

Simplified Version of the Recommended Practice for Evaluation of Strength Test Results of Concrete

Reported by ACI Committee 214

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The purpose of this report is to introduce the use of a simplified version of the statistical concepts as outlined in ACI 214 for the specification, control, and evaluation of the production of concrete. For a more elaborate discussion of the concepts, see the "Recommended Practice for the Evaluation of Strength Test Results of Concrete" (ACI 214).

Keywords: coefficient of variation; compression tests; compressive strength; concrete construction; concretes; cylinders; evaluation; quality control; sampling; standard deviation; statistical analysis; variations.

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INTRODUCTION

The strength test is widely used in specifying, controlling, and evaluating concrete quality. Quality concrete must be able to: 1) carry loads imposed upon it; 2) resist deterioration; and 3) be dimensionally stable.

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There are several tests that can be made with plastic and hardened concrete, but the strength test is generally accepted as a measure of the quality of concrete being placed on a project.

Although the strength test is not a direct measure of concrete durability or dimensional stability, it provides an indication of the water-cement ratio of the concrete. The water-cement ratio, in turn, directly influences the strength; durability; wear resistance; dimensional stability; and other desirable properties of concrete. The strength test is also used to measure the variability of concrete. By using statistical methods based on the strength test, realistic specifications can also be prepared.

VARIABILITY OF CONCRETE

Portland cement concrete is subject to numerous factors that affect its strength and other properties. These may include variations in the manufacture of portland cement; preparation of aggregates; batching, mixing, and curing of concrete; and finally in the preparation, handling, and testing of the cylinders. The major variables are listed in Table 1.

These variables must be considered when specifying, producing, or controlling the strength of concrete.

NORMAL DISTRIBUTION

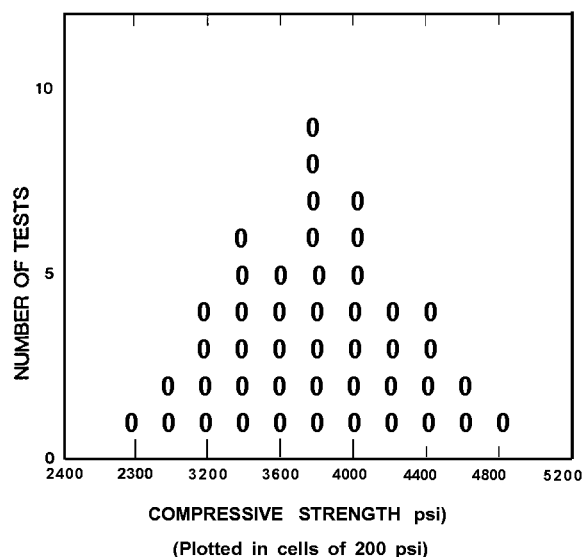
Test data from large concrete projects with many tests show a grouping around the average strength. A

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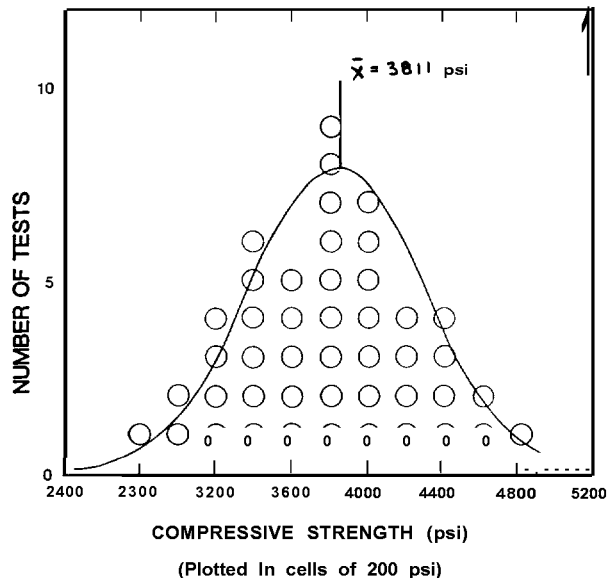
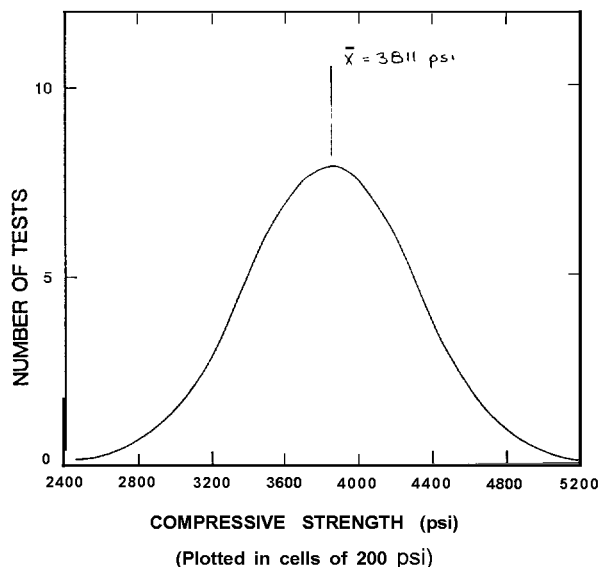
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Table 1 - Principal sources of variations in strength test results

Variations in properties of concrete	Discrepancies in testing methods
Changes in water-cement ratio Poor control of water Excessive variation of moisture in aggregate Retempering	Improper sampling procedures
Variations in water requirement Aggregate grading, absorption, particle shape Cement and admixture properties Air content Delivery time and temperature	Variations due to fabrication techniques Cylinder molding Poor quality molds Handling and curing of newly made cylinders
Variations in characteristics and proportions of ingredients Aggregates Cement Pozzolans Admixtures	Changes in curing Temperature variation Variable moisture Delays in bringing cylinders to the laboratory
Variations in batching, mixing, transporting, placing, and compaction Variations in temperature and curing	Poor testing procedures Care of cylinders, transportation and capping Improper placement in testing machine Testing machine platens out of specifications Incorrect speed of testing

