements through concrete, meaningful estimate of in situ strength may be obtained.[38] The advantages of the rebound hammer are that it is the cheapest method, and that a large number of readings can be taken in a relatively small area in order to obtain a statistical average.

4. *Pullout tests* — Briefly, a pullout test measures, with a special dynamometer, the force required to pull out from concrete a specially shaped steel rod whose enlarged end has been cast into that concrete. Because of its shape, the steel rod is pulled out with a cone of the concrete. The concrete is simultaneously in tension and in shear, the generating lines of the cone running approximately

45 deg to the vertical. The pullout force is then related to compressive strength, the ratio of the pullout: compressive strength being 0.1 to 0.3. The relationships between the pullout strength and 91-day compressive strength of drilled cores from specimens cast from the same concrete are shown in Fig. 7.[42]

The main advantages of the pullout tests are that they do measure the strength of concrete in a structure, the measured strength being a combination of shear and tensile strengths. The capital and operating cost of these tests is low in that the equipment can be assembled for less than $500 and the testing can be done in the field in a matter of minutes. Furthermore, if a pullout force of a given minimum strength is applied without failure, it may be assumed that a minimum strength has been reached in the in situ concrete and the structural unit need not be stressed to failure.

The major disadvantage is that damage to the concrete surface must be repaired but this does not appear to be too serious a problem. Another serious disadvantage is that the tests have to be planned in advance and, unlike the other in situ tests, cannot be performed at random after the concrete has hardened.

CONCLUDING REMARKS

In the foregoing pages, problems associated with the evaluation of strength of drilled cores have been outlined and the contradictory nature of the available data have been discussed. In order to create some semblance of order in an otherwise chaotic situation, a completely new approach has been suggested. This, of course, will involve fundamental changes in our approach to specifications and code writing, and it could take some time before the concrete community accepts it. In the meantime, a designer and a ready-mixed concrete supplier who are confronted with low strength tests need guidance. To this end, ACI Committee 214 has undertaken to produce a document on the evaluation of core test results. Also, ASTM Committee C9 hopes to produce correction factors for l/d other than 2 when cores are tested dry as allowed in ACI 318-71. Apart from this, greater emphasis should be placed on proper drilling of cores. It is also important that a designated representative of a designer should be present when cores are taken and tested to avoid disputes, and every effort should be made to maintain l/d as close to 2 as possible. In addition to drilling cores from structural members which are suspect because of low cylinder strength test results, it may be advisable to also drill cores from other adjacent areas of concrete which have been accepted on the basis of strength test results. The strength of cores from these areas should then be compared with strength of cores from the concrete under investigation; this comparison could be extremely helpful in the evaluation process.

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