

Guide to Evaluation of Strength Test Results of Concrete

Reported by ACI Committee 214



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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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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

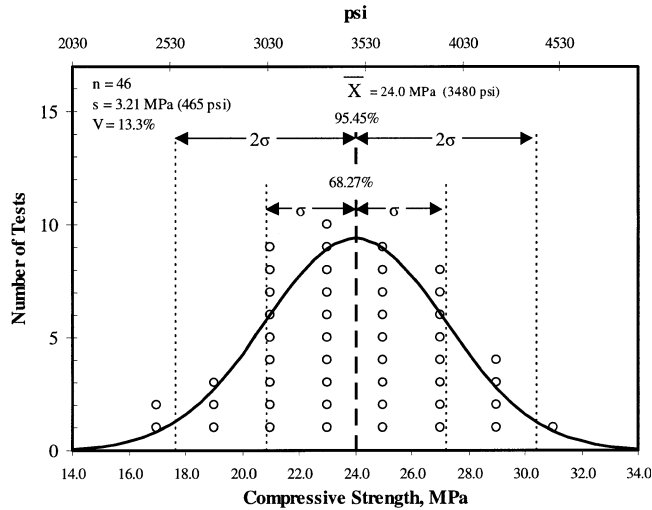


Fig. 4.1—Frequency distribution of strength data and corresponding assumed normal distribution.

making the histogram of test results appear tall and narrow. As variation in the strength results increases, the spread in data also increases, changing the normal distribution curve to flatter and wider (Fig. 4.2). When applied to concrete strength tests, these statistics can be calculated as shown in Sections 4.2.1 and 4.2.2.

4.2.1 Mean $\bar{X}$ —The average of strength test results $\bar{X}$ is calculated using Eq. (4-1)

$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n} = \frac{1}{n} \sum_{i=1}^n X_i = \frac{1}{n} (X_1 + X_2 + X_3 + \dots + X_n) \quad (4-1)$$

where X_i is the i -th strength test result, that is, the average of at least two 6 x 12 in. (150 x 300 mm) or three 4 x 8 in. (100 x 200 mm) concrete test cylinders. X_2 is the second strength test result, X_3 the third, and so on. $\sum X_i$ is the sum of all strength test results, and n is the number of tests in the record.

4.2.2 Sample standard deviation s —Standard deviation is the most recognized measure of dispersion of test data. An estimate of the population standard deviation σ is the sample standard deviation s . The population standard deviation consists of all possible data, often considered an infinite number of data points. The sample is a portion of the population, consisting of a finite number of data points. Sample standard deviation is obtained by Eq. (4-2a) or by its algebraic equivalent, Eq. (4-2b). The latter equation is preferable for computation because it is simpler and minimizes rounding errors. Many computer software packages calculate statistical functions. When using such programs, take care to ensure that the standard deviation calculated by the software is the same as the sample standard deviation shown in Eq. (4-2a)

$$s = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}} = \sqrt{\frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n-1}} \quad (4-2a)$$

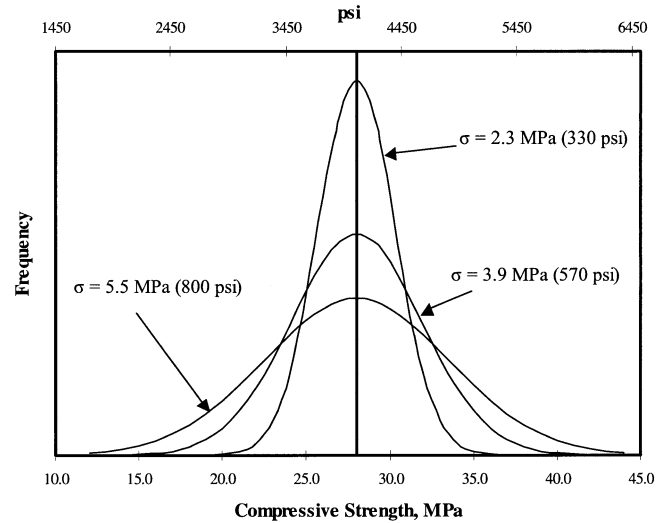


Fig. 4.2—Normal frequency curves for three different distributions with the same mean but different variability.

which is equivalent to Eq. (4-2b)

$$s = \sqrt{\frac{n \sum_{i=1}^n X_i^2 - \left(\sum_{i=1}^n X_i \right)^2}{n(n-1)}} = \sqrt{\frac{\sum_{i=1}^n X_i^2 - n\bar{X}^2}{n-1}} \quad (4-2b)$$

where s is the sample standard deviation; n is the number of strength test results in the record; $\bar{X}$ is the sample mean, or average strength test result; and $\sum X$ is the sum of strength test results.

When combining two separate records of concrete mixtures with similar strength test results, it is frequently necessary to determine the statistical average standard deviation, also termed the pooled standard deviation. The statistical average standard deviation of two records is calculated as shown in Eq. (4-3)

$$\bar{s} = \sqrt{\frac{(n_A - 1)(s_A)^2 + (n_B - 1)(s_B)^2}{(n_A + n_B - 2)}} \quad (4-3)$$

where $\bar{s}$ is the statistical average standard deviation, or pooled standard deviation, determined from two records; s_A and s_B are the standard deviations of Records A and B, respectively; and n_A and n_B are the number of tests in Records A and B, respectively.

4.2.3 Additional statistics—Additional statistical values are commonly used for comparing different data sets or for estimating dispersion in the absence of statistically valid sample sizes.

4.2.3.1 Coefficient of variation V —The sample standard deviation expressed as a percentage of the average strength $\bar{X}$ is called the coefficient of variation

$$V = \frac{s}{\bar{X}} \times 100 \quad (4-4)$$

where V is the coefficient of variation, s is the sample standard deviation, and $\bar{X}$ is the average strength test result.

The coefficient of variation is less affected by the magnitude of the strength level (Cook 1989; Anderson 1985); it is therefore more useful than the standard deviation for comparing the degree of control over a wide range of compressive strengths. The coefficient of variation is typically used when comparing the dispersion in groups of strength test results with a difference in average strength more than 1000 psi (7 MPa).

4.2.3.2 Range R —the statistic found by subtracting the lowest value from the highest value in a data set. When evaluating concrete test results, the within-test range R of a strength test result is found by subtracting the lowest single cylinder strength from the highest single cylinder strength of two or more cylinders comprising a strength test result. The average within-batch range is used for estimating the within-batch standard deviation. Refer to Section 4.3.1 for further discussion. When two cylinders of the same sample tested at the same time are used for a test, the range of that test is sometimes called the “pair difference.”

4.3—Strength variations

As noted in Chapters 1 and 3, variations in strength test results can be traced to batch-to-batch variations and within-batch variations.

4.3.1 Within-batch variation—Variability due to testing is estimated by the within-batch variation based on differences in the measured strengths of companion (replicate) cylinders comprising a strength test result. Within-batch variations can result from sampling of the batch sample, the fabrication, curing, or testing of the concrete test samples. A single strength test result of a concrete mixture, however, does not provide sufficient data for statistical analysis. As with any statistical estimator, confidence in the estimate is a function of the number of test results.

