

Guide for Obtaining Cores and Interpreting Compressive Strength Results

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Guide for Obtaining Cores and Interpreting Compressive Strength Results

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Guide for Obtaining Cores and Interpreting Compressive Strength Results

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Core testing is the most direct method to determine the compressive strength of concrete in a structure. Generally, cores may be obtained to assess whether concrete in a new structure complies with strength-based acceptance criteria or to evaluate the structural capacity of an existing structure based on the in-place concrete strength. In either case, the process of obtaining core specimens and interpreting strength test results is often confounded by various factors affecting in-place concrete strength or measured strength of test specimens. The scatter in strength test data, which is unavoidable given the inherent randomness of in-place concrete strengths and the uncertainty attributable to preparation and testing of the specimens, may further complicate compliance and evaluation decisions.

This guide summarizes practices for obtaining cores and interpreting core compressive strength test results. Factors that affect in-place concrete strength are reviewed so sampling locations that are consistent with objectives of the investigation can be selected. Strength correction factors are presented for converting the measured strength of non-standard core-test specimens to the strength of equivalent specimens with standard diameters, length-to-diameter ratios, and moisture conditioning. This guide provides direction for checking strength compliance of concrete in a structure under

construction and methods for determining equivalent specified strength to assess capacity of an existing structure. The materials, processes, quality control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI Certifications or equivalent.

Keywords: compressive strength; core; hardened concrete; sampling; test.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

Core testing is the most direct method to determine the in-place compressive strength of concrete in a structure. Generally, cores are obtained to:

- Assess, if required, whether concrete in a new structure complies with strength-based acceptance criteria; or
- Determine in-place concrete strengths in an existing structure for evaluation of structural capacity.

In new construction, cylinder strength tests failing to meet strength-based acceptance criteria can be investigated using provisions given in ACI 318. These criteria specify the circumstances when core tests are permitted, the number of cores to be tested, the conditioning of the cores before testing, the limits on the time interval between coring and testing, and the basis for determining whether the concrete in the area represented by the core strengths is structurally adequate. This

guide presents procedures for obtaining and testing cores and interpreting results in accordance with ACI 318.

If strength records are unavailable, the in-place strength of concrete in an existing structure can be evaluated using cores. This in-place strength determination is simplified when in-place strength data are converted into an equivalent specified compressive strength f'_c value that can be directly substituted into conventional strength equations with customary strength reduction factors. This guide presents procedures for performing this conversion in a manner consistent with the assumptions used to derive strength reduction factors for structural design.

1.2—Background

Analysis of core test data can be difficult and can subsequently lead to uncertain interpretations and conclusions. Based on 10 hypothetical core test results, 23 practitioners responding to a survey in 2000 estimated the compressive strength of in-place concrete between 3000 and 5000 psi (21 and 35 MPa) (Hanson 2007). Strength interpretations should always be made by, or with the assistance of, an investigator experienced in concrete technology. Factors contributing to the scatter of core strength test results include:

- Systematic variation of in-place strength along a member or throughout the structure;
- Random variation of concrete strength, both within one batch and among batches;
- Low test results attributable to flawed test specimens or improper test procedures;
- Effects of the size, aspect ratio, and moisture condition of the test specimen on the measured strengths; and
- Additional uncertainty attributable to testing that is present even for tests performed in strict accordance with standardized testing procedures.

1.3—Scope

This guide summarizes current practices for obtaining cores and interpreting core compressive strength test results in light of past and current research findings. Many of these findings are based on older references as the research has reached a mature state. Parallel procedures are presented for cases where cores are obtained to assess whether concrete strength in a new structure complies with strength-based acceptance criteria, and to determine a value based on the actual in-place concrete strength equivalent to the specified compressive strength f'_c . The latter can be directly substituted into conventional strength equations with customary strength reduction factors for strength evaluation of an existing structure. It is inappropriate to use procedures for determining the equivalent specified concrete strength to assess whether concrete strength in a new structure complies with strength-based acceptance criteria.

The order of contents parallels the logical sequence of activities in a typical core-test investigation. **Chapter 3** describes how bleeding, consolidation, curing, and micro-cracking affect in-place concrete strength in structures so the investigator can account for this strength reduction when planning the testing program. **Chapter 4** identifies preferred

sample locations and provides guidance on the number of specimens that should be obtained. **Chapter 5** summarizes coring techniques that should result in undamaged, representative test specimens. **Chapter 6** describes procedures for testing cores and detecting “outliers” by inspection of load-machine displacement curves or using statistical tests from ASTM E178. **Chapter 7** summarizes the subsequent analysis of strength test data including use of ASTM C42/42M precision statements that quantify expected variability of properly conducted tests for a sample of homogeneous material, research findings concerning accuracy of empirically derived core strength correction factors, and statistical analysis techniques that can determine if the data can be grouped into unique categories. **Chapter 8** briefly elaborates on criteria presented in ACI 318 for using core test results to investigate low-strength cylinder test results in new construction.

