

Guide to Evaluation of Strength Test Results of Concrete

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Guide to Evaluation of Strength Test Results of Concrete

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.

Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

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Reported by ACI Committee 214

Casimir Bognacki*
Chair

Jerry Parnes
Secretary

David J. Ackers
Madasamy Arockiasamy
William L. Barringer
F. Michael Bartlett*
Jerrold L. Brown
Bryan R. Castles*
James E. Cook
Ronald L. Dilly
Donald E. Dixon

Richard D. Gaynor
Alejandro Graf
Thomas M. Greene
Gilbert J. Haddad
Kal R. Hindo
Robert S. Jenkins
Alfred L. Kaufman Jr.
William F. Kepler
Michael L. Leming

Colin L. Lobo*
John J. Luciano
Allyn C. Luke*
Stephen S. Marchese
Richard E. Miller
Venkataswamy Ramakrishnan
D. V. Reddy
David N. Richardson*
James M. Shilstone Jr.

Bryce P. Simons
Luke M. Snell
Patrick J. E. Sullivan
Eugene Takhtovich*
Michael A. Taylor
Roger E. Vaughan
Woodward L. Vogt*
Orville R. Werner II

*Committee members who prepared this guide.

Statistical procedures provide valuable tools for evaluating the results of concrete strength tests. Information derived from such procedures is valuable in defining design criteria, specifications, and other parameters needed for structural evaluation and repair. This guide discusses variations that occur in concrete strength and presents statistical procedures useful in interpreting these variations with respect to specified testing and criteria.

Keywords: coefficient of variation; concrete strength; normal distribution; required overdesign; quality control; standard deviation; statistical methods.

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CHAPTER 1—INTRODUCTION**1.1—Introduction**

This guide provides an introduction to the evaluation of concrete strength test results. Procedures described are applicable to the compressive strength test results required by ACI 301, ACI 318, and similar specifications and codes. Statistical concepts described are applicable for the analysis of other common concrete test results, including flexural strength, slump, air content, density, modulus of elasticity, and other tests used for evaluating concrete and ingredient materials. This guide assumes that the concrete test results conform to a normal distribution.

Most construction projects in the United States and Canada require routine sampling of concrete and fabrication of standard molded cylinders. These cylinders are usually cast from a concrete sample taken from the discharge of a truck or a batch of concrete. They are molded and cured following the standard procedures of ASTM C31/C31M and tested as required by ASTM C39/C39M. If the concrete is so prepared, cured, and tested, the results are the compressive strength of the concrete cured under controlled conditions, not the in-place strength of the concrete within the structure. It is expected that, given the uniformity of the curing conditions, these cylinders would have essentially the same strength, thereby indicating concrete with consistent properties. It is these cylinders that are used for acceptance purposes.

Inevitably, strength test results vary. Variations in the measured strength of concrete originate from two sources:

- Batch-to-batch variations can result from changes to the ingredients or proportions of ingredients, water-cementitious material ratio (w/cm), mixing, transporting, placing, sampling of the batch, consolidating, and curing; and
- Within-batch variations, also called within-test variations, are primarily due to differences in sampling of the

batch sample, specimen preparation, curing, and testing procedures.

There are differences in individual mixer batches between the front and rear of the mixer, as recognized by ASTM C94/C94M. For this reason, ACI Field Level I Technicians are trained to make composite samples from the central portions of loads.

Conclusions regarding concrete compressive strength can be derived from a series of tests. The characteristics of concrete strength can be accurately estimated when an adequate number of tests are conducted in accordance with standard practices and test methods.

Statistical procedures provide valuable tools when evaluating strength test results. Information derived from them is also valuable in refining design criteria and specifications. This guide discusses variations in concrete strength and presents statistical procedures useful for interpreting them with respect to specified testing and acceptance criteria.

For the statistical procedures described in this guide to be valid, data should be derived from samples obtained through a random sampling plan. Random sampling is when each volume of concrete has an equal chance of being selected. To ensure this condition, selection should be made by using an objective mechanism, such as a table of random numbers. When sample batches are selected on the basis of the sampler's judgment, biases are likely to be introduced that will invalidate the analysis. Natrella (1963), Box et al. (2005), and ASTM D3665 discuss the need for random sampling, and provide a useful short table of random numbers.

1.2—Summary

This guide begins with a discussion in Chapter 3 of the batch-to-batch sources of variability in concrete production, followed by the within-batch sources of variability. Chapter 4 presents the statistical tools that are used to analyze and evaluate concrete variability and determine compliance with a given specification. Chapters 5 and 6 review statistically-based specifications.

