EVALUATION OF NONDESTRUCTIVE TESTS ANALYSIS TO ESTIMATE IN-PLACE STRENGTH OF CONCRETE

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ABSTRACT: There are a lot of reasons to use In-place tests. Construction schedules often require that operations such as form removal, post-tensioning, termination of curing, and removal of reshores be carried out as early as possible. To enable these operations to proceed safely as soon as possible requires the use of reliable in-place tests to estimate the in-place strength.
In-place test results are not reliable for engineering judgment. These results should be interpreted and correlated to standard compressive strength, based on the test method. In this paper some of these test procedures and their limitations are discussed.
In this study we will go on for Rebound number, Pullout, Ultrasonic pulse velocity, and Cast-in-place cylinder methods which are most useful methods in the Asia.

Key words: *compressive strength; construction; in-place tests; sampling; statistical analysis.*

1. INTRODUCTION

1.1 Scope

As standard-cured cylinders are usually tested for acceptance purposes at an age of 28 days; therefore, the results of these tests cannot be used to determine whether adequate strength exists at earlier ages for safe removal of formwork or the application of post-tensioning.
In-place tests are some methods that have been done instead of standard compressive strength method. These methods are almost used to estimate concrete compressive strength. But the result of these tests should be interpreted and correlated to standard compressive strength to become useful.
In-place testing not only increases safety but can result in substantial cost savings by permitting accelerated construction schedules.
In 1938, Skramtajev presented some of the reasons for the need for in-place testing:

• The curing conditions of standard test specimens are not representative of the concrete in the structure.
• The number of standard test specimens is insufficient to assure the adequacy of all members in a structure.
• Standard test specimens that are tested at an age of 28 days provide no information on the later-age strength of concrete in structure.

The needs for in-place methods are also clarified in new and existing constructions. In new construction such as post-tensioning structures and formwork releasing time estimations are the critical points which need in-place methods to be clarified.
In the case of existing structures some problems such as change in serviceability of structure and failure of some strength satisfactions can lead to use in-place methods.
At present, there are no standard practices for developing the required relationship between tests results and standard compressive strength. There are also no generally accepted guidelines for interpretation of in-place test results. These deficiencies have been obstacles to widespread adoption of in-place tests.
In this paper we will review some of in-place methods and discuss about their within limitations and variations. Then we will go on with strength relationship and finally we discuss about implementation of tests and interpretation of results.

2. REVIEW OF SOME IN-PLACE METHODS

2.1 Introduction

In this paper the following methods are discussed:

• Rebound number;
• Pullout;
• Ultrasonic pulse velocity; and
• Cast-in-place cylinder.

2.2 Rebound number

The right way to understand the limitations of this test for estimating strength is recognizing the factors influencing the rebound distance. From a fundamental point of view, the test is a complex problem of impact loading and stress-wave propagation (ACI 228.1R-03). The rebound distance depends on the kinetic energy in the hammer before impact with the shoulder of the plunger and the amount of that energy absorbed during the impact. Part of the energy is absorbed as mechanical friction in the instrument, and part of the energy is absorbed in the interaction of the plunger with the concrete. It is the latter factor that makes the rebound number an indicator of the concrete properties.

A low-strength, low-stiffness concrete will absorb more energy than a high-strength, high-stiffness concrete. Thus, the low-strength concrete will result in a lower rebound number. Because it is possible for two concrete mixtures to have the same strength but different stiffnesses, there could be different rebound numbers even if the strengths are equal. Conversely, it is possible for two concretes with different strengths to have the same rebound numbers.
Because aggregate type affects the stiffness of concrete, it is necessary to develop the strength relationship on concrete made with the same materials that will be used for the concrete in the structure.
In rebound-hammer testing, the concrete near the point where the plunger impacts influences the rebound value. Therefore, the test is sensitive to the conditions at the location where the test is performed. If the plunger is located over a hard aggregate particle, an unusually high rebound number will result. On the other hand, if the plunger is located over a large air void or over a soft aggregate particle, a lower rebound number will occur. Reinforcing bars with shallow concrete cover may also affect rebound numbers if tests are done directly over the bars. To account for these possibilities, ASTM C 805 requires that 10 rebound numbers be taken for a test. If a reading differs by more than six units from the average, that reading should be discarded and a new average should be computed based on the remaining readings. If more than two readings differ from the average by six units, the entire set of readings is discarded. Because the rebound number is affected mainly by the near-surface layer of concrete, the rebound number may not represent the interior concrete. The presence of surface carbonation can result in higher rebound numbers that are not indicative of the interior concrete. Similarly, a dry surface will result in higher rebound numbers than for the moist, interior concrete. Also curing conditions can affect the strength and stiffness of the near-surface concrete more than the interior concrete. The surface texture may also influence the rebound number. When the test is performed on rough concrete, local crushing occurs under the plunger and the indicated concrete strength will be lower than the true value.
A hard, smooth surface, such as a surface produced by trowel finishing, can result in higher rebound numbers. Finally, the rebound distance is affected by the orientation of the instrument, and the strength relationship must be developed for the same instrument orientation as will be used for in-place testing.
In summary, while the rebound number test is simple to perform, there are many factors other than concrete strength that influence the test results. As a result, estimated strengths are not as reliable as those from other in-place test methods to be discussed.

