

SP37-1

WHAT IS ACI STANDARD 214-65?

BY
EDWARD A. ABDUN-NUR

Synopsis: Recommended Practice for Evaluation of Compression Test Results of Field Concrete, ACI 214-65, is likened to a tool kit and the usefulness of each important tool in the kit is discussed. The variability concept is stressed and its significance as far as "minimum" requirements is discussed. Sources of variation are touched upon, and the applicable mathematical representation of variability from the practical standpoint is explained. The advantages of lowered variability from the economic standpoint is brought out.

It is shown that ACI 214-65 provides the tools to calculate variability, shows the use of simple control charts to help in control efforts, and indicates how to evaluate these results. In doing this it helps "stretch" society's resources, thus reducing potential pollution--most valuable aims in this day and age.

Keywords: coefficient of variation; compressive strength; concretes; control charts; moving average; quality control; standard deviation; standards; statistical analysis; variations.

realism in the
application of

ACI standard 214-65

ACI member Edward A. Abdun-Nur is a consulting engineer who has been a consultant on many outstanding projects in the U. S. and abroad, including the Illinois Toll Highway, State Department AID projects, Armco Project "600", Sunshine Skyway across Tampa Bay, a specifications study for the Bureau of Public Roads, and an action plan for the Chicago Department of Public Works.

INTRODUCTION

At this 25th Anniversary of ACI Committee 214, and the 15th Anniversary of the first edition of the RECOMMENDED PRACTICE FOR THE EVALUATION OF COMPRESSION TEST RESULTS OF FIELD CONCRETE (which formed the basis for this standard), it is appropriate to pause and ask the questions:

1. WHAT IS ACI STANDARD 214-65?
2. WHY IS IT WORTHY OF A CONVENTION SYMPOSIUM RELATING TO ITS APPLICATION?

The answer to the first question, from the point of view of this author, is that it is a most useful tool kit without which the concrete engineer could hardly carry out his work properly. The answer to the second question will, it is hoped, develop as the characteristics of this tool kit are discussed in this paper.

The usefulness of this standard is enhanced by the simple language in which it is couched thus making it intelligible to anyone who can read--and the fact that the tools comprising this kit can be used for the evaluation of other data in addition to "compression Test Results," such as compression tests at any age or accelerated methods tests, air content, slump, cement content, tensile strength, flexural beam strength, splitting tensile strength, thickness of pavement, dimensional variations, and many other quantitative sets of observations made by the concrete engineer. It is true that the evaluation parameters will be different in each one of these cases, but the basic mathematical and probability principles will be identical.

VARIABILITY CONCEPT

General

Probably the tool with the widest application in this kit

is the variability concept. Back in 1955 when ACI Committee 214 issued its first report, the majority of engineers thought that concrete in their structures was uniform and met the minimum strength specifications then currently in vogue, and that sampling and testing had detected all the weak concrete and rejected it, so that none of it would have found its way into their carefully calculated and designed structural members. But how about the batches that were not tested, which constituted probably 98 percent of the concrete in the structure? Research data shows that under current construction practices and design procedures, a proportion of the concrete in any structure, serving its purpose adequately over the years, is bound to be below the minimum nominal design strength called for in the specifications, and that the balance of the strength even though equal to or above this "magic minimum" still shows marked variability that affects future maintenance and influences the overall performance of the concrete in the structure (1).

This fresh concept spelled heresy to most engineers, and knocked the props out from under their feelings of security and confidence, even though this concept was not new, having been a useful tool in many of both the physical and even the social sciences--this author had used it in a study on mental fatigue as far back as 1932 (2).

Although this variability concept created a shock in the profession comparable to an atomic explosion, it has brought realism into concrete and is well on its way as a strong factor in releasing producers and contractors from their classical "master-servant" relationship with the owner. Yet even now, 15 years later, there are still unrealistic attitudes of insistence on minimum requirements and on impossible and non-existent "uniformity" in many new standards, codes, and specifications. With 15 years of exposure to this concept, it is high time that we open our minds to the facts of life and come to use this variability concept too and its accompanying laws of probability to interject realism into our thinking, our specifications and our market place buying and contractual relationships in the concrete industry.

Sources of Variation

The second tool in the ACI 214-65 kit, is a detailing of the principal sources of variation in the concrete field--Table 1 of the Standard (next page). This list of possible variations may be simplified in what is known as the 4M of variability: material, man, machine and measuring method. Even though

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TABLE 1—PRINCIPAL SOURCES OF STRENGTH VARIATION

Variations in the properties of concrete	Discrepancies in testing methods
Changes in water-cement ratio: Poor control of water content Excessive variation of moisture in aggregate	Inconsistent sampling procedures
Variations in water requirement: Aggregate grading Nonuniform materials	Nonuniform fabrication techniques: Amount of compaction Excessive handling of sample Care of fresh cylinders
Variations in characteristics and proportions of ingredients: Aggregates Cement Pozzolans Admixtures	Change in curing: Temperature variation Variable moisture
Variations in transporting, placing, and compaction	Poor testing procedures: Cylinder capping Compression tests
Variations in temperature and curing	

the overall variability introduced by the 4M may be reduced, there is a limit where the cost (economic, human, environmental, etc.) of further reduction exceeds the benefits, and thus when further reduction becomes impractical or undesirable.