Chapter 9 presents two methods for estimating the lower tenth-percentile value of in-place concrete strength using core test data to quantify in-place strength. This value is equivalent to the specified compressive strength f'_c and can be directly substituted into conventional strength equations with customary strength reduction factors for strength evaluation of an existing structure.

Example calculations are presented in an **appendix** for:

- Outlier identification in accordance with ASTM E178 criteria;
- Determining whether a difference in mean strengths of cores from beams and columns is statistically significant; and
- Computing the equivalent specified strength using the two approaches presented in **Chapter 9**.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

C	= a constant related to the number of batches, number of members, and type of construction, Alternate Method
d	= diameter of core, in. (mm)
e	= predetermined maximum error expressed as a percentage of the population average
F_d	= correction factor for core damage
F_{dia}	= correction factor for core diameter
$F_{\ell/d}$	= correction factor for length-to-diameter ratio of core
F_{mc}	= correction factor for moisture content of core
$f_{0.10}$	= compressive strength of concrete at 10% fractile, psi (MPa)
f_c	= equivalent in-place compressive strength of concrete, psi (MPa)
$\bar{f}_c$	= sample mean of equivalent in-place compressive strength of concrete, psi (MPa)
f'_c	= specified compressive strength of concrete, psi (MPa)
$(\bar{f}_c)_{CL}$	= lower bound estimate of the sample mean equivalent in-place compressive strength of concrete at confidence limit CL, Alternate Method, psi (MPa)
$f'_{c,eq}$	= equivalent design compressive strength of concrete; applies to both methods, psi (MPa)

f_{ci}	= equivalent in-place compressive strength of individual core specimen, psi (MPa)
f_{core}	= compressive strength of concrete determined by core test, psi (MPa)
K	= correction factor for number of cores, Tolerance Factor Method
ℓ	= length of core, in. (mm)
n	= number of samples
s_d	= standard deviation of strength correction factors, psi (MPa)
s_c	= sample standard deviation of equivalent in-place compressive strength of concrete, psi (MPa)
s_o	= overall standard deviation, psi (MPa)
T	= statistic related to the probability of an occurrence, Student's t test method
V	= coefficient of variation, ratio of standard deviation to average, percent
V_d	= coefficient of variation associated with F_d , percent
V_{dia}	= coefficient of variation associated with F_{dia} , percent
$V_{\ell/d}$	= coefficient of variation associated with $F_{\ell/d}$, percent
V_{mc}	= coefficient of variation associated with F_{mc} , percent
V_{WS}	= coefficient of variation of in-place strengths
Z	= correction factor to adjust for the uncertainty of strength correction factors; applies to both methods

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://terminology.concrete.org>. Definitions provided herein complement that resource.

core—a cylindrical sample of hardened concrete obtained by means of a core drill.

core test—compression test on a concrete sample cut from hardened concrete by means of a core drill.

strength, concrete compressive—the measured maximum resistance of a concrete specimen to axial compressive loading; expressed as force per unit cross-sectional area.

strength, in-place concrete compressive—the estimated in-place compressive strength, f_c , computed by adjusting the core test result for length-to-diameter ratio, diameter, moisture condition, and drilling direction.

strength, specified concrete compressive—the compressive strength of concrete used in design, f'_c .

strength, specified concrete equivalent—in-place concrete compressive strength, $f'_{c,eq}$, adjusted by correction factors that can be directly substituted into conventional strength equations with customary strength reduction factors.

CHAPTER 3—VARIATION OF IN-PLACE CONCRETE STRENGTH IN STRUCTURES

Chapter 3 discusses the variation of in-place concrete strength in structures so that the investigator can anticipate relevant factors in early stages of planning the testing program. Selecting core extraction locations and analyzing and interpreting data obtained are simplified and streamlined when pertinent factors are identified beforehand.

The quality of “as-delivered” concrete depends on the quality and relative proportions of the constituent materials

and on the care and control exercised during batching, mixing, and handling. The final in-place quality depends on placing, consolidation, and curing practices. Recognizing that delivery of high-quality concrete does not ensure high-quality in-place concrete, some project specifications require minimum core compressive strength results for concrete acceptance (Ontario Ministry of Transportation 1998). Core test results may not represent the quality of concrete as delivered to the site if mixing water was added at the site, or poor placing, consolidation, or curing practices were followed.

Generally, the in-place concrete strength at the top of a member as cast is less than the strength at the bottom (Bloem 1965; Bungey 1989; Dilly and Vogt 1993).