2.3 Pullout test

The pullout test measures the maximum force required to pull an embedded metal insert with an enlarged head from a concrete specimen or structure. As the insert is pulled out, a roughly cone-shaped fragment of the concrete is extracted.
Unlike the rebound hammer, the pullout test subjects the concrete to a static loading that lends itself to stress analysis.
Reaction ring and that additional load is resisted by aggregate interlock across the circumferential crack. In this case, failure occurs when sufficient aggregate particles have been pulled out of the mortar matrix. According to the aggregate interlock that affect the ultimate load in the test, maximum pullout force is not directly related to the compressive strength. There is good correlation, however, between ultimate pullout load and compressive strength of concrete because both values are influenced by the mortar strength (Stone and Carino 1984). it is necessary to develop an empirical relationship between the pullout strength and the compressive strength of the concrete. The relationship that is developed is applicable to only the particular test configuration and concrete materials used in the correlation testing.
The pullout strength is primarily governed by the concrete located next to the conic frustum defined by the insert head and reaction ring. Commercial inserts have embedment depths of about 25 to 30 mm (1 to 1.2 in.). Thus, only a small volume of concrete is tested, and because of the inherent heterogeneity of concrete, the average within-batch coefficient of variation of these pullout tests has been found to be between 7 and 10%, which is about two to three times that of standard cylinder-compression tests. In existing construction, it is possible to perform pullout tests using post-installed inserts.
The test geometry is the same as for the cast-in-place insert. In a commercial test system, known as CAPO (for Cut and Pullout), the insert is a coiled, split ring that is expanded with specially designed hardware. The CAPO system performs similarly to the cast-in-place system of the same geometry (Petersen 1984, 1997).
In summary, the pullout test can be used to estimate the strength of concrete by measuring the force required to extract an insert embedded in fresh concrete or installed in hardened concrete. While the exact failure mechanism is still a matter of controversy, there is a strong relationship between the compressive strength of concrete and pullout strength.

2.4 Ultrasonic pulse velocity

The ultrasonic pulse velocity test, as described in ASTM C 597, determines the propagation velocity of a pulse of vibrational energy through a concrete member (Jones 1949; Leslie and Cheesman 1949). A pulser sends a short-duration, high-voltage signal to a transducer, causing the transducer to vibrate at its resonant frequency. At the start of the electrical pulse, an electronic timer is switched on. The transducer vibrations are transferred to the concrete through a viscous coupling fluid. The vibrational pulse travels through the member and is detected by a receiving transducer coupled to the opposite concrete surface. When the pulse is received, the electronic timer is turned off and the elapsed travel time is displayed. The direct path length between the transducers is divided by the travel time to obtain the pulse velocity through the concrete.
From the principles of elastic wave propagation, the pulse velocity is proportional to the square root of the elastic modulus (ACI 228.2R). Because the elastic modulus and

strength of a given concrete increase with maturity, it follows that pulse velocity may provide a means of estimating strength of concrete, even though there is no direct physical relationship between these two properties.
At early maturities, a given increase in compressive strength results in a relatively large increase in pulse velocity, while at later maturities the velocity increase is smaller for the same strength increase. Thus, the sensitivity of the pulse velocity as an indicator of change in concrete strength decreases with increasing maturity and strength.
The pulse velocity depends strongly on the type and amount of aggregate in the concrete, but the strength of normal-strength concrete (less than about 40 MPa or 6000 psi) is less sensitive to these factors. As the volumetric aggregate content of concrete increases, pulse velocity increases, but the compressive strength may not be affected appreciably (Jones 1962). Another important factor is moisture content. As the moisture content of concrete increases from the air-dry to saturated condition, it is reported that pulse velocity may increase up to 5% (Bungey 1989). The curing process also affects the relationship between pulse velocity and strength, specially when accelerated methods are used (Teodoru 1986). The amount and orientation of the steel reinforcement will also influence the pulse velocities. Because the pulse velocity through steel is about 40% greater than through concrete, the pulse velocity through a heavily reinforced concrete member may be greater than through one with little reinforcement.
The measured pulse velocity may also be affected by the presence of cracks or voids along the propagation path from transmitter to receiver. The pulse may be diffracted around the discontinuities, thereby increasing the travel path and travel time.
Without additional knowledge about the interior condition of the concrete member, the apparent decrease in pulse velocity could be incorrectly interpreted as a low compressive strength. In this test method, all of the concrete between the transmitting and receiving transducers affects the travel time. Test results are, therefore, relatively insensitive to the normal heterogeneity of concrete. Consequently, the test method has been found to have an extremely low within-batch coefficient of variation.