Although a sample of more than 30 tests is preferred, the within-batch standard deviation s_1 can be estimated from the average range $\bar{R}$ of at least 10 same age strength test results. $\bar{R}$ is divided by factor d_2 .

$$s_1 = \frac{1}{d_2} \bar{R} \quad (4-5)$$

The appropriate value of d_2 can be selected from Table 4.1 based on the number of samples represented in each strength test result. The table is composed of d_2 values extracted from Table 49 of ASTM Manual 7A. The d_2 values increase because, for a population with a given standard deviation, the expected range from a set of four specimens is larger than that of two.

The within-batch coefficient of variation V_1 , expressing the amount of variation as a percentage of the average strength, is determined from the within-batch standard deviation and the average strength $\bar{X}$

Table 4.1—Factors for computing within-batch standard deviation from range of tests using two, three, or four specimens*

No. of specimens	d_2
2	1.128
3	1.693
4	2.059

*In the case where the range should be computed from test results using a different number of cylinders, d_2 is the average of d_2 's weighted by the number of tests. For example, if d_2 was to be computed based on 12 tests, five of which used two cylinders, four of which used three, and three used four: $d_2 = 1.128(5/12) + 1.693(4/12) + 2.059(3/12) = 1.643$.

$$V_1 = \frac{s_1}{\bar{X}} \times 100 \quad (4-6)$$

For example, when two cylinders are cast for each of 10 separate strength tests, and the average within-batch strength range is 254 psi (1.75 MPa), the estimated within-batch standard deviation ($d_2 = 1.128$ for two cylinders) is $254/1.128 = 225$ psi (1.75/1.128 = 1.55 MPa). The precision statement in ASTM C39/C39M indicates the within-batch coefficient of variation for 6 x 12 in. (150 x 300 mm) cylinder specimens made in the lab to be 2.4% and for cylinders made in the field to be 2.9%. For 4 x 8 in. (100 x 200 mm) cylinders made under laboratory conditions, a coefficient of variation of 3.2% is indicated.

Consistent errors or bias in testing procedures will not necessarily be detected by comparing test results of cylinders from the same concrete sample. When an improperly conducted test is performed consistently, variations may be small.

4.3.2 Batch-to-batch variations—Differences in strength from batch-to-batch can be attributed to variations resulting from two major categories, the:

1. Characteristics and properties of the ingredients; and
2. Batching, mixing, transporting procedures, sampling of the batch, and climatic conditions.

Batch-to-batch variations can be estimated from strength test results of a concrete mixture when each test result represents a separate batch of concrete.

4.3.3 Overall variation—The overall variation, measured by the standard deviation σ (for a population) or s (for a sample,) has two component variations: 1) the within-batch σ_1 (population) or s_1 (sample); and 2) batch-to-batch σ_2 (population) or s_2 (sample).

The batch-to-batch sample standard deviation estimates the variations attributable to constituent material suppliers and the concrete producer. The within-batch sample variation results from sampling of the batch sample, specimen preparation, curing, and testing. Values for the overall and within-batch sample standard deviations, as well as the coefficients of variation associated with different control standards, are provided in Section 4.5.

4.4—Interpretation of statistical parameters

Once statistical parameters have been computed and the assumed and verified histogram plotted (Fig. 4.1), with results that follow a normal frequency distribution curve, additional

Table 4.2—Expected percentages of individual tests lower than f'_c *

Average strength μ	Expected percentage of low tests	Average strength μ	Expected percentage of low tests
$f'_c + 0.10\sigma$	46.0	$f'_c + 1.6\sigma$	5.5
$f'_c + 0.20\sigma$	42.1	$f'_c + 1.7\sigma$	4.5
$f'_c + 0.30\sigma$	38.2	$f'_c + 1.8\sigma$	3.6
$f'_c + 0.40\sigma$	34.5	$f'_c + 1.9\sigma$	2.9
$f'_c + 0.50\sigma$	30.9	$f'_c + 2.0\sigma$	2.3
$f'_c + 0.60\sigma$	27.4	$f'_c + 2.1\sigma$	1.8
$f'_c + 0.70\sigma$	24.2	$f'_c + 2.2\sigma$	1.4
$f'_c + 0.80\sigma$	21.2	$f'_c + 2.3\sigma$	1.1
$f'_c + 0.90\sigma$	18.4	$f'_c + 2.4\sigma$	0.8
$f'_c + 1.00\sigma$	15.9	$f'_c + 2.5\sigma$	0.6
$f'_c + 1.10\sigma$	13.6	$f'_c + 2.6\sigma$	0.45
$f'_c + 1.20\sigma$	11.5	$f'_c + 2.7\sigma$	0.35
$f'_c + 1.30\sigma$	9.7	$f'_c + 2.8\sigma$	0.25
$f'_c + 1.40\sigma$	8.1	$f'_c + 2.9\sigma$	0.19
$f'_c + 1.50\sigma$	6.7	$f'_c + 3.0\sigma$	0.13

*Where μ exceeds f'_c by amount shown.

analysis of the test results is possible. Figure 4.1 shows the approximate division of the area under the normal frequency distribution curve. It was seen that approximately 68% of the area (equivalent to 68% of the results) lies within $\pm 1\sigma$ of the average, and 95% lies within $\pm 2\sigma$. This property of the normal distribution permits an estimate of the portion of the test results expected to fall within multiples z of the standard deviation σ of the average or of any other specific value.

Data histograms tend to more closely resemble a normal distribution as the sample size is increased. When only a few results are available, they may not fit the standard, bell-shaped pattern. Errors in sampling, making, curing, and testing can also cause a lack of agreement between a histogram of strength test results and a normal distribution. Failure to sample in a truly random manner, sampling from different populations, or the presence of skew or kurtosis in high-strength concretes (Cook 1989) are factors that can result in substantial differences between measured strengths and a normal distribution.

Table 4.2 was adapted from the normal cumulative distribution, which is the normal probability integral. Listed is the probability that a test will fall below f'_c when the required average strength μ equals $f'_c + z\sigma$.

4.5—Standards of control

One primary purpose of the statistical evaluation of concrete data is to identify sources of variability. This knowledge can be used to determine appropriate steps for maintaining quality control. Several techniques can be used to detect variations in concrete production, materials processing and handling, and contractor and testing agency operations. A simple approach is to compare overall variability and within-batch variability using standard deviation or coefficient of variation, as appropriate, with previous performance.

Table 4.3—Standards of concrete control for $f'_c \leq 5000$ psi (35 MPa)

Overall variation					
Class of operation	Standard deviation for different control standards, psi (MPa)				
	Excellent	Very good	Good	Fair	Poor
General construction testing	Below 400 (below 2.8)	400 to 500 (2.8 to 3.4)	500 to 600 (3.4 to 4.1)	600 to 700 (4.1 to 4.8)	Above 700 (above 4.8)
Laboratory trial batches	Below 200 (below 1.4)	200 to 250 (1.4 to 1.7)	250 to 300 (1.7 to 2.1)	300 to 350 (2.1 to 2.4)	Above 350 (above 2.4)
Within-batch variation					
Class of operation	Coefficient of variation for different control standards, %				
	Excellent	Very good	Good	Fair	Poor
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

Table 4.4—Standards of concrete control for $f'_c \geq 5000$ psi (35 MPa)

Overall variation					
Class of operation	Coefficient of variation for different control standards, %				
	Excellent	Very good	Good	Fair	Poor
General construction testing	Below 7.0	7.0 to 9.0	9.0 to 11.0	11.0 to 14.0	Above 14.0
Laboratory trial batches	Below 3.5	3.5 to 4.5	4.5 to 5.0	5.0 to 7.0	Above 7.0
Within-batch variation					
Class of operation	Coefficient of variation for different control standards, %				
	Excellent	Very good	Good	Fair	Poor
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

Whether standard deviation or coefficient of variation is the appropriate measure of dispersion to use in a given situation depends on which measure is most constant over the range of strengths of concern. Field experience indicates that standard deviation remains reasonably constant over a limited range of strengths; however, several studies show that coefficient of variation is more nearly constant over a wider range of strengths, especially higher strengths (Cook 1982, 1989). A comparison of level of control between compressive and flexural strengths is easier to evaluate using the coefficient of variation. The coefficient of variation is also a better statistic for within-batch evaluations (Neville 1959; Metcalf 1970; Murdock 1953; Erntroy 1960; Rüsch 1964; and ASTM C802). Standard deviation or the coefficient of variation can be used to evaluate the level of control of conventional-strength concrete mixtures; but for strengths exceeding 5000 psi (35 MPa), the coefficient of variation is preferred.

