Report on Methods for Estimating In-Place Concrete Strength

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This report provides methods for estimating the in-place strength of concrete in new and existing construction. These methods include: rebound number, penetration resistance, pullout, pull-off, ultrasonic pulse velocity, maturity, and cast-in-place cylinders. The principle, inherent limitations, and repeatability of each method are reviewed. Procedures are presented for developing the relationship needed to estimate compressive strength from in-place results. Factors to consider in planning in-place tests are discussed, and statistical techniques to interpret test results are presented. The use of in-place tests for acceptance of concrete is introduced. The Appendix A provides information on the number of strength levels that should be used to develop the strength relationship and explains a regression analysis procedure that accounts for error in both dependent and independent variables.

Keywords: coefficient of variation; compressive strength; construction safety; in-place tests; nondestructive tests; sampling; statistical analysis.

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CHAPTER 1—INTRODUCTION

1.1—Scope

In-place tests are performed typically on concrete within a structure, in contrast to tests performed on molded specimens made from the concrete to be used in the structure. Historically, they have been called nondestructive tests because some of the early tests, such as rebound number and ultrasonic pulse velocity, were noninvasive and did not damage the concrete. Over the years, however, new methods have developed that result in superficial local damage. Therefore, the terminology "in-place tests" is used as a general name for these test methods, which includes those that do not damage the concrete and those that result in some near-surface damage. In this report, the principal application of in-place tests is to estimate the compressive strength of the concrete. The pull-off test can be used to estimate the tensile strength of concrete or evaluate bond strength between layers. The significant characteristic of most of these tests is that they do not directly measure the compressive strength of the concrete in a structure. Instead, they measure some other property that can be correlated to compressive strength (Popovics 1998). The strength is then estimated from a previously established relationship between the measured property and concrete strength. The uncertainty of the estimated compressive strength depends on the variability of in-place test results and the uncertainty of the relationship between these two parameters. These sources of uncertainty are discussed in this report. An alternative approach for correlation between tests results and concrete strength is presented in EN 13791 (2007) and BS 6089 (2010).

In-place tests can be used to estimate concrete strength during construction so that operations requiring a specific strength can be performed safely or curing procedures terminated. They can also be used to estimate concrete strength during the evaluation of existing structures. These two applications require slightly different approaches, so parts of this report are separated into sections dealing with new and existing construction.

A variety of techniques are available for estimating the in-place strength of concrete (Malhotra 1976; Bungey et al. 2006; Malhotra and Carino 2004). No attempt is made to review all methods in this report; only those methods that have been standardized by ASTM International are discussed. Examples of methods not covered include internal fracture tests (Chabowski and Bryden-Smith 1980; Domone and Castro 1987) and torque tests (Stoll 1985).

1.2—Need for in-place tests during construction

In North American practice, the most widely used test for concrete is the compressive strength test of standard cylinders (ASTM C39/39M). This test procedure is relatively easy to perform in terms of sampling, specimen preparation (ASTM C31/C31M), and strength measurement. When properly performed, this test has low single-operator variation and low interlaboratory variation and, therefore, the method lends itself to use as a standardized testing procedure. The compressive strength so obtained is used to verify that the specified strength (f_c') used to calculate the nominal strengths of structural members has been achieved. Therefore, the compressive strength of standard cylinders is an essential parameter in design codes and project specifications.

When carried out according to standard procedures, however, the results of the cylinder compression test represent the potential strength of the concrete as delivered to a site. The test is used mainly as a basis for quality assurance of the concrete to ensure that contract requirements are met. It is not intended for determining the in-place strength of the concrete because it makes no allowance for the effects of placing, consolidation, or curing. It is unusual for the concrete in a structure to have the same properties as a standard-cured cylinder at the same test age. Also, 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. The concrete in some parts of a structure, such as columns, may develop strength equal to the standard 28-day cylinder strength by the time it is subjected to design loads. Concrete in flexural members, especially pretensioned members, can be required to support a large percentage of the design load before an age of 28 days. For these reasons, in-place tests are used to estimate the concrete strength at critical locations in a structure and at times when crucial construction operations are scheduled.