2.5 Cast-in-place cylinders
This is a good technique to obtain cylindrical concrete specimens from newly cast slabs without drilling cores. The method involves using a mold. The outer sleeve is nailed to the formwork and is used to support a cylindrical mold. The sleeve can be adjusted for different slab thicknesses. The mold is filled when the slab is cast, and the concrete in the mold is allowed to cure with the slab. The objective of the technique is to obtain a test specimen that has been subjected to the same thermal history as the concrete in the structure. There will always be some uncertainty in the actual in-place strength because the length-diameter ratio correction factors are inherently approximate.

2.6 Combination of in-place methods
The term Combination of in-place methods refers to the use of two or more in-place test methods to estimate concrete strength. By combining results from more than one in-place test, a multivariable correlation can be established to estimate strength. Combined methods are reported to increase the reliability of the estimated strength. The underlying concept is that if the two methods are influenced in different ways by the same factor, their combined use results in a canceling effect that improves the accuracy of the estimated strength. For example, an increase in moisture content increases pulse velocity but decreases the rebound number. So this is a very good hint in planning in-place methods. Combinations, such as pulse velocity and rebound number (or pulse velocity, rebound number, and pulse attenuation), have resulted in strength relationships with higher correlation coefficients than when these methods are used individually (ACI 228.1R-03).
It is emphasized that combining methods is not an end in itself. A combined method should be used in those cases where it is the most economical way to obtain a reliable estimate of concrete strength (Leshchinsky 1991).

Table 2.1 Relative performance of in-place tests

Test Method	Accuracy		Ease of use
	New construction	Existing construction	
Rebound number	+	+	++
Pull out	++	++	+
Pulse velocity	++	+	+
Cast-in-place cylinders	++	N/A	+

*A test method with a ++ results in a more accurate strength estimate or is easier to use than a method with a +. N/A indicates that the method is not applicable to existing construction.

3. STATISTICAL CHARACTERISTICS OF TEST RESULTS

3.1 Need for statistical analysis
In designing a structure to safely resist the expected loads, the engineer uses the specified compressive strength (f΄c) of the concrete. The strength of the concrete in a structure is variable and, as indicated in ACI 214, the specified compressive strength is approximately the strength that is expected to be exceeded with about 90% probability (10% of tests are expected to fall below the specified strength.). To ensure that this condition is satisfied, the concrete supplied for the structure must have an average standard-cured cylinder strength more than f΄c as specified in Chapter 5 of ACI 318-02. When the strength of concrete in a structure is in question because of low standard-cured cylinder strengths or suspected curing deficiencies, ACI 318 states that the concrete is structurally adequate if the in-place strength, as represented by the average strength of three cores, is not less than 0.85fc¢ (ACI 228.1R-03).

To arrive at a reliable estimate of the in-place compressive strength by using in-place tests, one must account for the following primary sources of uncertainty:

1. The average value of the in-place test results;
2. The relationship between compressive strength and the in-place test results; and
3. The inherent variability of the in-place compressive strength.

The first source of uncertainty is associated with the inherent variability (repeatability) of the test method.

3.2 Repeatability of test results

The uncertainty of the average value of the in-place test results is a function of the standard deviation of the results and the number of tests. The standard deviation is in turn a function of the repeatability of the test and the variability of the concrete in the structure.

3.2.1 Rebound number- The precision statement of ASTM C 805 states that the within-test standard deviation of the rebound hammer test is 2.5 rebound numbers. Teodoru reported an average standard deviation of 3.75, for average rebound numbers ranging from 20 to 40, and the standard deviation was independent of the average rebound number.

The average coefficients of variation from the studies by Carette and Malhotra (1984) and by Keiller (1982) have equal values of 11.9, while the average value from the study by Yun et al. (1988) was 10.4 and Teodoru reported a value of 10.2%. Thus, it appears that the repeatability of the rebound number technique may be described by a constant coefficient of variation, which has an average value of about 10%.