Table 4.3 gives control standards appropriate for concretes with f'_c up to 5000 psi (35 MPa). Table 4.4 provides control standards for concretes with f'_c exceeding 5000 psi (35 MPa). These control standards were adopted based on examination and analysis of compressive strength data by ACI Committees 214, Evaluation of Strength Tests, and 363, High-Strength Concrete. Strength tests were conducted using

6 x 12 in. (150 x 300 mm) cylinders. The control standards are, therefore, applicable to specimens of this size that have been tested at 28 days. These standards may be applicable with minor differences to other cylinder sizes, such as 4 x 8 in. (100 x 200 mm), as recognized in ASTM C31/C31M.

The overall and within-batch coefficient of variation for 4 x 8 in. (100 x 200 mm) cylinders was found to be slightly higher compared with 6 x 12 in. (150 x 300 mm) cylinders for the same concrete mixture (Detwiler et al. 2006; ASTM C39/C39M). Therefore, to reduce the variation of test results from 4 x 8 in. (100 x 200 mm) cylinders, the average strength of at least three 4 x 8 in. (100 x 200 mm) cylinders should be used to determine compressive strength, as required by ACI 318.

As a measure of the within-batch error, some international specifiers find averaged pair differences up to 145 psi (1 MPa) representative of “good” control, and accept differences up to 290 psi (2 MPa) as “acceptable” control (Day 2006). Because the pair differences represent the range of two-cylinder tests, the standard deviations at these levels can be estimated by dividing the pair difference by 1.128, from Table 4.1, to get 128 psi (0.88 MPa) and 257 psi (1.77 MPa), respectively.

CHAPTER 5—CRITERIA

5.1—General

The concrete cylinders used to measure strength for contractual acceptance are to be sampled (ASTM C172/C172M), fabricated, standard cured (ASTM C31/C31M), and tested (ASTM C39/C39M) under highly controlled conditions. Generally, the strengths of these cylinders are the primary evidence of the quality of concrete used in the structure. The engineer specifies the desired strength, testing frequency, and the permitted tolerance in compressive strength (ACI 301).

Any specified quantity should be expressed with a tolerance. It is impractical to specify an absolute minimum strength because lower strengths are possible due to random variation, even when control is good.

The concrete industry has developed methodologies using standard probabilistic methods and quality-control techniques to determine the magnitude of that tolerance as it applies to the specification and testing of concrete strength. The basic assumption is that concrete strength tests are normally distributed.

With the acceptance of a normal distribution for a population of concrete tests, for a given mean strength, some percentage of test results can be expected to fall below the required concrete strength f'_c ; and some will be greater than the f'_c . When samples are selected randomly, there is a small probability that the low strength results correspond to concrete located in a critical area. The consequences of a localized zone of low-strength concrete in a structure depend on many factors, including:

- Early overload probability;
- Location and magnitude of the low-quality zone in the structural element;
- Degree of reliance placed on strength in design;
- Cause of the low strength; and
- Implications, economic and otherwise, of loss of serviceability or structural failure.

Some tests will fall below f'_c . ACI 318 and most other building codes and specifications establish statistically-based acceptance criteria for complying with f'_c acceptance criteria, analogous to the tolerances for other building materials.

To satisfy statistically-based, strength-performance requirements, the minimum required average strength of the concrete mixture proportion f'_{cr} should exceed f'_c . The f'_{cr} is a function of the variability of test results measured by the coefficient of variation or standard deviation and on the proportion of tests allowed below the specified strength.

5.2—Data used to establish minimum required average strength

To establish the required average strength f'_{cr} , an estimate is needed of the variability of concrete to be supplied for construction. The strength test record used to estimate standard deviation or coefficient of variation should represent a group of at least 30 tests. Data used to estimate variability should represent concrete produced to meet a specified strength close to that specified for the proposed work and similar in composition and production.

The requirement for 30 consecutive strength tests can be satisfied using a test record of 30 batches of the same concrete class within 1000 psi (7 MPa) of specified f'_c or the statistical average of two test records totaling 30 or more tests. In the latter case, the pooled standard deviation can be calculated using Eq. (4-3).

When the number of test results available is fewer than 30, a more conservative approach is needed. ACI 318 allows test records with as few as 15 tests to estimate the standard deviation. However, the value of the sample standard deviation should be increased by up to 16% to account for greater uncertainty in the estimated population standard deviation. A conservative approach is thereby required and concrete is proportioned to produce higher average strengths than would be needed if more test results were available and the standard deviation more accurately determined. When there are 15 to 30 strength test results, the calculated standard deviation should be multiplied by the modification factor obtained from Table 5.1 to provide estimates conservative enough to account for uncertainty in calculated standard deviation. This is the methodology adopted by ACI 318, Chapter 5.

When there are fewer than 15 strength test results, the calculated standard deviation is not sufficiently reliable. In these cases, concrete is proportioned using Table 5.2, which can be expected to require higher strengths than those computed from an established standard deviation.

As a project progresses and more strength tests become available, all available strength tests should be analyzed to obtain the most reliable estimate of the standard deviation for the concrete being used on that project. A revised value of f'_{cr} , which is typically lower than the original one, could then be computed and used.

5.3—Criteria for strength requirements

There are several criteria that can be used to ensure that a concrete's performance meets the specific requirements. Most simply, this is done by requiring the average required

strength f'_{cr} to equal or exceed the specified strength f'_c by a multiple, chosen to represent the percentage of tests allowed to be defective, of the strength variation that finds a place in Table 5.3, which is

$$f'_{cr} = f'_c + z s \quad (\text{refer to Eq. (5-3b)})$$

A detailed discussion of the criteria needed to fully utilize this table, with examples using the equations, is presented in 5.3.1.

As the multiple applied to the strength variation increases, the less likely it will be that an individual strength test will exceed f'_c . This is seen in Fig. 5.1, which shows that for a given specified strength, the average required strength overdesign increases as the variation, expressed as the coefficient of variation, rises.

These equations all require a reliability factor value z , which is selected to provide a sufficiently high probability that f'_c will be equaled or exceeded. For concretes having a normal distribution of strength test results, the z value can be taken from Table 5.4. The computed value of f'_{cr} will be the same for a given set of strength test results regardless of whether the coefficient of variation or standard deviation equation is used.

Table 5.1—Modification factors for standard deviation*

Number of tests	Modification factors
Fewer than 15	Refer to Table 5.2
15	1.16
20	1.08
25	1.03
30 or more	1.00

*Table 5.3.1.2 of ACI 318.