Traditionally, a measure of the strength of the concrete in the structure has been obtained by using field-cured cylinders prepared and cured in accordance with ASTM C31/C31M. These cylinders are cured on or in the structure under, as nearly as possible, the same conditions as the concrete in the structure. Measured strengths of field-cured cylinders may be significantly different from in-place strengths because it is difficult, and often impossible, to have identical bleeding, consolidation, and curing conditions for concrete in cylinders and concrete in structures (Soutsos et al. 2000). Field-cured specimens should be handled with care and stored properly to avoid misleading test results.

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 keep the project on schedule. To enable these operations to proceed safely at the earliest possible time requires the use of reliable in-place tests to estimate the in-place strength. The need for such strength information is emphasized by several construction failures that possibly could have been prevented had in-place testing been used (Lew 1980; Carino et al. 1983a). In-place testing not only increases safety but can result in substantial cost savings by permitting accelerated construction schedules (Bickley 1982a).

1.3—Influence of ACI 318

Before 1983, ACI 318 required testing of field-cured cylinders to demonstrate the adequacy of concrete strength before removal of formwork or reshoring. In 1983, ACI 318 first allowed the use of other procedures instead of tests for field-cured cylinders, if approved by the building official (ACI Committee 318 1983). The design professional, when requested by the building official, however, was required to approve the alternative procedure before its use. Since 1983, ACI 318 has permitted the use of in-place testing as an alternative to testing field-cured cylinders if approved by the licensed design professional and, if requested, approved by the building official. The commentary to ACI 318-14 (Section R26.11.2.1(e)) lists four procedures, which are covered in this report, that may be used provided there are sufficient correlation data.

Most design provisions in ACI 318 are based on the compressive strength of standard cylinders. Thus, to evaluate structural capacity under construction loading, it is necessary to have an estimate of the equivalent cylinder strength of the concrete as it exists in the structure. If in-place tests are used, a valid relationship between the results of in-place tests and the compressive strength of cylinders is required. At present, there are no standard practices for developing the required relationship.

1.4—Recommendations in other ACI documents

After the 1995 version of this report was published, other ACI documents incorporated in-place tests as alternative procedures for estimating in-place strength. One of these documents is ACI 301, a specification for new concrete construction. In the 2016 version of ACI 301, Section 1.6.4.2 on in-place testing of hardened concrete includes the following:

> Use of the rebound hammer in accordance with ASTM C805/C805M or the pulse-velocity method in accordance with ASTM C597 may be specified by Architect/Engineer to evaluate uniformity of in-place concrete or to select areas to be cored. These methods shall not be used to evaluate in-place strength.

Regarding the validity of in-place strength tests, ACI 301-16 states in Section 1.6.5.3(a):

> Results of in-place strength tests will be evaluated by Architect/Engineer and are valid only if tests are conducted using properly calibrated equipment in accordance with recognized standard procedures and an acceptable correlation between test results and concrete compressive strength is established and submitted.

Section 1.6.6.4 of ACI 301-16, however, restricts the use of these tests in acceptance of concrete by stating that, "In-place tests shall not be used as the sole basis for accepting or rejecting concrete," but they may be used if specified to "evaluate" concrete if standard-cured cylinder strengths fail to meet the specified strength criteria.

ACI 301-16 also mentions in-place tests in Section 2.3.4 dealing with required strength for removal of formwork. Specifically, it is stated that if specified in Contract Documents, the following methods may be used to estimate in-place strength:

(a) ASTM C873/C873M (cast-in-place cylinders)
(b) ASTM C803/C803M (penetration resistance)
(c) ASTM C900 (pullout)
(d) ASTM C1074 (maturity method)

These same methods may be used, if specified, as alternatives to testing field-cured cylinders for estimating in-place strength for the purpose of terminating curing procedures.

ACI 562-16, the repair code for existing concrete buildings, allowed the use of in-place test methods for assessment of concrete strength. Section 6.4.3.2 states:

> Nondestructive strength testing to evaluate in-place strength of concrete shall be permitted if a valid correlation is established with core sample compressive strength test results and nondestructive test results. Quantifications of concrete compressive strength by NDT alone shall not be permitted as a substitute for core sampling and testing.