3.2.2 Pullout test- ASTM C 900 states that the average within-test coefficient of variation is 8% for cast-in-place pullout tests with embedments of about 25 mm (1 in.) in concrete with nominal maximum aggregate size of 19 mm. Thus, it may be concluded that the coefficient of variation should be used as a measure of the repeatability of the pullout test. For the conditions studied, it was found that embedment depth and apex angle did not greatly affect repeatability. On the other hand, the maximum nominal aggregate size appeared to have some affect, with the 19 mm aggregate resulting in slightly greater variability than the smaller aggregates. The aggregate type also appears to be important. For tests with low-density aggregate, the variability was lower than for tests with normal-density aggregates Experimental evidence suggests that the variability of the pullout test should be affected by the ratio of the mortar strength to coarse-aggregate strength and by the maximum aggregate size. As aggregate strength and mortar strength become similar, repeatability is improved. In general, it appears that an average within-test coefficient of variation of 8% is typical for pullout tests conforming with the requirements of ASTM C 900 and with embedment depths of about 25 mm (ACI 228.1R-03).

3.2.3 Pulse velocity- In contrast to the previous test techniques that examine a relatively thin layer of the concrete in a structure, the pulse-velocity method (using through transmission) examines the entire thickness of concrete between the transducers. Localized differences in the composition of the concrete because of inherent variability are expected to have a negligible effect on the measured travel times of the ultrasonic pulses. Thus, the repeatability of this method is expected to be much better than the previous techniques. ASTM C 597 states that the repeatability of test results is within 2%, for path lengths from 0.3 to 6 m through sound concrete and for different operators using the same instrument or one operator using different instruments (ACI 228.1R-03).

3.2.4 Cast-in-place cylinder- ASTM C 873 states that the single-operator coefficient of variation is 3.5% for a range of compressive strength between 10 and 40 MPa (ACI 228.1R-03).

4. STRENGTH RELATIONSHIPS

4.1 General

Manufacturers of in-place testing equipment typically provide generalized relationships in the form of graphs or equations that relate the property measured by the particular test device to the compressive strength of standard concrete specimens. These relationships, however, often do not accurately represent the specific concrete being tested. These relationships should not be used unless their validity has been established through correlation testing on concrete similar to that being investigated and with the specific test instrument that will be used in the investigation.

4.2 New construction

4.2.1 General- For new construction, the preferred approach is to establish the strength relationship by a laboratory-testing program that is performed before using the in-place test method in the field. The testing program typically involves preparing test specimens using the same concrete mixture proportions and materials to be used in construction. At regular intervals, measurements are made using the in-place test technique, and the compressive strengths of standard specimens are also measured. The paired data are subjected to regression analysis to determine the best-fit estimate of the strength relationship.

For some techniques it may be possible to perform the in-place test on standard specimens without damaging them, and the specimens can be subsequently tested for compressive strength. Usually, in-place tests are carried out on separate specimens, and it is extremely important that the in-place tests and standard tests are performed on specimens having similar consolidation and at the same maturity. This may be achieved by using curing conditions that ensure similar internal temperature histories. Alternatively, internal temperatures can be recorded and test ages can be adjusted so that the in-place and standard tests are performed at the same maturity index. In developing the test plan to obtain a reliable strength relationship, the user should consider the following questions:

• How many strength levels (test points) are needed?
• How many replicate tests should be performed at each strength level?
• How should the data be analyzed? (ACI 228.1R-03)

4.2.2 Number of strength levels- The number of strength levels required to develop the strength relationship depends on the desired level of precision and the cost of additional tests. it was concluded that in planning the correlation testing program, six to nine strength levels should be considered. The range of strengths used to establish the correlation should cover the range of strengths that are to be estimated in the structure (ACI 228.1R-03).

4.2.3 Number of replications- The number of replicate tests at each strength level affects the uncertainty of the average values. in acceptance testing, ACI 318 considers a test result as the average compressive strength of two molded cylinders. Therefore, in correlation testing, two replicate standard compression tests can be assumed to be adequate for measuring the average compressive strength at each level. The number of companion in-place tests at each strength level should be chosen so that the averages of the in-place tests and compressive strengths have similar uncertainty. To achieve this condition, the ratio of the number of tests should equal the square of the ratio of the corresponding within-test coefficients of variation. If the number of replicate compression tests at each strength level is two, the required number of replicate in-place tests is

$$n_i = 2\left(\frac{V_i}{V_s}\right)^2 \qquad (4\text{-}1)$$

Where
ni = number of replicate in-place tests;
Vi = coefficient of variation of in-place test; and
Vs = coefficient of variation of standard test.

For planning purposes, the coefficients of variation given in Chapter 3 may be used for the in-place tests. For molded cylinders prepared, cured, and tested according to ASTM standards, the within-test coefficient of variation can be assumed to be 3% (ASTM C 39/C 39M). For cores a value of 5% may be assumed (ACI 228.1R-03).