Table 5.2—Minimum required average strength without sufficient historical data*

Required average compressive strength	Specified compressive strength
$f'_{cr} = f'_c + 1000$ psi ($f'_{cr} = f'_c + 7$ MPa)	when $f'_c < 3000$ psi ($f'_c < 21$ MPa)
$f'_{cr} = f'_c + 1200$ psi ($f'_{cr} = f'_c + 8$ MPa)	when $f'_c \geq 3000$ psi and $f'_c \leq 5000$ psi ($f'_c \geq 21$ MPa and $f'_c \leq 35$ MPa)
$f'_{cr} = 1.10f'_c + 700$ psi ($f'_{cr} = 1.10f'_c + 5$ MPa)	when $f'_c > 5000$ psi ($f'_c > 35$ MPa)

*Table 5.3.2.2 of ACI 318.

The minimum f'_{cr} can be computed using Table 5.2 or applying Eq. (5-1) through (5-4), as appropriate with the criteria listed in Table 5.3.

When a specification requires a combination of the average number of tests, such as the average of three consecutive tests, the standard deviation or coefficient of variation of such an average will be lower than that computed using all individual test results (Section 5.3.2.1). Standard deviation of an average is calculated by dividing the standard deviation (Section 5.3.2.2) of individual test results by the square root of the number of tests (n) in each average, in the form of Eq. (5-2) in Table 5.3.

The value of n typically specified is 3. This value should not be confused with the number of strength test results used to estimate the mean or standard deviation of the record. Table 5.4 provides values of z for various percentages of tests falling between the mean $\pm z\sigma$ and the probability a test will fall below the mean minus $z\sigma$. Examples are shown in Section 5.3.2.

The amount by which f'_{cr} exceeds f'_c depends on the acceptance criteria specified for the particular project. The examples that follow show how different criteria may be used to determine f'_{cr} for various specifications or elements of specifications. Numerical examples are presented in both inch-pound and SI units in a parallel format that has been

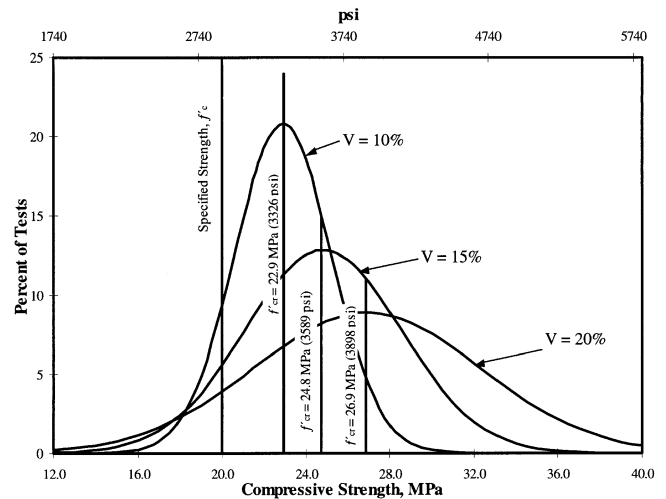


Fig. 5.1—Normal frequency curves for coefficients of variation of 10, 15, and 20%.

Table 5.3—Equations to determine minimum required average strength

	Criterion 1	Criterion 2	Criterion 3*	Criterion 4†
	Maximum percent of individual tests $< f'_c$	Maximum percent of moving average of n consecutive tests $< f'_c$	Maximum percent of individual tests $< (f'_c - k)$	Maximum percent of individual tests $< (k\% \text{ of } f'_c)$
Coefficient of variation formula	$f'_{cr} = f'_c / (1 - zV)$	$f'_{cr} = f'_c / (1 - zV / \sqrt{n})$	$f'_{cr} = (f'_c - k) / (1 - zV)$	$f'_{cr} = kf'_c / (1 - zV)$
Equation number	(5-1a)	(5-2a)	(5-3a)	(5-4a)
Standard deviation formula	$f'_{cr} = f'_c + z s$	$f'_{cr} = f'_c + (z s / \sqrt{n})$	$f'_{cr} = (f'_c - k) + z s$	$f'_{cr} = kf'_c + z s$
Equation number	(5-1b)	(5-2b)	(5-3b)	(5-4b)

*Criterion 3 is for $f'_c \leq 5000$ psi (35 MPa).

†Criterion 4 is for $f'_c > 5000$ psi (35 MPa).

Table 5.4—Probabilities associated with values of z

Percentages of tests within $\pm z\sigma$	Chances of falling below $f'_c - z\sigma$	z
40	3 in 10 (30%)	0.52
50	2.5 in 10 (25%)	0.67
60	2 in 10 (20%)	0.84
68.27	1 in 6.3 (15.9%)	1.00
70	1.5 in 10 (15%)	1.04
80*	1 in 10 (10%)*	1.28*
90	1 in 20 (5%)	1.65
95	1 in 40 (2.5%)	1.96
95.45	1 in 44 (2.3%)	2.00
98*	1 in 100 (1%)*	2.33*
99	1 in 200 (0.5%)	2.58
99.73	1 in 741 (0.13%)	3.00

*Commonly used values.

hard converted; thus, they reflect the values commonly used in the respective unit system. ACI 318 contains variations of these equations.

5.3.1 Criterion No. 1—The engineer may specify a maximum percentage of individual, random strength test results permitted to fall below the f'_c . This is the form of many international specifications, which tend to use a reliability factor of 1.65, implying acceptance of only a 5% failure rate. This criterion is no longer used in ACI 318, but may occur in situations where the average strength is a fundamental part of the design methodology, such as in some pavement specifications. A typical requirement permits no more than 10% strength tests to fall below f'_c . Specified strength in these situations generally ranges from 3000 to 5000 psi (21 to 35 MPa).

5.3.1.1 Coefficient of variation method—Assume sufficient data exist for which a coefficient of variation of 10.5% has been calculated for a concrete mixture with an f'_c of 4000 psi (28 MPa). From Table 5.3, 10% of the normal probability distribution is more than 1.28 standard deviations below the mean. Using Eq. (5-1a) from Table 5.3

$$f'_{cr} = f'_c / (1 - zV)$$

$$f'_{cr} = 4000 / (1 - 1.28 \times 0.105) = 4620 \text{ psi}$$

$$[f'_{cr} = 28 / (1 - 1.28 \times 0.105) = 32.3 \text{ MPa}]$$

Therefore, for an f'_c of 4000 psi (28 MPa), proportion the concrete mixture for an average strength no less than 4620 psi (32.3 MPa) so that, on average, no more than 10% of the results fall below f'_c .

5.3.1.2 Standard deviation method—Assume sufficient data exist for which a standard deviation of 519 psi (3.58 MPa) has been calculated for a concrete mixture with an f'_c of 4000 psi (28 MPa). According to Table 5.4, 10% of the normal probability distribution is more than 1.28 standard deviations below the mean. Using Eq. (5-1b) from Table 5.3

$$f'_{cr} = f'_c + z\sigma$$

$$f'_{cr} = 4000 \text{ psi} + 1.28 \times 519 \text{ psi} = 4660 \text{ psi}$$

$$[f'_{cr} = 28 \text{ MPa} + 1.28 \times (3.58) \text{ MPa} = 32.6 \text{ MPa}]$$

To produce a concrete mixture with f'_c of 4000 psi (28 MPa) that is expected, on average, to have no more than 10% of the test results fall below f'_c , the concrete mixture should be proportioned to produce an average strength of no less than 4660 psi (32.6 MPa).