ACI 308.1 also mentions in-place tests as acceptable methods for estimating in-place strength for the purpose of terminating curing procedures. Project specifications can, therefore, reference standard specifications that allow in-place testing as an alternative to testing field-cured cylinders. ACI 325.11R discusses the use of in-places tests for estimating early-age concrete strength in fast-track concrete paving projects.

In all cases, sufficient correlation data are required, and permission may have to be granted before using in-place test methods. This report explains how the required correlation data can be acquired and provides guidance on how to implement an in-place testing program.

1.5—Existing construction

Reliable estimates of the in-place concrete strength are required for structural evaluation of existing structures (ACI 437R and ACI 562). Historically, in-place strength has been estimated by testing cores drilled from the structure. In-place tests can supplement coring and permit more economical evaluation of concrete in the structure. The critical step in such applications is to establish the relationship between in-place test results and concrete strength. More recently, the approach is to correlate results of in-place tests performed at selected locations with the strength of corresponding cores. Although in-place testing does not eliminate the need for coring, it can reduce the total amount of coring needed to evaluate a large volume of concrete. A sound sampling plan is required to acquire the correlation data, and appropriate statistical methods should be used for reliable interpretation of test results.

1.6—Report objective

This report reviews ASTM test methods for estimating the in-place strength of concrete in new construction and existing structures. The overall objective is to provide the potential user with a guide to assist in planning, conducting, and interpreting the results of in-place tests.

Chapter 2 includes the notation and definitions of terms used in this report. Chapter 3 discusses the underlying principles and inherent limitations of in-place tests. Chapter 4 reviews the statistical characteristics of in-place tests. Chapter 5 outlines procedures to develop the relationship needed to estimate in-place compressive strength. Chapter 6 discusses factors to be considered in planning the in-place testing program. Chapter 7 presents statistical techniques to interpret in-place test results. Chapter 8 discusses in-place testing for acceptance of concrete. Appendix A provides details and an illustrative example on the statistical principles discussed.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a = intercept of line
b = slope of line, used in development of strength relationship
C = average of in-place compressive strengths
c = individual compressive strength test results
d_{yx} = deviation of each test point from the best-fit line
I = in-place test result
i = individual in-place strength test results
$\ln C$ = average of natural logarithms of compressive strengths
$\ln I$ = average of natural logarithms of in-place test results
$\ln PO$ = average of natural logarithms of pullout loads
K = one-sided tolerance factor (Table 6.1.2a)
k = b/λ, where λ is obtained from the single-operator variability during correlation testing as given by Eq. (A.2d).
$M(t)$ = temperature-time factor at age t, deg-days or deg-hours
m = number of replicate in-place tests performed on an element of a structure
N = number of test points used to establish the strength relationship
n_i = number of replicate in-place tests
n_x = number of replicate in-place tests at each strength level
n_y = number of replicate compressive strength tests at each strength level
PO = average of natural logarithms of pullout loads
Q = apparent activation energy divided by the gas constant, K (kelvin)
S_e = estimated residual standard deviation
S_{uu} = modified sum of the squares as given by Eq. (A.2i(a))
S_{xx} = sum of squares of the deviations about $\bar{X}$ of the X values used to develop the strength relationship, $S_{xx} = \sum(X - \bar{X})^2$
s_{cf} = standard deviation of the logarithms of concrete strength in the structure
s_{cl} = standard deviations of logarithm of compressive strength in the laboratory
s_e = error of fit of strength relationship as given by Eq. (A.2j)
s_{il} = standard deviation of logarithms of the in-place results in the laboratory
s_X = standard deviation of the logarithms of the in-place tests performed on the structure
s_{xj} = standard deviation of the logarithms of the in-place tests at strength level j
s_Y = standard deviation of estimated value of Y (average concrete strength)
s_{yj} = standard deviation of the logarithms of the compressive strength tests at strength level j
T_a = average concrete temperature during time interval Δt, °C (°F) or K
T_0 = datum temperature, °C (°F)
T_s = specified curing temperature, K