CHAPTER 2—NOTATION AND DEFINITIONS**2.1—Notation**

- d_2 = factor for computing within-batch standard deviation from average range (Table 4.1)
- f'_c = specified compressive strength of concrete, psi (MPa)
- f'_{cr} = required average compressive strength of concrete (to ensure that no more than a permissible proportion of tests will fall below the specified compressive strength) used as the basis for selection of concrete proportions, psi (MPa)
- M = the median of a distribution, that is, half the values above and half the values below
- n = number of tests in a record
- R = within-batch range
- $\bar{R}$ = average range
- $\bar{R}_m$ = maximum average range, used in certain control charts

s	= sample standard deviation, an estimate of the population standard deviation, also termed $s_{overall}$
$\bar{s}$	= statistical average standard deviation, or “pooled” standard deviation
s_1	= sample within-batch standard deviation, also termed $s_{within-batch}$
s_2	= sample batch-to-batch standard deviation, also termed $s_{producer}$
V	= coefficient of variation
V_1	= within-batch coefficient of variation
$\bar{X}$	= average of strength test results, also called the mean
X_i	= a strength test result
z	= constant multiplier for standard deviation s that depends on number of tests expected to fall below f'_c (Table 5.3)
μ	= population mean
σ	= population standard deviation
σ_1	= population within-batch standard deviation
σ_2	= population batch-to-batch standard deviation

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.

companion cylinders—cylinders made from the same sample of concrete.

concrete sample—a portion of concrete, taken at one time, from a single batch or single truckload of concrete.

individual strength—(also known as single cylinder strength) is the compressive strength of a single cylinder (ASTM C39/C39M); a single cylinder strength is part of, but individually does not constitute, a test result.

normal distribution—a frequently occurring natural distribution that has predictable properties. The analysis of strength test results presented in this guide assumes that the test results under consideration are normally distributed. Although this assumption is reasonable, it is not always the case; users should check the actual distribution of the data to ensure it is reasonably close to normally distributed.

single cylinder strength—(also known as individual strength) is the compressive strength of a single cylinder (ASTM C39/C39M); a single cylinder strength is part of, but individually does not constitute, a test result.

strength test or **strength test result**—the average compressive strength of two or more single-cylinder strengths of companion cylinders tested at the same age.

test record—a collection of strength test results from a single concrete mixture.

within-batch range—the difference between the maximum and minimum strengths of individual concrete specimens that comprise one strength test result. Sometimes called the within-test range. When referring to a test of two cylinders, the within-batch range is sometimes called the pair-difference.

CHAPTER 3—VARIATIONS IN STRENGTH

3.1—General

The variations in the strength of concrete test specimens can be traced to two fundamentally different sources:

1. Variability in strength-producing properties of the concrete mixture and production process, some causes of which are listed under the batch-to-batch variations in Table 3.1; and

2. Variability in the measurement of strength coming from the testing procedures detailed in the within-batch variations column of Table 3.1.

Variation in measured characteristics may be random or assignable depending on the cause. Random variation is normal for any process; a stable process will show only random variation. Assignable causes represent systematic changes typically associated with a shift in a fundamental statistical characteristic, such as mean, standard deviation, coefficient of variation, or other statistical measure. The standard deviation is the most commonly used indicator of data scatter around the mean. However, it is often more informative to use the coefficient of variation when comparing variability in data between two sets of results with markedly different mean strengths.

3.2—Influence of batch-to-batch variations on concrete strength

For a given set of raw materials, concrete strength is largely governed by the water-cementitious material ratio (w/cm). Controlling the w/cm is of primary importance for producing concrete of consistent strength. Because the quantity of cementitious material can be measured with accuracy, maintaining a constant w/cm principally involves strict control of the total quantity of water used (Neville 1996).

Strength variations often result from variation of air content. The entrained air content influences both the water requirement and strength. There is an inverse relationship between strength and air content (Kosmatka et al. 2002). The air content of a specific concrete mixture can vary depending on variations in constituent materials, extent of mixing, and ambient site conditions. For good concrete control, the entrained air content is usually monitored closely at the construction site.

The temperature of fresh concrete affects the amount of water needed to achieve the proper consistency and entrained air content. In addition, the concrete temperature during the first 24 hours of curing can significantly affect later-age strengths of the concrete. Concrete cylinders that are not standard cured in accordance with ASTM C31/C31M—respecting the times at which particular events should occur, the acceptable temperature range, and the need to prevent damage and moisture loss—will not necessarily reflect the potential strength of the concrete.

Misuse of admixtures can cause concrete strength reductions. The known performance of admixtures at normal temperatures may be different at extremely low or high temperatures. The performance of an admixture when used by itself may be different if it is used in combination with another admixture.