5.3.2 Criterion No. 2—The engineer can specify a probability that an average of n consecutive strength tests will fall below f'_c . For example, ACI 318, Section 5.6.3.3, stipulates that the average of any three consecutive strength test results should equal or exceed f'_c . The f'_{cr} should be established where failure to meet f'_c is anticipated at no more than 1 in 100 times (0.01).

5.3.2.1 Coefficient of variation method—Assume sufficient data exist for which a 10.5% coefficient of variation has been calculated for a concrete mixture with an f'_c of 4000 psi (28 MPa). From Table 5.4, 1% of the normal probability distribution is more than 2.33 standard deviations below the mean. Using Eq. (5-2a) from Table 5.3

$$f'_{cr} = f'_c / [1 - (zV/\sqrt{n})]$$

$$f'_{cr} = 4000 \text{ psi} / [1 - (2.33 \times 0.105/\sqrt{3})] = 4660 \text{ psi}$$

$$[f'_{cr} = 28 \text{ MPa} / [1 - (2.33 \times 0.105/100/\sqrt{3})] = 32.6 \text{ MPa}]$$

Therefore, for a 4000 psi (28 MPa) mixture, proportion for an average strength no less than 4660 psi (32.6 MPa) so that, on average, no more than 1% of the moving average of three consecutive strength-test results fall below f'_c .

5.3.2.2 Standard deviation method—Assume sufficient data exist for which a standard deviation of 519 psi (3.58 MPa) has been calculated for a concrete mixture with an f'_c of 4000 psi (28 MPa). From Table 5.4, 1% of the normal probability distribution is more than 2.33 standard deviations below the mean. Using Eq. (5-2b) from Table 5.3

$$f'_{cr} = f'_c + z\sigma/\sqrt{n}$$

$$f'_{cr} = 4000 \text{ psi} + [(2.33 \times 519 \text{ psi})/\sqrt{3}] = 4700 \text{ psi}$$

$$f'_{cr} = 28 \text{ MPa} + [(2.33 \times 3.58 \text{ MPa})/\sqrt{3}] = 32.8 \text{ MPa}$$

Therefore, for an f'_c of 4000 psi (28 MPa), proportion the concrete mixture for an average strength no less than 4700 psi (32.8 MPa) so that, on average, no more than 1% of the moving average of three strength-test results falls below f'_c .

Equation (5-2b) from Table 5.3 is presented in different form than Eq. (5-1), Table 5.3.2.1 in ACI 318. The value 1.34 in ACI 318 is equivalent to $z\sigma/\sqrt{n} = 2.33\sigma/\sqrt{3} = 1.34$, because both z and n are already specified.

5.3.3 Criteria No. 3 and 4—The engineer may specify a certain probability that a random individual strength test result will be no more than a certain amount below f'_c . For example, Criterion No. 3 is used in ACI 318 by stipulating that no individual strength test result falls below f'_c by more than 500 psi (3.5 MPa). An alternative Criterion No. 4 is appropriate for concrete with $f'_c > 5000$ psi (35 MPa),

requires that no individual strength test result falls below 90% of f'_c . These two criteria are equivalent at 5000 psi (35 MPa). The minimum value of f'_{cr} is established so that nonconformance of an individual, random test is anticipated no more often than 1 in 100 times in either case.

5.3.3.1 Coefficient of variation method, $f'_c \leq 5000$ psi (35 MPa)—Assume sufficient data exist for which a coefficient of variation of 10.5% has been calculated for a concrete mixture with an f'_c of 4000 psi (28 MPa). From Table 5.4, 1% of the normal probability distribution is more than 2.33 standard deviations below the mean. Using Eq. (5-3a), with k set to 500 psi (3.5 MPa), from Table 5.3

$$f'_{cr} = (f'_c - k)/(1 - zV)$$

$$f'_{cr} = (4000 \text{ psi} - 500 \text{ psi})/[1 - (2.33 \times 0.105)] = 4630 \text{ psi}$$

$$[f'_{cr} = (28 \text{ MPa} - 3.5 \text{ MPa})/[1 - (2.33 \times 10.5/100)] = 32.4 \text{ MPa}]$$

Therefore, for an f'_c of 4000 psi (28 MPa), proportion the concrete mixture for an average strength no less than 4630 psi (32.4 MPa) so that, on average, no more than 1% of the individual strength test results fall below f'_c by more than 500 psi (3.5 MPa).

5.3.3.2 Standard deviation method, $f'_c \leq 5000$ psi (35 MPa)—Assume sufficient data exist for which a standard deviation of 519 psi (3.58 MPa) has been calculated for a concrete mixture with an f'_c of 4000 psi (28 MPa). From Table 5.4, 1% of the normal probability distribution is more than 2.33 standard deviations below the mean. Using Eq. (5-3b) from Table 5.3 with k set equal to 500 psi (3.5 MPa)

$$f'_{cr} = (f'_c - k) + z s$$

$$f'_{cr} = (4000 \text{ psi} - 500 \text{ psi}) + (2.33 \times 519 \text{ psi}) = 4710 \text{ psi}$$

$$[f'_{cr} = (28 \text{ MPa} - 3.5 \text{ MPa}) + (2.33 \times 3.58 \text{ MPa}) = 32.8 \text{ MPa}]$$

Therefore, for a specified compressive strength of 4000 psi (28 MPa), proportion the concrete mixture for an average strength no less than 4710 psi (32.8 MPa) so that, on average, no more than 1% of the individual strength test results fall below f'_c by more than 500 psi (3.5 MPa).

5.3.3.3 Coefficient of variation method, $f'_c > 5000$ psi (35 MPa)—Assume sufficient data exist for which a coefficient of variation of 8.2% has been calculated for a concrete mixture with an f'_c of 9000 psi (62 MPa). From Table 5.4, 1% of the normal probability distribution is more than 2.33 standard deviations below the mean. Using Eq. (5-4a) with k set equal to 0.90 from Table 5.3.

$$f'_{cr} = 0.90 \times f'_c / (1 - zV)$$

$$f'_{cr} = (0.90 \times 9000 \text{ psi})/[1 - (2.33 \times 0.082)] = 10,010 \text{ psi}$$

$$[f'_{cr} = (0.90 \times 62 \text{ MPa})/[1 - (2.33 \times 8.2/100)] = 69 \text{ MPa}]$$

Therefore, for an f'_c strength of 9000 psi (62 MPa), proportion the concrete mixture for an average strength no less than

10,010 psi (69 MPa) so that, on average, no more than 1% of the individual strength test results fall below $0.90f'_c$.

5.3.3.4 Standard deviation method, $f'_c > 5000$ psi (35 MPa)—Assume a standard deviation of 814 psi (5.61 MPa) has been calculated for a concrete mixture with an f'_c of 9000 psi (62 MPa). From Table 5.4, 1% of the normal probability distribution is more than 2.33 standard deviations below the mean. Using Eq. (5-4b) with k set equal to 0.90 from Table 5.3

$$f'_{cr} = 0.90 \times f'_c + z s$$

$$f'_{cr} = 0.90 \times 9000 \text{ psi} + 2.33 \times 814 \text{ psi} = 10,000 \text{ psi}$$

$$[f'_{cr} = (0.90 \times 62 \text{ MPa}) + (2.33 \times 5.61 \text{ MPa}) = 68.9 \text{ MPa}]$$

Therefore, for an f'_c of 9000 psi (62 MPa), proportion the concrete mixture for an average strength no less than 10,000 psi (68.9 MPa) so that, on average, no more than 1% of the individual strength-test results fall below $0.90f'_c$.

