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Obtaining Cores and Interpreting Core Compressive Strength Results—Guide

Reported by ACI Committee 214

ACI PRC-214.4-21



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Obtaining Cores and Interpreting Core Compressive Strength Results—Guide

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Obtaining Cores and Interpreting Core Compressive Strength Results—Guide

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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 structural capacity of an existing structure based on 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 the measured strength of a test specimen. 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 specimen, 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 measured strength of nonstandard core-test specimens to strength of equivalent specimens with standard diameters, length-to-diameter ratios, and moisture conditioning that have been derived using data for normalweight concrete with strengths between 2000 and 13,400 psi (14 and 92 MPa). This guide also provides direction for checking strength compliance of concrete in a structure under construction and methods for determining equivalent specified strength to assess existing structure capacity.

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

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ACI PRC-214.4-21 supercedes ACI 214.4R-10 was adopted and published May 2021.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

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

- a) Assess, if required, whether concrete in a new structure complies with strength-based acceptance criteria
- b) 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 301. 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 301.

If strength records are unavailable, the in-place strength of concrete in an existing structure can be evaluated using cores. In-place concrete compressive strength determination is simplified when in-place strength data are converted into equivalent specified concrete compressive strength f'_c values 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.

Analysis of core test data can be difficult and lead to uncertain interpretations and conclusions. Based on 10 hypothetical core test results (Hanson 2007), 23 practitioners estimated the concrete compressive strength of in-place concrete between 3000 and 5000 psi (21 and 35 MPa). 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:

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

1.2—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. Distinct procedures are presented for two cases:

- 1) To assess whether concrete strength in a new structure complies with strength-based acceptance criteria
- 2) To determine an in-place concrete strength that is equivalent to the specified concrete compressive strength f'_c to 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 in **Chapter 9** for determining equivalent specified concrete strength to assess whether suspect concrete 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 microcracking affect in-place concrete strength in structures so the investigator can account for this strength variation 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 high-quality, 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/C42M** precision statements, research findings concerning accuracy of empirically derived core strength correction factors, and statistical analysis techniques. **Chapter 8** briefly elaborates on criteria presented in **ACI 301** 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 concrete 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 the 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
- Applying minimum strength acceptance criteria for samples with more than three cores
- Computing the equivalent specified strength using the two approaches presented in **Chapter 9**

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

- C = constant related 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 damage
- F_{dia} = correction factor for core diameter
- $F_{\ell/d}$ = correction factor for length-to-diameter ratio
- F_{mc} = correction factor for moisture content
- $f_{0.10}$ = compressive strength of concrete at 10 percent 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)
- $(\bar{f}_c)_{CL}$ = lower bound estimate of the sample mean equivalent in-place compressive strength of concrete at confidence limit CL , alternate method, psi (MPa)
- f'_c = specified compressive strength of concrete, psi (MPa)
- $f_{c,eq'}$ = equivalent design compressive strength of concrete, tolerance factor method, psi (MPa)
- f_{ci} = equivalent in-place compressive strength of individual core specimen, psi (MPa)
- f_{co} = compressive strength of concrete core, corrected for ℓ/d , in accordance with **ASTM C42/C42M** psi (MPa)
- $\bar{f}_{co}$ = sample mean core compressive strength of concrete, psi (MPa)
- f_{core} = core compressive strength of concrete, psi (MPa)
- $f_{min,eq}$ = equivalent minimum strength for samples of more than three cores, psi (MPa)
- K = correction factor for number of cores, tolerance factor method
- K_1 = coefficient used in equivalent minimum-strength criterion computation
- K_2 = coefficient used in equivalent minimum-strength criterion computation
- ℓ = length of core, in. (mm)
- n = number of samples
- P_1 = probability used to determine acceptable minimum strength criteria for samples of more than three cores
- P_2 = probability computed in equivalent minimum-strength criterion computation
- $p_1(y)$ = probability computed using binomial distribution in determination of equivalent number of low strengths criterion
- s_a = standard deviation of strength correction factors, psi (MPa)
- s_c = sample standard deviation of equivalent in-place compressive strength of concrete, psi (MPa)
- s_{co} = sample standard deviation of core compressive strength of concrete, psi (MPa)
- s_o = overall standard deviation, psi (MPa)
- T = factor related to the probability of an occurrence, student's t test method
- V = coefficient of variation, ratio of standard deviation to arithmetic 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, tolerance factor method
- ϕ = standard normal cumulative distribution function

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

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

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

This chapter 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.

Quality of as-delivered concrete depends on quality and relative proportions of constituent materials and on care and control exercised during batching, mixing, and handling. Final in-place quality depends on placing, consolidation, and curing practices. Recognizing that delivery of quality concrete does not ensure quality in-place concrete, some project specifications therefore require minimum core compressive strength results for concrete acceptance (Ontario Ministry of Transportation 2018, 2019). 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 concrete 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 cast in a horizontal orientation. The compressive 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).