4.2.4 Regression analysis- After the data are obtained, the strength relationship should be determined. The usual practice is to treat the average values of the replicate compressive strength and in-place test results at each strength level as one data pair. The data pairs are plotted using the in-place test value as the independent value (or X variable) and the compressive strength as the dependent value (or Y variable).
Historically, most strength relationships have been assumed to be straight lines, and ordinary least-squares (OLS) analysis has been used to estimate the corresponding slopes and intercepts. The use of OLS is acceptable if an estimate of the uncertainty of the strength relationship is not required to analyze in-place test results (ACI 228.1R-03).

4.2.5 Procedures for correlation testing

4.2.5.1 Rebound number - At least 12 standard cylinders should be cast. At each test age, a set of 10 rebound numbers (ASTM C 805) should be obtained from each pair of cylinders held firmly in a compression testing machine or other suitable device at a pressure of about 3 MPa (500 psi). The rebound tests should be made in the same direction relative to gravity as they will be made on the structure. The cylinders should then be tested in compression.

4.2.5.2 Pullout test- Several techniques have been used. A good alternative is to cast standard cylinders for compression testing and to place pullout inserts in cubes (or slabs or beams) so that the pullout tests can be made in the companion specimen when the standard cylinders are tested. The latter approach is the preferred method, providing consolidation is consistent between the standard cylinders and the cubes or other specimens containing the pullout inserts, and the maturity of all specimens at the time of testing is the same. The recommended minimum size for cubes is 200 mm (8 in.) when 25 mm (1 in.) diameter inserts are used. Four inserts can be placed in each cube, one in the middle of each vertical side.
For each test age, two standard cylinders should be tested and eight pullout tests performed. The same procedure applies to post-installed pullout tests. Install the inserts on the same day that pullout tests will be done.

4.2.5.3 Ultrasonic pulse velocity- It is preferable to develop the strength relationship from concrete in the structure. Tests should be on cores obtained from the concrete being evaluated. Tests with standard cylinders can lead to unreliable correlations because of different moisture conditions between the cylinders and the in-place concrete. The recommended procedure is to select certain areas in the structure that represent different levels of pulse velocity. At these locations, it is recommended that five velocity determinations be made to ensure a representative average value of the pulse velocity. Then obtain at least two cores from each of the same locations for compressive strength testing. Pulse velocity measurements on these cores, once they have been removed from the structure, will usually not be the same as the velocities measured in the structure and are not representative of the pulse velocity of the structure.

4.2.5.4 Cast-in-place cylinder- If necessary, test results should be corrected for the height-diameter ratio using the values given in ASTM C 42/C 42M. No other correlation is needed because the specimens represent the concrete in the placement and the test is a uniaxial compression test.

4.3 Existing construction

4.3.1 General- There is often a need to evaluate the in-place strength of concrete in existing structures. For example, planned renovation or change in the use of a structure may require determination of the concrete strength for an accurate assessment of structural capacity. There also may be a need to evaluate concrete strength after a structural failure, fire damage, or environmental degradation has occurred. In-place tests can be used in two ways to evaluate existing construction. First, they can be used qualitatively to locate those portions of the structure where the concrete appears to be different from other portions. In this case, the in-place tests can be used without a strength relationship for the concrete in the structure. The main purpose of the in-place testing is to establish where cores should be taken for strength determinations and other pertinent tests (ACI 437R). The rebound number and the pulse velocity method are widely used for this purpose. Second, in-place methods can be used for a quantitative assessment of the strength. In this case, a strength relationship must be established for the concrete in the structure. The relationship can be developed only by performing in-place tests at selected locations and taking companion cores for strength testing. Thus, the use of in-place testing does not eliminate the need for coring, but it can reduce the amount of coring required to gain an understanding of the variations of strength in a structure, and it can give a higher degree of confidence that the cores taken truly represent the conditions being investigated (ACI 228.1R-03).

4.3.2 Developing strength relationship- Because in-place testing for evaluations of existing construction is not preplanned, the techniques that have traditionally been used are ultrasonic pulse velocity, rebound number, and probe penetration. In the United Kingdom, the pull-off test is also used (Long and Murray 1984; Murray and Long 1987). In Scandinavia and other parts of Europe, a post-installed pullout test is widely used (Petersen 1984, 1997). This test involves drilling a hole into the concrete and cutting out a cylindrical slot to accommodate an expandable ring that functions as the insert head. In 1999, this type of post-installed pullout test was incorporated into ASTM C 900.