5.3.4 Multiple criteria—In many instances, multiple criteria are specified. ACI 318 requires that concrete strengths conform to both individual test criteria and the moving average of three test criteria. Because both criteria are in effect, the required f'_{cr} should meet or exceed all requirements; that is, f'_{cr} should be the highest strength calculated using all relevant criteria. For example, assume sufficient data exist for which an 8.2% coefficient of variation has been calculated for a concrete mixture with an f'_c of 8700 psi (60 MPa). The required average strength for this concrete mixture should meet both of these criteria:

1. Individual strength criterion (5.3.3.4): $f'_{cr} = 0.90 \times f'_c / (1 - 2.33V) = 9690 \text{ psi}$ (66.8 MPa); and

2. Moving average of three strength tests criterion (5.3.2.2): $f'_{cr} = f'_c / (1 - 2.33V/\sqrt{3}) = 9780 \text{ psi}$ (67.4 MPa).

Moving average criterion governs, because it produces the largest f'_{cr} , that is, 9780 psi > 9690 psi (67.4 MPa > 66.8 MPa), and f'_{cr} should be the larger strength calculated for the two criteria.

CHAPTER 6—EVALUATION OF DATA

6.1—General

The evaluation of strength data is required in many situations. Three commonly required applications are:

1. Evaluation for mixture submittal purposes;
2. Evaluation of level of control; and
3. Evaluation to determine compliance with specifications.

These evaluations are important for identifying departures from desired target values and, where possible, assisting with formulating an appropriate response. In all cases, usefulness of the evaluation is a function of the amount of test data and the statistical rigor of the analysis. Applications for routine quality control and compliance overlap considerably. Many evaluation tools or techniques used in one application are appropriate for use in another.

Chapter 5, which reviews techniques appropriate for concrete mixture submittal evaluation, discusses techniques for routine quality control and compliance applications. Criteria for rejecting doubtful results, determining testing frequency, and guidelines for additional test procedures are also discussed.

It is useful to determine the likelihood of various outcomes when there is, at most, a 1% probability of a test less than f'_c by more than 500 psi (3.5 MPa) and, at most, a 1% probability that the moving average of three consecutive tests will be less than f'_c . The maximum probability that at least one event will occur in n independent tests may be estimated using Eq. (6-1) (Leming 1999)

$$Pr\{\text{at least 1 event} \mid n \text{ tests}\} = 1 - (1 - p)^n \quad (6-1)$$

where p is the probability of a single event.

When evaluating concrete tests, p is the single event probability of noncompliance with the strength criteria in ACI 318. Because p includes both possible cases of f'_c by more than 500 psi (3.5 MPa) and the moving average of three consecutive tests falling to less than f'_c , p lies between 1.0 and 2.0%. Without more details, assume the probability of a single test failing to meet the strength criteria of ACI 318 to be 1.5%. Table 6.1 provides probabilities of at least one occurrence of a noncompliant result given various numbers of independent tests n when the single event probability p equals 1.5% (a test does not meet ACI 318 strength criteria) and 10% (a test falls below f'_c).

The probability for noncompliance is not trivial, even for relatively small projects. For example, there is approximately a 10% probability of having at least one noncompliant test 500 psi (3.5 MPa) below f'_c , and a greater than 50% probability that at least one test falls below f'_c for a project with only seven tests. There is a high probability of such an occurrence on most projects, and it is a near certainty on large projects, even if variation is due exclusively to random effects and minimum average strength was determined using statistically valid methods. Probabilities are reduced somewhat for larger projects due to the effects of interference; however, the probabilities are still appreciable (Leming 1999).

6.2—Numbers of tests

For a particular project, a sufficient number of tests should be made to ensure accurate representation of the concrete. ACI 318 defines a strength test as the average strength of two or more specimens of the same age fabricated from a sample taken from a single batch of concrete. Testing frequency can be established on the basis of time elapsed or volume placed. The engineer should base the required number of tests on job conditions.

A project where one engineer supervises all concrete operations provides an excellent opportunity for control and accurate estimates of the mean and standard deviation with minimum testing. Once operations are progressing smoothly, tests taken each day or shift, depending on the volume of concrete produced, can be sufficient to obtain data that reflect the variations of the concrete as delivered. The engineer can reduce the number of tests required by the project specifications as the levels of control of the producer, laboratory, and contractor are established. To avoid bias, all sampling for acceptance testing should be conducted using randomly selected batches of concrete.

Table 6.1—Probability of at least one event in n tests for selected single-event probabilities

n	Single event probability = 1.5%	Single event probability = 10%
1	1.5%	10.0%
5	7.3%	41.0%
7	10.0%	54.3%
10	14.0%	65.1%
20	26.1%	87.8%
50	53.0%	99.5%
100	77.9%	Approximately 100%

For routine building construction, ACI 318 requires at least one test per day. There should be one test for every 150 yd³ (115 m³) of concrete placed, or one test for every 5000 ft² (460 m²) of the surface area of slabs and walls; but ACI 318 permits the engineer to waive testing on quantities less than 50 yd³ (40 m³). Testing frequency should satisfy each criterion. These testing frequencies generally result in testing concrete in one out of 10 to 20 trucks. Testing more frequently than this can slow the construction process.

Testing each load of delivered concrete for potential strength is rarely required. For members where structural performance is sensitive to compressive strength, testing once for every 100 yd³ (80 m³) may be appropriate. One test for every 50 yd³ (40 m³) would be appropriate only for the most critical applications. Very frequent testing should be specified only for compelling reasons, such as specialized or critical member applications.

Each different class of concrete placed during any one day will be represented by at least one test. At least five tests should be conducted for each class of concrete on a given project. Refer to ACI 301, ACI 318, and ASTM C94/C94M for routine testing requirements.

6.3—Rejection of doubtful specimens

Arbitrarily rejecting strength test results that appear too far out of line is not recommended because normal distribution anticipates the possibility of such results. Discarding test results indiscriminately can seriously distort the strength distribution, making analysis of results unreliable. Occasionally, the strength of one cylinder from a group made from a sample deviates so far from the others that it is considered highly improbable. If questionable variations are observed during fabrication, curing, or testing of a specimen, the single cylinder specimen should be rejected on that basis.

ASTM E178 provides criteria for rejecting the test result for one specimen in a set of specimens. Generally, the result from a single specimen in a set of three or more specimens can be discarded if its deviation from a test mean is greater than three times the previously established within-batch standard deviation (Chapter 4). The result should be investigated if its deviation is greater than two times the within-batch standard deviation. The test average should be computed from the remaining specimens. A test, that is, the average of all specimens of a single sample tested at the same age, should not be rejected unless it is likely that the specimens are faulty. The test represents the best available estimate for the sample strength.

6.4—Additional test requirements

Normally, potential compressive strength and variability of concrete are based on test results using cylinders that have been sampled, molded, and standard cured in accordance with ASTM C31/C31M until the specified test age, which is normally 28 days. Test cylinder diameter should be at least three times the size of the nominal maximum aggregate in the mixture. Concrete specimens made or cured under nonstandard conditions may provide additional information, but should be analyzed and reported separately. Specimens that have not been produced, cured, or tested under standard conditions may not accurately reflect potential concrete strength. Discrepancies and deviations from standard testing conditions should be noted on strength test reports.