3.1—Bleeding

Shallow voids under coarse aggregate caused by bleeding can reduce the compressive strength transverse to the direction of casting and consolidation (Johnson 1973), which is typically vertical, but would be horizontal for a precast concrete column or tilt-up panel cast in a horizontal orientation. The strength of cores with axes parallel to the casting direction can therefore be greater than that of cores with axes perpendicular to the casting direction. Experimental findings are contradictory because some investigators observed appreciable differences (Sanga and Dhir 1976; Takahata et al. 1991) whereas others did not (Bloem 1965). Although bleeding varies greatly with mixture proportions and constituent materials, available core strength data do not demonstrate a relationship between bleeding and the top-to-bottom concrete strength differences.

3.2—Consolidation

Concrete is usually consolidated by vibration to expel entrapped air after placement, unless it is a self-consolidating concrete (SCC). Strength is reduced by approximately 7% for each percent by volume of entrapped air remaining when concrete is insufficiently consolidated (Popovics 1969; Concrete Society 1987; ACI 309.1R). The investigator can assess the extent of poor consolidation in the concrete in question by simply inspecting the cores or using nondestructive techniques reported in ACI 228.2R.

Consolidation of fresh concrete in the lower portion of a column or wall is enhanced by static pressure of fresh concrete in the upper portion. These consolidation pressures can cause a strength increase (Ramakrishnan and Li 1970; Toossi and Houde 1981), so the lower portions of cast vertical members can have relatively greater strengths.

3.3—Curing

Proper curing procedures, which control the temperature and moisture environment of the concrete, are essential for high-quality concrete. Low initial curing temperatures reduce initial strength development rate but can result in higher long-term strength. Conversely, high initial-curing temperatures increase initial strength development but reduce long-term strength (ACI 308R).

High initial temperatures generated by hydration can significantly reduce strength of the interior regions of

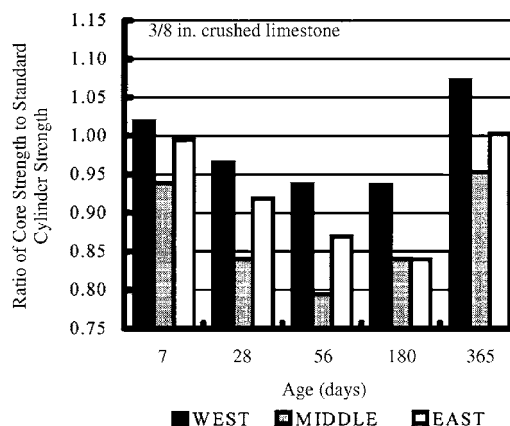


Fig. 3.1—Relationships between compressive strengths of column core samples and standard-cured specimens cast with high-strength concrete (Cook 1989).

massive elements (ACI 305R). For example, results in Fig. 3.1 indicate the strength of cores obtained from the middle of mock 30 x 30 in. (760 x 760 mm) columns is consistently less than the strength of cores obtained from exterior faces (Cook 1989). Mock columns were cast using high-strength concrete with an average 28-day standard cylinder strength exceeding 11,200 psi (77 MPa). Similarly, data analysis from large specimens reported by Yuan et al. (1991), Mak et al. (1990, 1993), Burg and Ost (1992), and Miao et al. (1993) indicate a strength loss of approximately 3% of the average strength in the specimen for every 10°F (5°C) increase of average maximum temperature sustained during early hydration (Bartlett and MacGregor 1996a). Maximum temperatures recorded in these specimens varied between 110 and 200°F (45 and 95°C).

The in-place strength of slabs or beams is more sensitive to the presence of moisture than the in-place strength of walls or columns because the unformed top surface is a relatively large fraction of the total surface area. Data from four studies (Bloem 1965, 1968; Meynick and Samarin 1979; Szypula and Grossman 1990) indicate the strength of cores from poorly cured shallow elements averages 77% of the strength of cores from properly cured elements for concrete ages of 28, 56, 91, and 365 days (Bartlett and MacGregor 1996b). Data from two studies investigating walls and columns (Bloem 1965; Gaynor 1970) indicate that strength loss at 91 days, attributable to poor curing, averages approximately 10% (Bartlett and MacGregor 1996b).

3.4—Microcracking

Microcracks in a core reduce strength (Szypula and Grossman 1990), and their presence explains why average strengths of cores from two ends of a beam cast from a single batch of concrete with a cylinder strength of 7850 psi (54.1 MPa) differed by 11% of their average (Bartlett and MacGregor 1994a). Microcracks can be present in regions of the structure that were subjected to stress from applied loads or restraint of imposed deformations. Rough handling of the core specimen can also cause microcracking. Strength

Table 3.1—Coefficient of variation due to in-place strength variation within structure V_{ws}

Structure composition		One member	Many members
One batch of concrete		7%	8%
Many batches of concrete	Cast-in-place	12%	13%
	Precast	9%	10%

results of cores taken where microcracking has occurred or where cracks are visible should be interpreted with caution.