For some test methods, certain factors should be considered when testing existing structures. For example, for surface tests (rebound number, penetration resistance, and pull-off), the user must pay special attention to those factors that may affect the near-surface strength, such as carbonation, moisture content, or surface degradation from chemical or physical processes. Surface grinding may be necessary to expose concrete that represents the concrete within the structure. In selecting the core locations, it is desirable to include the widest range of concrete strengths in the structure that is possible. Often, rebound numbers or pulse velocity values are determined at points spread over a grid pattern established on the area being evaluated. When the data are plotted on a map, contour lines can be sketched in to outline the variations in the concrete quality (Murphy 1984). Based on this initial survey, six to nine different locations should be selected for coring and measurement of the in-place test parameter. At each location, a minimum of two cores should be obtained to establish the in-place compressive strength. The number of replicate in-place tests at each location depends on the test method and economic considerations, as discussed in its chapter. Because at least 12 cores are recommended to develop an adequate strength relationship, the use of in-place testing may only be economical if a large volume of concrete is to be evaluated. After the averages and standard deviations of the in-place test parameter and core strength are determined at each test location, the strength relationship is developed using the same approach as for new construction (Section 4.2.4). In evaluating the average and standard deviation of the replicate in-place results, the recorded values should be checked for outliers (ASTM E 178). In general, test results that are more than two standard deviations from the average should be scrutinized carefully (ACI 228.1R-03).

5. IMPLEMENTATION OF IN-PLACE TESTING

5.1 New construction

5.1.1 Preconstruction consensus- Before starting construction of the components of the structure that are to be tested in-place, a meeting should be held among the parties who are involved. The participants typically include the owner, construction manager, structural engineer, testing company, general contractor, subcontractors (such as formwork contractor or post-tensioning contractor), and concrete supplier. The objective of the preconstruction meeting is to clarify the test procedures to be used, the access requirements, the criteria for interpretation of test data, and the interaction among the parties. A mutual understanding among the involved parties will reduce the potential for dispute during construction. The meeting should achieve a consensus on the following critical issues:

- Agreement on type of formwork material that will be used because it may affect the correlation testing;
- The test procedure(s) to be used, number and locations of tests, the access requirements for testing, and the assistance to be provided by the contractors in preparing and protecting test locations and testing equipment;
- The criteria for acceptable test results for performing critical operations, such as form removal, post-tensioning, removal of reshores, or termination of accelerated or initial curing;
- Procedures for providing access and any modifications to formwork required to facilitate testing;
- Procedures and responsibilities for placement of testing hardware, where required, and protection of test sites;
- Procedures for the timing and execution of testing;
- Reporting procedures to provide timely information to site personnel;
- Approval procedures to allow construction operations to proceed if adequate strength is shown to have been achieved; and • Procedures to be followed if adequate strength is not shown to have been achieved.

5.1.2 Number of test locations- It is important that the tests provide a reliable measure of the strength of the tested component at the time the tests are made. Therefore, sufficient test locations need to be provided so that there are sufficient test results to adequately characterize the concrete strength within the portion of the structure being evaluated. The term “test location” means a region on the structure where an in-place test procedure is to be executed. At a test location, one or more single or replicate in-place tests may be performed. The number of test locations should account for the following considerations: • Because tests will be performed at early ages when strength gain of concrete depends highly on temperature, the initial tests may show that adequate strength has not yet been achieved. It will then be necessary to stop testing after the initial tests have been made and to retest at a later age. Sufficient test locations have to be provided to allow for repeat tests and to satisfy the criterion for number of tests required to allow critical operations to proceed; and • If tests are made at ages under 12 h after the concrete is cast, it is expected that the in-place strength will have high variability due to variations in temperature at the test locations. In this case, it is advisable to increase the number of provided test locations by 10 to 25%.

5.1.3 Number of tests per location- The number of in-place tests to be performed at a test location could, in theory, be determined based on the within-test repeatability of the test method. Consideration, however, should be also given to practicality; otherwise, in-place testing programs will be avoided because of the financial burden.

Table 5.1 Number of replicate tests at each location

Test method	Minimum number of locations to test
Rebound number	10
Pull out	1
Pulse velocity	2
Cast-in-place cylinders	2

5.1.4 Providing access to test locations—To perform in-place tests during construction, it is necessary to provide access to the hardening concrete. The specific details will depend on the test method, the type of structural component, and the type of formwork. Test locations should be selected to avoid reinforcing steel. Finally, it should be kept in mind that the water absorption characteristics of the form surface at the location of the in-place testing might affect the results of surface tests, such as the rebound number and pin-penetration methods. Form materials for the in-place test specimens in the correlation testing must be similar to those used in construction.

5.1.5 Distribution of tests- Test locations should be distributed throughout the component being tested so that the results provide an accurate indication of the strength distribution within the component. In selecting the testing locations, consideration should be given to the most critical locations in the structure in terms of strength requirements (such as post-tensioning stressing locations) and exposure conditions (such as slab edges), especially during cold weather.

5.1.6 Critical dimensions- Tests such as rebound number, penetration resistance, pullout, and break-off produce some surface damage to the concrete, and test results are affected by the conditions within the zone of influence of the particular test.