Construction practices can cause variations of in-place strength due to inadequate mixing, improper consolidation, placement delays, improper curing, and insufficient protection

Table 3.1—Principal sources of strength variation

Batch-to-batch variations	Within-batch variations
<i>Variations in characteristics and proportions of ingredients:</i> • Aggregates; • Cementitious materials, including pozzolans; and • Admixtures. <i>Changes in w/cm caused by:</i> • Poor control of water; • Variation of aggregate stockpile moisture conditions; • Variable aggregate moisture measurements; and • Retempering. <i>Variations in mixing, transporting, and sampling:</i> • Mixing time and speed; • Distance between plant and placement; • Road conditions; and • Failure to obtain a representative sample from the batch. <i>Variations in placing, and consolidation:</i> • Chute, pump, or buggy; • Internal or external vibration; and • Different operators. <i>Variations in concrete temperature and curing:</i> • Season; • Ambient humidity; and • Wind speed.	<i>Improper sampling from the batch sample.</i> <i>Variations due to fabrication techniques:</i> • Substandard conditions; • Incorrect tools; • Poor quality, damaged, or distorted molds; • Nonstandard molding and consolidation; and • Incorrect handling of fresh test samples. <i>Differences in curing:</i> • Delays in beginning initial curing; • Temperature variation; • Variable moisture control; • Nonstandard initial curing; • Delays in bringing cylinders to the laboratory; • Rough handling of cylinders in transport; and • Improper final curing. <i>Variations in sample testing:</i> • Uncertified tester; • Specimen surface preparation; • Inadequate or uncalibrated testing equipment; • Nonstandard loading rate; and • Poor record keeping.

*Applies to in-place strength of the structure.

at early ages. These differences will not be reflected in specimens fabricated and stored under standard laboratory conditions (ASTM C31/C31M) but will be reflected in strength assessments using nondestructive testing methods or strength testing of cores.

3.3—Influence of within-batch variations on concrete strength

Testing to determine compliance with contract specifications should be conducted according to the methods specified in the contract documents, such as ASTM C31/C31M and C39/C39M. Acceptance tests assess the compressive strength of the concrete when prepared and cured under standard conditions, not the in-place strength. It is not the purpose of such tests to determine the in-place strength of the structure, but rather to assure that the concrete delivered and placed was the concrete specified. Deviations in field sampling, specimen preparation, curing, and testing procedures may cause lower strength test results. Field sampling, making, curing, handling, and testing of specimens should be performed by ACI Certified Technicians or equivalently trained and certified personnel. Provisions for maintaining specified curing conditions should be made. Specimens from concrete that are hardening and gaining strength should not be disturbed until sufficient strength is achieved to prevent cylinder damage (ASTM C31/C31M).

Using accurate, properly calibrated testing equipment and proper sample preparation procedures is essential. Test results with low variability do not necessarily indicate accurate test results. A routinely applied, systematic error can provide

results that are biased but uniform. Laboratory equipment and procedures should be calibrated and checked periodically. Testing personnel should be trained ACI Certified Technicians or the equivalent who are evaluated routinely.

CHAPTER 4—ANALYSIS OF STRENGTH DATA

4.1—General

A sufficient number of tests is needed to accurately indicate the variation of the concrete strength and permit application of appropriate statistical procedures for interpreting the test results. Statistical procedures provide a sound basis for determining the potential quality and strength of the concrete and for expressing results in the most useful form.

4.2—Statistical functions

A strength test result is the average strength of all specimens of the same age, fabricated from a sample taken from a single batch of concrete. A strength test cannot be based on only one cylinder. ACI 318 states that a “strength test shall be the average strength of at least two 6 x 12 in. (150 x 300 mm) cylinders, or three 4 x 8 in. (100 x 200 mm) cylinders of the same concrete batch tested at the same age...”

In this guide, strength test results are assumed to follow a normal distribution. Figure 4.1 shows the “bell-shaped curve” characteristic of the normal distribution. The normal distribution is mathematically defined completely by two statistical parameters: the population mean μ and standard deviation σ . A mathematical characteristic of the normal distribution is that 68.27% of the data lies within 1 standard deviation from the mean, and that 95.45% of the data is within 2 standard deviations. On the chart are notes indicating the number of samples n ; the sample standard deviation s , which is an estimate of σ ; the coefficient of variation V ; and the sample mean $\bar{X}$, which estimates μ . Also on the chart is a histogram of the measured test results sorted into strength ranges. Each dot represents a test, which indicates that this data set is normally distributed. Plotting histograms is one of the easiest ways to check the data for normality.

When evaluating concrete strength tests, a normal distribution cannot always be assumed. A normal distribution is appropriate in most cases when the concrete strength does not exceed 10,000 psi (70 MPa) (Cook 1982). However, Cook (1989) further reported that a skewed distribution may result for high-strength concrete when the limiting factor is the aggregate strength. When data are not symmetrical about the mean, but concentrated to the right or left, the distribution is said to be skewed. When a distribution curve is either too peaked or too flat, kurtosis is said to exist. Data exhibiting skewness, or kurtosis, may not be normally distributed; and any analysis presuming a normal distribution may be very misleading. Skewness and kurtosis should be considered for statistical evaluation of high-strength concretes. Cook (1989) provides simplified equations that calculate relative skewness and kurtosis for a particular data set. Further discussion of these topics is beyond the scope of this document; interested readers should consult statistical references.

When there is satisfactory control of a concrete mixture, strength test values tend to cluster near the average value.