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 percent for each percent by volume of entrapped air remaining when concrete is insufficiently consolidated (Popovics 1969; The Concrete Society 1987; ACI 309.1R). The investigator can assess the extent of poor consolidation in the concrete in question by 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

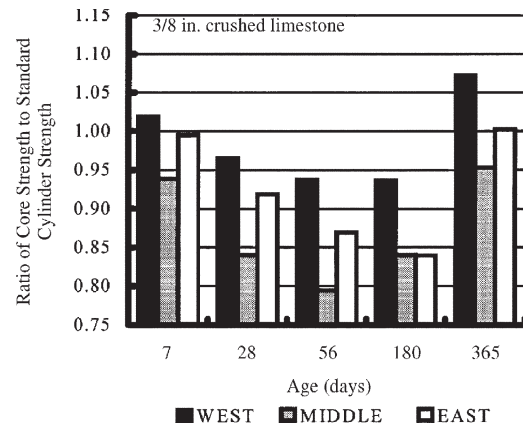


Fig. 3.3—Relationships between concrete compressive strengths of column core samples and standard-cured specimens cast with high-strength concrete (Cook 1989). (Note: 1 in. = 25.4 mm.)

concrete in the upper portion. These consolidation pressures can cause a strength increase (Ramakrishnan and Li 1970; Toossi and Houde 1981); therefore, the lower portions of cast vertical members can have relatively greater strength.

3.3—Curing

Proper curing procedures, which control the temperature and moisture environment, are essential for 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 cementitious material hydration can significantly reduce strength of the interior regions of massive elements (ACI 305R). For example, results in Fig. 3.3 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 percent of the average strength in the specimen for every 10°F (5°C) increase of average maximum temperature sustained during early cement hydration (Bartlett and MacGregor 1996a). Maximum temperatures recorded in these specimens varied between 110 and 200°F (45 and 95°C).

In-place strength of slabs or beams is more sensitive to the presence of moisture than 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 percent of the strength of cores from properly cured elements for concrete

Table 3.5—Coefficient of variation due to in-place strength variation within structure (V_{ws})

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

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 percent (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 percent of their average (Bartlett and MacGregor 1994a). Microcracks can be present in regions of the structure that have been subjected to stress from applied loads or restraint of imposed deformations. Rough handling of the core specimen can also cause microcracking. Strength results of cores taken where microcracking has occurred or cracks are visible should be interpreted with caution.

In massive concrete elements, cementitious material 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 concrete compressive strengths

Estimates of overall variability of in-place concrete strengths reported by Bartlett and MacGregor (1995) are presented in Table 3.5. 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 in Table 3.5 are for concrete produced, placed, and protected in accordance with normal industry practice (ASTM C94/C94M; ACI 304R; ACI 308R) and may not pertain to concrete produced to high or low standards of quality control.

CHAPTER 4—PLANNING 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; Section 4.2 presents procedures for evaluating strength capacity of an existing structure using in-place strengths.

As noted in Chapter 3, strength of concrete in a placement usually increases with depth. In walls or 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 percent, or in the bottom 12 in. (300 mm), where it can increase by 10 percent (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 301, three cores are required for each strength test 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 same concrete specified mixture proportion: 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, 2 in. (50 mm) diameter cores can be taken from columns where 1 in. (25 mm) maximum size aggregate was used. After trimming the cores, however, ℓ/d may be less than 1.0 because the cover is only 2 in. (50 mm) and reinforcement bars cannot be cut. Although strength tests of short cores may not accurately represent the column strength, a comparison of the short core strengths can indicate that the questionable concrete strength is comparable to that in the other placement or that further investigation is warranted.

4.2—Evaluating existing structure capacity using in-place strengths

To establish in-place strength values for existing structures, 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 sample size increases, result accuracy 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. (4.2) to achieve a 1-in-20 chance that the difference between the measured sample average and population average, expressed as percentage of population average, will be less than some predetermined error.

$$n = (2V/e)^2 \quad (4.2)$$

where V can be estimated from values shown in Table 3.5 or from other available information.



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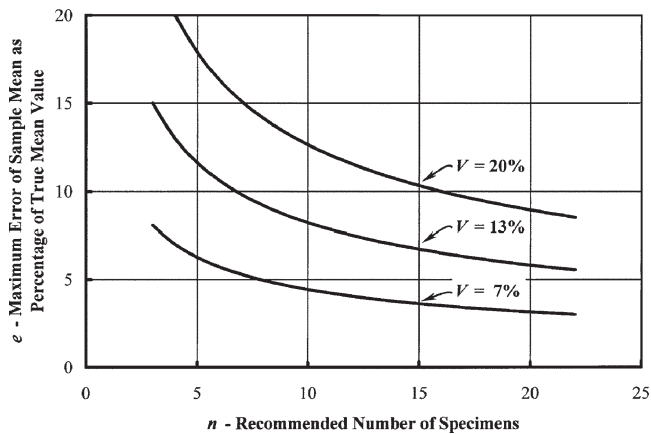


Fig. 4.2—Maximum error of sample mean for various recommended number of specimens.