5.2 Existing construction

5.2.1 Pretesting meeting- In-place testing is often one facet of an overall investigation to establish structural adequacy. The plan for the in-place testing program will depend on the purpose of the investigation. A pretesting meeting should be held among the members of the team who share a common interest in the test results. At the conclusion of the meeting, there should be a clear understanding of the objective of the investigation; there should be agreement on the responsibilities of the team members in acquiring the test data; and there should be agreement on the procedures for obtaining and analyzing the test results. When access to the concrete for testing is restricted by architectural coverings, detailed plans should be developed to accomplish this access.

5.2.2 Sampling plan- In developing the testing program, consideration should be given to the most appropriate sampling plan for the specific situation. ASTM C 823 provides guidelines for developing the sampling plan.

In general, two sampling situations may be encountered. In one situation, all of the concrete is believed to be of similar composition and quality. For this case, random sampling should be spread out over the entire structure and the results treated together.

The second sampling situation arises when available information suggests that the concrete in different sections of the structure may be of different composition or quality, or when the purpose of the investigation is to examine failure or damage in a specific section of a structure. In this case, random sampling should be conducted within each section of the structure where the concrete is suspected of being nominally identical.

5.2.3 Number of tests—as was discussed in Section 4.3, the in-place testing program for an existing structure involves two phases. First, the strength relationship must be established by testing drilled cores and measuring the corresponding in-place test parameter near the core locations. The locations for correlation testing should be chosen to provide a wide range in concrete strength. As mentioned in Section 4.3.2, a minimum of six to nine test locations should be selected for obtaining the correlation data. In general, cores should be drilled after the in-place tests are performed. At each location, two cores should be drilled, and the following number of replicate in-place tests should be performed to provide the average value of the companion in-place test parameter. The number of replicate in-place tests is based on considerations of the within-test variability of the method and the cost of additional testing. For example, the within-test repeatability of the ultrasonic pulse velocity test is low, and the cost of replicate readings at one location is low. Therefore, five replicate readings are recommended to ensure that a representative value will be obtained because of the variability in the efficiency of the coupling of the transducer to the structure (ACI 228.1R-03).

6. INTERPRETATION AND REPORTING OF RESULTS

6.1 General

Standard statistical procedures should be used to interpret in-place tests. It is not sufficient to simply average the values of the in-place test results and then compute the equivalent compressive strength by means of the previously established strength relationship. It is necessary to account for the uncertainties that exist. While no procedure has yet been agreed upon for determining the tenth-percentile in-place strength based on the results of in-place tests, proponents of in-place testing have developed and are using statistically based interpretations.

6.2 Statistical method

6.2.1 Danish method (Bickley 1982b)- This method has been developed for analysis of pullout test results. The pullout strengths obtained from the field tests are converted to equivalent compressive strengths by means of the strength relationship (correlation equation) determined by regression analysis of previously generated data for the particular concrete being used at the construction site. The standard deviation of the converted data is then calculated. The tenth percentile compressive strength of the concrete is obtained by subtracting the product of the standard deviation and a statistical factor K (which varies with the number of tests made and the desired level of confidence) from the mean of the converted data. The K factors for different number of tests and a 75% confidence level are given in some tables in references.

6.2.2 General tolerance factor method (Hindo and Bergstrom 1985)- The acceptance criteria for strength of concrete cylinders in ACI 214 are based on the assumption that the probability of obtaining a test with strength less than fc¢ is less than approximately 10%. A suggested method for evaluating in-place tests of concrete at early ages is to determine the lower tenth percentile of strength, with a prescribed confidence level. It has been established that the variation of cylinder compressive strength can be modeled by the normal or the lognormal distribution function depending upon the degree of quality control. In cases of excellent quality control, the distribution of compressive strength results is better modeled by the normal distribution; in cases of poor control, it is better modeled by a lognormal distribution (Hindo and Bergstrom 1985). In the tolerance factor method, the lower tenth percentile compressive strength is estimated from in-place test results by considering quality control, number of tests n, and the required confidence level p. Three quality control levels are considered: excellent, average, and poor, with the distribution function of strength assumed as normal, mixed normal-lognormal, and lognormal, respectively. Suggested values of p are 75% for ordinary structures, 90% for very important buildings, and 95% for crucial parts of nuclear power plants (Hindo and Bergstrom 1985). Because safety during construction is the primary concern, it may be adequate to use the same p value for all structures. A value of p equal to 75% is widely used in practice. The tolerance factor K, the sample average Y, and standard deviation sY are used to establish a lower tolerance limit, that is, the lower tenth percentile strength. For a normal distribution function, the estimate of the tenth percentile strength Y0.10 can be determined as follows:

$$Y_{0.10} = Y - Ks_Y \qquad (6\text{-}1)$$

where

Y0.10 = lower tenth percentile of strength (10% defective);
Y = sample average strength;
K = one-sided tolerance factor; and
Sy = sample standard deviation.