Concrete strength testing at later ages, such as 56, 91, or 182 days, may be more relevant than the 28-day strength, particularly where a pozzolan, low heat cement, or cement of slow strength gain is used. Some structural elements or structures will not be loaded until concrete has matured longer than 28 days and advantage can be taken of this strength gain.

If a design is based on later-age strengths, it may be necessary to correlate with 28-day strength because it is not always practical to use later-age specimens for concrete acceptance. This correlation should be established by field or laboratory tests before construction starts. Concrete batching plants could preestablish this correlation for later reference, even if later-age concrete may not be immediately involved (it should be checked occasionally and, ultimately, checked against the actual concrete used.)

Many times in the early stages of a job, it is necessary to estimate the strength of concrete being produced before 28-day strength results are available. Concrete cylinders should be made and tested from the same batch at 7 days and, in some instances, even at 3 days. Testing at early ages using accelerated test procedures, such as found in ASTM C684, can also be adopted. The 28-day strength can be estimated on the basis of a previously established correlation for the specific mixture using the method described in ASTM C918/C918M. These early tests provide an indication only of acceptable performance. Tests used for acceptance purposes conducted at 28 days are usually the contractual standard. Field or job-cured specimens (ASTM C31) are sometimes recommended or required in applications such as fast-track construction or post-tensioning, to assure that acceptable in-place strength has been attained, particularly at early ages, so that the member can be safely loaded or stressed as soon as possible. Tests of job-cured specimens can be used to determine the time of form removal, particularly in cold weather, and when establishing the strength of steam-cured concrete or concrete pipe and block. Field-cured cylinders are also acceptable as a way to evaluate curing done by the contractor. Field cured cylinders should not be confused with standard cured cylinders, which are placed under highly controlled conditions within 2 days, and tests of which are used for acceptance purposes.

6.5—Quality-control charts

Many manufacturing industries use quality-control charts to reduce variability, increase production efficiency, and

identify trends as early as practicable. Well-established methods for setting up charts similar to those about to be presented are outlined in ASTM MNL 7A.

Trends become more apparent based on the pattern of previous results and limits established from ASTM MNL 7A. Data falling outside established limits indicate something has affected the control of the process, and action or interference with the existing process variables to bring it back under control is often required. These actions or process interference limit values are generally established using methods like those used by this guide, based on contract specifications or other values at which action should be taken. Frequently, action or interference limits are equal to the acceptance criteria specified for a particular project.

Figure 6.1 presents three simplified charts prepared specifically for concrete control. These charts are combined into one diagram so they can be evaluated simultaneously. These charts may not contain all the features of formal control charts, but they can be useful to the concrete engineer, architect, contractor, and supplier. Control charts of this type are strongly recommended for concrete in continuous production over considerable periods.

6.5.1 Simple strength chart—Chart (a) in Fig. 6.1, which shows the results of all individual strength tests plotted in succession based on casting date, shows the variation between a pair of cylinders made from the same concrete sample. The required average strength in Fig. 6.1 was established using Eq. (5-1b), though it could have been established by Eq. (5-1a) or Table 5.2. The chart often also includes the specified strength. This chart is useful because it shows all the available data, but it is limited at identifying trends and shifts in data.

6.5.2 Moving average strength—Chart (b) in Fig. 6.1 shows the moving average of consecutive tests. This type of chart reduces noise and scatter in the individual test chart. Performance trends are easily identified, and the influence of effects, such as seasonal changes and changes in materials, are shown more effectively. The chart often includes the specified strength when the moving average of three tests is plotted.

The more tests used to compute the average, the more powerful the chart is for identifying trends. There is an obvious trade-off with timeliness, however. A trend should be identified as soon as possible so that appropriate corrective actions can be taken. Because the moving average of three consecutive strength tests is one of the compliance criteria of ACI 318, this parameter is frequently tracked on a control chart. Because tracking the moving average of three tests may not provide sufficient analytical power, the moving average of five consecutive strength tests is frequently used. The number of tests averaged for this control chart and the appropriate interference limit can be varied to suit each job.

A concrete supplier with a large number of tests for a particular mixture can elect to track the moving average of 10 or 15 tests. A target value can be established based on f'_{cr} . Whereas requiring large amounts of data, any trends detected with this approach will be strong and shifts in average strength can be easily detected. The averages of 10 and 15 tests can also be used in mixture submittal documentation.