*Fig. 1-Plot of 45 strength tests in cell width of 200 psi*

typical grouping is illustrated in Fig. 1. To produce Fig. 1, the strength tests are divided into cells. The cell width for Fig. 1 is 200 psi. For example, the seven tests that fall between 3900 and 4099 psi have been plotted in the cell listed as 4000 psi.* Similarly, all other strengths from the series of tests have been plotted in their respective cells. Since the grouping of tests on each side of the average is nearly symmetrical, it is called a normal distribution. It is possible to superimpose a normal

*Fig. 2-Strength tests plotted in Fig. 1 with normal distribution curve superimposed on data**Fig. 3-Normal distribution curve represents variation of individual test results plotted in Fig. 1 and 2*

distribution on the plot of individual strengths. As shown in Fig. 2, this curve smooths out the plot by reducing the effect of individual differences through averaging. The center of the curve is located at the average of all the tests. The area under the curve represents 100 percent of the tests. Fig. 3 shows the normal distribution curve used to represent all of the tests, rather than using the individual tests plotted in their respective cells. This curve will be used to represent all of the strength tests without the individual plotted tests throughout the remainder of this report. The example illustrated in this report is the compressive strength test, but the procedures outlined here may be used on test data from any test used to determine the strength of concrete.

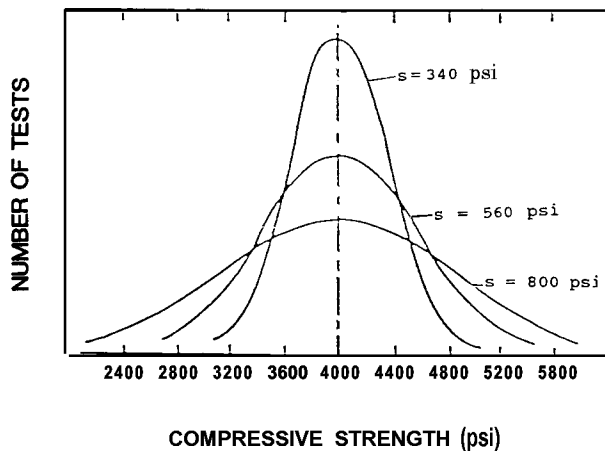


Fig. 4-Plot of three normal distribution curves with the same average. Curves illustrate low variability ($s = 340$ psi), medium variability ($s = 560$ psi), and high variability ($s = 800$ psi) (cell width is 400 psi)

The normal distribution curve can be either steep or flat, depending on the grouping of the individual tests on each side of the mean. Three normal distribution curves are illustrated in Fig. 4. The shape of the curve indicates the variability in the test data. The steep curve represents a series of strength tests with low variability. Strength tests are closely grouped around the average. The flat curve represents a series of tests with high variability. Whatever the shape of the normal distribution curve, it reveals significant information about the test data it represents. The top of the curve is located at the average of all the tests.

STATISTICAL EVALUATION

Concrete samples should be obtained by randomly sampling batches of a given class of concrete used on the project. Different portions of a structure may require different concrete mix designs. Each mix is often called a class of concrete. Each class of concrete usually has its own proportions, and should be sampled and evaluated separately. If the number of randomly obtained samples of a given class of concrete is large enough, the strength test results can be statistically evaluated. The statistical values calculated from the test data, which are useful in the evaluation, follow.

Average $\bar{X}$

The average (often called the mean) is the approximate middle value between extremes. The average can be calculated using the following formula

$$\bar{X} = \frac{X_1 + X_2 + X_3 + \dots + X_n}{n} \quad (1)$$

Where $\bar{X}$ is the average strength; $X_1, X_2, X_3, \dots, X_n$ are individual strength tests; and n is the total number of tests.

The formula may be represented by

$$\bar{X} = \frac{\Sigma X_i}{n} \quad (2)$$

Where X_i is each strength test from $i = 1$ to $i = n$, and ΣX_i represents the sum of all the tests.

More than one concrete cylinder is usually made from the same sample of concrete. A strength test is defined as the average strength of all cylinders made from the same sample of concrete cured under the same conditions and tested at the same age. Variations in strength between cylinders cast from the same sample may be attributed to variability of the concrete within the sample, cylinder molding, care, transportation, and testing procedures. If testing procedures are uniform, variations observed between strength tests can be attributed to variations in materials, batching, mixing, transportation, and curing.

Standard deviation s

The standard deviation is a measure of the variability or scatter of test values around the average. The higher the standard deviation, the greater the variability. The standard deviation can be calculated using one of the following equations

$$s = \sqrt{\frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n - 1}} \quad (3)$$

where

s = standard deviation

$X_1, X_2, \dots, X_n$ = individual strength tests

n = total number of tests

$\bar{X}$ = average strength of all the tests

The preceding formula may be represented by

$$s = \sqrt{\frac{\Sigma(X_i - \bar{X})^2}{n - 1}} \quad (4)$$

where X_i is each strength test from $i = 1$ to $i = n$, and $\bar{X}$ is the average strength of all the tests.

Some calculators compute the average and standard deviation in the same operation. If a calculator with statistical functions is not available, the standard deviation may be determined from the following formula using a simple four-function calculator

$$s = \sqrt{\frac{\Sigma(X_i^2) - \frac{(\Sigma X_i)^2}{n}}{n - 1}} \quad (5)$$

where $\Sigma(X_i)^2$ is the sum of the square of each test, and $(\Sigma X_i)^2$ is the sum of all the tests squared.