The tolerance factor is determined from statistical characteristics of the normal probability distribution and depends on the number of tests n, the confidence level p, and the defect percentage. Values of K are found in reference books such as that by Natrella (1963). For the lognormal distribution, the lower tenth percentile of strength can be calculated in the same manner, but using the average and standard deviation of the logarithms of strengths in Eq. (6-1). By dividing both sides of Eq. (6-1) by the average strength Y, the following is obtained

$$\frac{Y_{0.10}}{Y} = 1 - KV_Y \qquad (6\text{-}2)$$

where VY = coefficient of variation (expressed as a decimal).

In the above Eq., the tenth-percentile strength is expressed as a fraction of the average strength.

6.2.5 Summary- With the exception of cast-in-place cylinder tests, in-place tests provide indirect measures of concrete strength. To arrive at a reliable estimate of the in-place strength, the uncertainties involved in the estimate must be considered. Therefore, they may be adequate for test methods that have good correlation with compressive strength, such as the pullout test. The tolerance factor methods, however, do not account for the main sources of uncertainty in a rational way. This has led to the development of more rigorous procedures.

6.3 Reporting results

Report forms for the different tests and different purposes will vary. A variety of report forms will be appropriate. Usually, relevant ASTM standards describe the inforation required on a report. Where in-place testing is made at early ages, some particular reporting data are desirable. These may serve as useful models for developing forms to report the results of other in-place tests. Briefly, the three forms provide for the following:

1. Record of test locations—This form gives a plan view of a typical floor in a specific multistory building.

The location of each test is noted. The location of maturity meters, if installed, can also be shown. Location data are important in case of low or variable results. Where tests are made at very early ages and the time to complete a placement is long, there may be a significant age-strength variation from the start to the finish of the placement.

2. Record of field-test results—This is the form on which test data, the calculated results, and other pertinent data are recorded at the site. It includes provisions for entering information on maturity data, protection details, and concrete appearance to corroborate the test data during cold weather. Due to the critical nature of formwork removal, a recommended procedure is for the field technician to phone the data to a control office and obtain confirmation of the calculations before giving the results to the contractor.

3. Report of test results—This form is used to report the in-place test results. This form is a multicolor self-carbon form designed to be completed at the site by the technician, with copies given to the contractor's and structural engineer's representatives when the results have been checked. It provides for identification of the placement involved, the individual results, and the calculated mean and minimum strengths. It records the engineer's requirements for form removal and states whether these requirements have been met. It requires the contractor's representative's signature on the testing company's copy (ACI 228.1R-03).

7. IN-PLACE METHODS AS MANAGEMENT TOOLS

There are so many benefits, which can be derived from utilizing in-place methods. Construction engineering deals greatly with concrete as most useful material in project.

In the other hand scheduling the construction should be based on concrete characters. So in-place methods can be called as management tools. Some of the applications of in-place methods which make these tests as management tools are mentioned below;

- Construction schedules; Estimation of in-place strength of concrete can recognize the time of form removal, post-tensioning, etc. Satisfaction of required strength for these operations is earlier than 28 days.
- Quality management; The application of in-place tests can be developed to concrete production sites to assure quality management. In the other hand these methods can be used for concrete inspection at construction sites.

Therefore at the start of every construction project, the use of in-place methods should be pre-planned.

8. CONCLUSIONS

There are so many in-place tests to estimate concrete strength. These tests are almost easier and cheaper than standard compressive strength. But as they are not so reliable, the engineer should consider their limitations and their special points in application. The correlation should be done by the use of mentioned methods. Interpretation of results is very important.

Although these methods are not as reliable as standard test, but they can substitute the standard test. The main reason of this suggestion is their low cost and ease of application. But on the other hand all of members of the team who share a common interest in construction should consider the possibility of using in-place methods in the consruction project. So it is suggested for every construction project to anticipate the use of these tests and provide them with the details and tools needed.

It is suggested to use some good reports such as ACI 228.1R-03 and develop the methods of correlation for each project and each mix design. There are so many useful figures and diagrams in those reports to use.

On the other hand it is suggested to study more about these tests as easy ways, which are almost very economical and fast to apply for every designer and construction manager.

REFERENCES

[1] American Concrete Institute
228.1R In-place Methods to Estimate Concrete Strength

[2] Bungey J.H. and Millard S.G., "Testing of concrete in structures", Chapman & Hall, 1996

[3] "Concrete construction engineering handbook", CRC Press, 1997