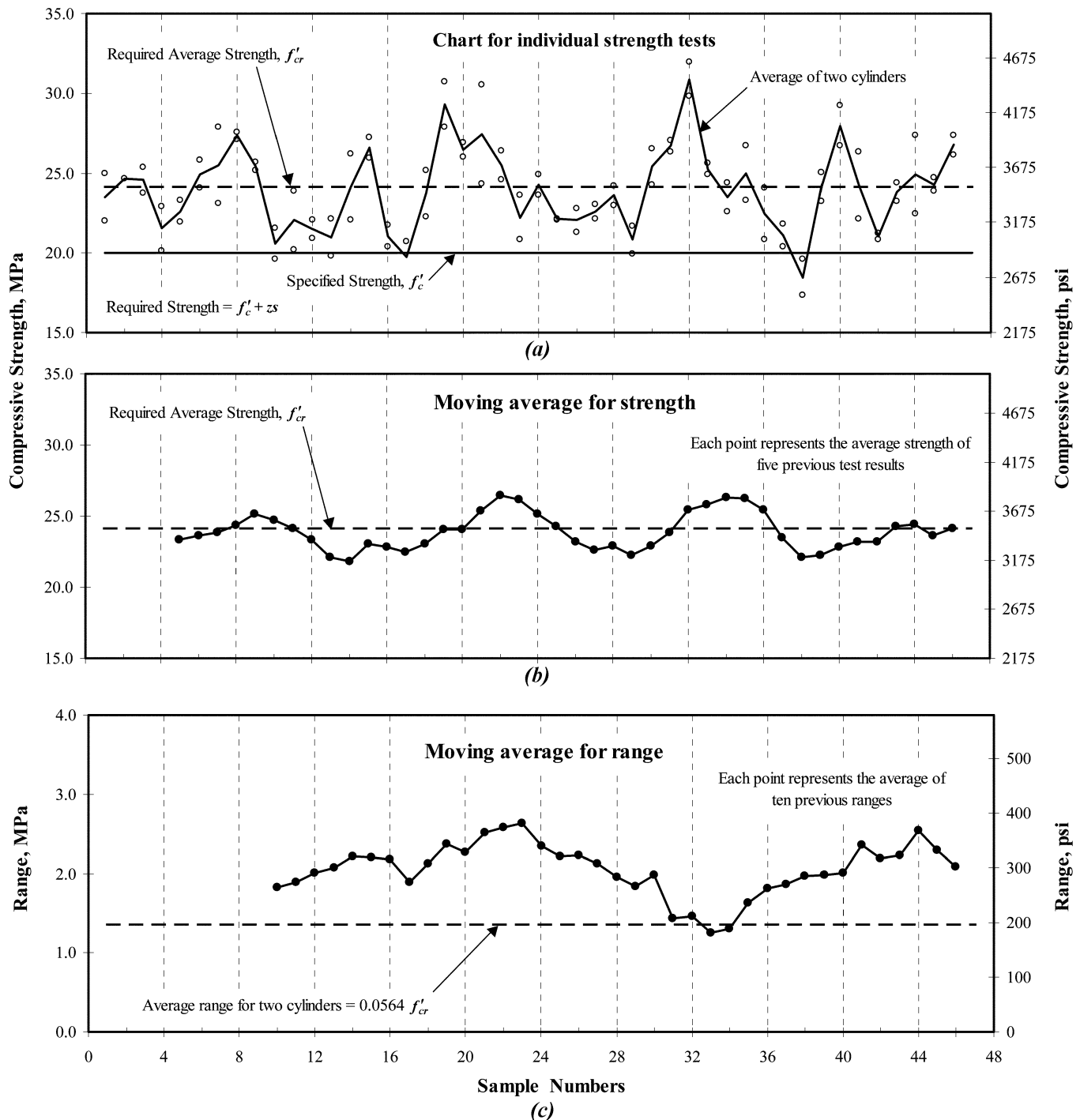


Fig. 6.1—Three simplified quality control charts: (a) individual strength tests, (b) moving average of five strength tests, and (c) range of two cylinders in each test and moving average for range.

6.5.3 Testing variability

6.5.3.1 Purpose—Chart (c) in Fig. 6.1 shows the moving average of the range with the maximum difference between companion cylinders comprising a single strength test, which is used to monitor the repeatability of testing. The laboratory is responsible for accurate testing; the contractor may be penalized if tests show greater variations or lower average strength levels than actually exist. Because the range in strength between companion specimens from the same sample is the responsibility of the laboratory, the laboratory may maintain a

control chart for the ranges as a check on the uniformity of its operations. These changes will not reveal day-to-day differences in testing, curing, capping, and testing procedures.

The average range of the previous 10 consecutive tests (sets of companion cylinders as discussed in 4.3.1) is typically plotted. Interference limits for this control chart are based on average strength and desired level of control.

6.5.3.2 Calculation of acceptable testing variation—Calculation of the acceptable range between companion cylinders of a test depends on the number of specimens in the

group and the within-batch variation, as discussed in Chapter 4. The following process can establish interference limits for the moving average range control chart.

The expected value of the average range $\overline{R}_m$ can be determined by reformulating Eq. (4-5) and Eq. (4-6) as shown in Eq. (6-2)

$$\overline{R}_m = f'_{cr} V_1 d_2 \quad (6-2)$$

The within-batch coefficient of variation V_1 should not be greater than 5% for good control of field cast samples (Table 4.2). Therefore, for groups of two companion cylinders, the estimate of the corresponding average range will be

$$\overline{R}_m = (0.05 \times 1.128) f'_{cr} = 0.05640 f'_{cr} \quad (6-3a)$$

or for groups of three companion cylinders

$$\overline{R}_m = (0.05 \times 1.693) f'_{cr} = 0.08465 f'_{cr} \quad (6-3b)$$

Because of the unacceptably large statistical uncertainties introduced by the use of small samples, these interference limits are effective only after the average range, computed from companion cylinder strengths from at least 10 strength tests, has been calculated.

6.5.4 Summary—To be effective, control charts should be maintained for the duration of each project. As a minimum, the testing laboratory should maintain a control chart for average range. Other control charts may be offered as a service to the engineer or architect. Because a single mixture can be used on multiple projects, concrete suppliers can track the moving average range on a mixture by mixture basis. Many suppliers track individual projects to obtain data for their own use.

6.6—Additional evaluation techniques

Many other techniques exist for evaluating a series of data for quality control purposes. As with basic control charts, although these techniques were developed for general industrial applications, they have been adapted for use with concrete properties.

6.6.1 Overall variability and concrete supplier's variability—Normally, mean compressive strength is estimated with as few as 10 tests, whereas at least 15 tests are needed to estimate standard deviation. Changes in the mixture materials or proportions have a larger effect on the average strength level than on standard deviation. For these reasons, most control charts are based on averages of compressive strength. Monitoring overall standard deviation can provide insight into changes in the level of control, or variability of production or raw materials for the concrete supplier.

An estimate of variation due to testing, the within-batch standard deviation, can be obtained from the average range chart or by direct computation. As discussed in Chapter 4, the within-batch variation due to variation in raw materials and production, that is, the concrete supplier's or producer's

variability, can be determined from the overall standard deviation and the within-batch standard deviation.

The concrete supplier can directly track production process variability. When within-batch standard deviation is consistent, as it is in a well-run testing program, the supplier can track the overall standard deviation, which is easier. For constant within-batch variation, changes in overall standard deviation can indicate changes in raw materials or the concrete production and are, therefore, valuable to the concrete supplier.

Control charts should incorporate a moving standard deviation of at least 10 and, preferably, 15 tests. Computer-based spreadsheets make this type of control chart easy to implement, but the large number of tests required limits the chart's usefulness for rapidly identifying process changes.

6.6.2 Cumulative sum (CUSUM)—CUSUM is another industrial process control method that has been adapted to the concrete industry. It is able to rapidly identify changes in various measured properties of concrete in production. Quality control and problem resolution require that the cause for the change in the average strength level or in strength variability be identified. Early detection of changes in the average strength level is useful for identifying causes and taking steps to avoid future problems or reduce costs. This requires the ability to distinguish between random variations and variations from assignable causes.

A process that is under control will produce strength results that vary randomly around a mean value. The sum of these random differences from the mean will be zero. The CUSUM chart tracks the cumulative sum of the differences. When the differences do not add-up to zero, the CUSUM plot will veer off the usually horizontal trend, forming an angle indicating a change has occurred. It provides a detection method for small but real changes in average concrete strength or other measures of concrete performance. CUSUM charts help identify the size of these changes and when they began. CUSUM generally provides greater sensitivity in detecting small, systemic changes in average strength than basic control charts and detects them faster (Box et al. 2005; Day 2006; Dewar 1995).

There are limitations in using a CUSUM chart when data are highly variable, but the technique is only slightly more complicated than conventional strength analysis. CUSUM is easily implemented manually, by an electronic spreadsheet, or by a commercially available computer program. As with any technique, the conclusions reached using a CUSUM chart should be confirmed by additional analysis or investigation before making critical decisions.

CUSUM is usually used to monitor compressive strength, but it can be used to monitor any number of variables. Day (2006) reports successfully using CUSUM charts to monitor a variety of concrete properties. He also notes monitoring multiple-product CUSUM charts, which track a variety of concrete properties simultaneously, reduces the probability that a change will be missed, and makes it easier to identify the reason for the change.

CHAPTER 7—REFERENCES

7.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

301	Specifications for Structural Concrete
318	Building Code Requirements for Structural Concrete and Commentary

ASTM International

MNL 7A	Manual on Presentation of Data and Control Chart Analysis, 7th Edition
C31/C31M	Practice for Making and Curing Concrete Test Specimens in the Field
C39/C39M	Test Method for Compressive Strength of Cylindrical Concrete Specimens
C94/C94M	Specification for Ready-Mixed Concrete
C172/C172M	Practice for Sampling Freshly Mixed Concrete
C684	Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens
C802	Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials
C918/C918M	Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength
D3665	Standard Practice for Random Sampling of Construction Materials
E178	Standard Practice for Dealing with Outlying Observations

These publications may be obtained from the following organizations:

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48333-9094
www.concrete.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

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