In massive concrete elements, hydration causes thermal gradients between the interior, which becomes hot, and the element surfaces, which remain relatively cool. In this case, surfaces are restrained from contracting by the interior of the element, which can cause microcracking that reduces strength at the surface. This phenomenon has been clearly observed in some investigations (Mak et al. 1990) but not in others (Cook et al. 1992).

3.5—Overall variability of in-place strengths

Estimates of overall variability of in-place concrete strengths reported by Bartlett and MacGregor (1995) are presented in Table 3.1. Variability is expressed as the coefficient of variation V_{ws} , which is the ratio of standard deviation of in-place strength to average in-place strength. Overall variability depends on the number of members in the structure, number of concrete batches present, and whether construction is precast or cast-in-place. Values shown are for concrete produced, placed, and protected in accordance with normal industry practice, for example, ASTM C94/C94M, ACI 304R, and ACI 308R, and may not pertain to concrete produced to high or low standards of quality control.

CHAPTER 4—PLANNING THE TESTING PROGRAM

The procedure for planning a core-testing program depends on the objective of the investigation. Section 4.1 presents procedures for checking whether concrete in a new structure complies with strength-based acceptance criteria, whereas Section 4.2 presents procedures for evaluating the strength capacity of an existing structure using in-place strengths.

As noted in Chapter 3, the strength of concrete in a placement usually increases with depth. In single-story columns, cores should be obtained from the central portion, where strength is relatively constant, and not in the top 18 to 24 in. (450 to 600 mm), where it can decrease by 15%, or in the bottom 12 in. (300 mm), where it can increase by 10% (Bloem 1965).

4.1—Investigating concrete in a new structure using strength-based acceptance criteria

To investigate low-strength test results in accordance with ACI 318, three cores are required from that part of the structure cast from concrete represented by the low-strength test result. The investigator should only sample areas where suspect concrete was placed.

In some situations, such as thin or heavily reinforced sections, it is difficult or impracticable to obtain cores meeting all the length and diameter requirements of ASTM C42/C42M. Nevertheless, cores can allow a relative comparison of two or more

portions of a structure representing different concrete batches. For example, consider two sets of columns placed with the concrete with the same mixture proportions: one acceptable based on standard strength tests and one questionable because of low strength test results. Nondestructive testing methods (ACI 228.1R) may indicate that the concrete quality in suspect columns exceeds that in acceptable columns. Alternatively, it is appropriate to take 2 in. (50 mm) diameter cores from columns where 1 in. (25 mm) maximum size aggregate was used. After trimming the cores, however, ℓ/d will be less than 1.0 where the cover is only 2 in. (50 mm) and reinforcement bars cannot be cut. Acknowledging that strength tests of short cores may not produce results that accurately reflect column concrete strength, a relative comparison of the two concrete placements can sufficiently determine if concrete strength in question is comparable to the other placement or if more investigation is warranted.

4.2—Evaluating existing structure capacity using in-place strengths

To establish in-place strength values for existing structures, the sample size and locations from which cores are extracted need to be selected using procedures such as those described in ASTM E122 and ASTM C823/C823M.

As the sample size increases, the accuracy of the result improves. The likelihood of detecting a spurious value in the data set also improves but greater costs are incurred and the risk of weakening the structure increases. ASTM E122 recommends computing sample sizes using Eq. (4-1) to achieve a 1-in-20 chance that the difference between the measured sample average and population average, expressed as a percentage of population average, will be less than some predetermined error.

$$n = \left(\frac{2V}{e} \right)^2 \quad (4-1)$$

where

- n = recommended sample size;
- e = predetermined maximum error expressed as a percentage of the population average; and
- V = estimated coefficient of variation of the population, in percent, and may be estimated from values shown in Table 3.1 or from other available information.

For example, if the estimated coefficient of variation of in-place strength is 15%, and it is desired that the measured average strength should be within 10% of the true average strength approximately 19 times out of 20, Eq. (4-1) indicates that (for $V = 15\%$ and $e = 10\%$) a total of nine cores should be obtained. If a higher confidence level is desired, or if smaller percentage error is necessary, then a larger sample size is required. Statistical tests for determining whether extreme values should be rejected, such as those in ASTM E178, become more effective as sample size increases. As indicated by relationships between the percentage error and the recommended number of specimens shown in Fig. 4.1, the number of larger sample sizes diminishes. ASTM C823/C823M recom-