For example, if the estimated coefficient of variation of in-place strength is 15 percent, and it is desired that the measured average strength should be within 10 percent of the population average strength approximately 19 times out of 20, Eq. (4.2) indicates that for $V = 15$ percent and $e = 10$ percent, 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 percentage error and recommended number of specimens shown in Fig. 4.2, which is derived using Eq. (4.2), the benefits of larger sample sizes diminish. [ASTM C823/C823M](#) recommends a minimum of five core test specimens be obtained for each concrete category with a unique condition or specified quality, specified mixture proportion, or specified material property. [ASTM C823/C823M](#) also provides guidance for repeating the sampling sequence for large structures.

The investigator should select core extraction locations based on the overall objective of the investigation by characterizing overall in-place strength for general evaluation purposes or determining in-place strength of a specific group of components, not the ease of obtaining samples. To characterize the overall in-place strength of an existing structure for general evaluation purposes, cores should be drilled from randomly selected locations throughout the structure using a written sampling plan. When in-place strength for a specific component or group of components is sought, the investigator should extract cores at randomly selected locations from those specific components.

When determining sample locations, the investigator should consider whether different strength categories of concrete may be present in the structure. For example, in-place strengths of walls and slabs cast from a single batch of concrete may differ ([Meininger 1968](#)) or concrete with different required strengths may have been used for the footings, columns, and floor slabs in a building. If the concrete volume under investigation contains two or more concrete categories, the investigator should objectively select sample

locations so as not to bias the outcome. Alternatively, the investigator should randomly select a sufficient number of sampling locations for each concrete category with unique composition or properties. The investigator can use nondestructive testing methods ([ACI 228.1R](#)) to perform a preliminary survey to identify regions in a structure that have different concrete properties. [ACI SP-2](#) and [ASTM C823/C823M](#) contain guidance concerning sampling techniques.

CHAPTER 5—OBTAINING TEST SPECIMENS

Coring techniques should result in high-quality, undamaged, representative test specimens. The investigator should delay coring until the concrete being cored has sufficient strength and hardness so the bond between mortar and aggregate will not be disturbed. [ASTM C42/C42M](#) suggests that concrete should not be cored before it is 14 days old, unless other information indicates the concrete can withstand the coring process without damage. [ASTM C42/C42M](#) further suggests in-place nondestructive tests ([ACI 228.1R](#)) can be performed to estimate the level of concrete strength development before coring is attempted.

Core specimens for compression tests should not contain reinforcing bars. Several nondestructive methods are available to locate reinforcement embedded in concrete, including magnetic induction using a pachometer or cover meter, X-ray or gamma-ray radiography, and short-pulse radar (ground penetrating radar) ([Malhotra and Carino 2004](#)). Also, avoid cutting sections containing conduit, ductwork, or prestressing tendons.

As described in [Chapter 7](#), specimen strength is affected by core diameter and ratio of length-to-diameter, ℓ/d , of the specimen. Strength correction factors for these effects are derived empirically from test results ([Bartlett and MacGregor 1994b](#)) and should be applied in accordance with the limits of these tests. Moreover, [ASTM C42/C42M](#) requires the minimum core diameter to be 3.70 in. (94 mm), except under special circumstances. Therefore, it is preferable to obtain specimens with diameters of 4 to 6 in. (100 to 150 mm) and ℓ/d between 1.5 and 2 to minimize errors introduced by strength correction factors ([Neville 2001](#)).

Core drilling should be performed by an experienced operator using a diamond-impregnated bit attached to the core barrel. The drilling apparatus should be rigidly anchored to the member to avoid bit wobble, which results in a specimen with variable cross section and introduces large strains in the core. The drill bit should be lubricated with water and resurfaced or replaced when worn. The operator should be informed beforehand that the cores are for strength testing and require proper handling and storage.

Because a damaged specimen will not accurately represent in-place concrete strength, core specimens require protection from freezing and damage during transit.

Drilling a core with a water-cooled bit results in a moisture gradient between exterior and interior of the core that adversely affects concrete compressive strength ([Fiorato et al. 2000](#); [Bartlett and MacGregor 1994c](#)). [ASTM C42/C42M](#) presents moisture protection and scheduling requirements intended to achieve moisture distribution in core speci-