Mathematical Representation of Variability

The next powerful tool in the ACI 214 tool kit, is the engineering assumption that variability in concrete may be adequately represented for practical purposes by the probabilities of the normal probability curve--Figure 1 of the Standard:

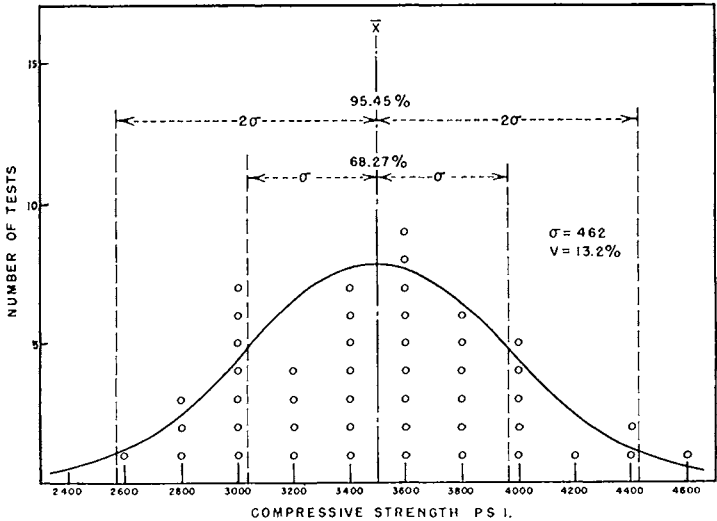


Fig. 1—Normal frequency distribution of strength data from 46 tests

This bell-shaped curve is such an important tool to the concrete engineer, because it simplifies the analysis of data and provides a means of calculating the probabilities with which any event is likely to occur, from a relatively small number of observations. The curve is symmetrical about the average or mean, and its lateral extent, or scatter, or dispersion, is defined by the standard deviation, which is a means of expressing mathematically the spread of the universe (total concrete strengths in a project), around this mean. Even though the curve is asymptotic to the X-axis, for practical purposes the whole universe is assumed to be three standard deviations either side of the mean. This again simplifies working with this kind of distribution, as the curve can be delineated or defined easily, simply by calculating the mean and the standard deviation--once these are known the other characteristics can be found in tables available in many books and handbooks.

The calculation of the mean or average is simple and is very common knowledge, yet the writers of the Standard, in order to make this kit complete, have given us Formula 1 as the next tool to help calculate the average or mean:

Average, $\bar{X}$ — The average strength of all cylinders.

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

Where $X_1, X_2, X_3 \dots X_n$ are the strength results of individual specimens and n is the total number of specimens tested.

The next tool provided for the user of this Standard is the calculating of the standard deviation or measure of variability or dispersion around the mean or average. Here, the writers of the Standard have given us a multiheaded tool like a set of socket wrenches, so that the user can select the one that suits his purpose best. These are expressed in Formulas 2, 3, 3a, and 4:

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Standard deviation, σ —The most generally recognized measure of dispersion is the root-mean-square deviation of the strengths from their average. Referring to Fig. 1 the standard deviation is the radius of gyration of the area under the theoretical probability curve about the center. The standard deviation is found by extracting the square root of the average of the squares of deviations of individual strengths from their average.*

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

For ease of computation, when a calculating machine is available, standard deviation can be obtained by dividing the sum of the squares of individual strengths by the numbers of cylinders, subtracting the square of their average, and extracting the square root.

$$\sigma = \sqrt{\frac{X_1^2 + X_2^2 + X_3^2 + \dots + X_n^2}{n} - \bar{X}^2} \quad (3)$$

or rearranged to bring the fraction from under the square root sign:

$$\sigma = \frac{1}{n} \sqrt{n(X_1^2 + X_2^2 + X_3^2 + \dots + X_n^2) - (X_1 + X_2 + X_3 + \dots + X_n)^2} \quad (3a)$$

Coefficient of variation, V —The standard deviation expressed as a percentage of the average strength is called the coefficient of variation.

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

This function makes it possible to express the degree of dispersion on a percentage basis rather than the absolute. Table 2 shows the coefficients of variation that can be expected on controlled projects. The ratings of control are based on experience from a large number of projects and are presented as a general guide in evaluation of concrete control.

Formula 4, for the calculation of the coefficient of variation, is simply an expression of the standard deviation as a percentage of the mean, which, because it is dimensionless, is an advantageous form in many applications. For good reliability, the standard deviation or coefficient of variation should be calculated from a large number of observations, say thirty or more. But when such data are not available, the standard deviation may be calculated with another socket of this fine tool, and that is from the average range of several sets of strength tests of fewer observations (no less than 10 sets), and this, the Standard provides in Formulas 5 and 6 and Table 3.

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$$\sigma_1 = \frac{1}{d_1} \bar{R} \dots \dots \dots (5)$$

$$V_1 = \frac{\sigma_1}{\bar{X}} \times 100 \dots \dots \dots (6)$$

where

σ_1 = within-test standard deviation

$\frac{1}{d_1}$ = a constant depending upon the number of cylinders in each group (Table 3)

$\bar{R}$ = average range of groups of companion cylinders

V_1 = within-test coefficient of variation

$\bar{X}$ = average strength

TABLE 3—FACTORS FOR COMPUTING
WITHIN-TEST STANDARD DEVIATION*

Number of specimens	d_1	$1/d_1$
2	1.128	0.8865
3	1.693	0.5907
4	2.030	0.4857
5	2.326	0.4299
6	2.531	0.3946
7	2.704	0.3698
8	2.817	0.3512
9	2.970	0.3367
10	3.078	0.3249

*From Table B2, "Manual on Quality Control of
Materials," *ASTM Special Technical Publication No.*
15-C.

APPLICATION TOOLS

General

The foregoing section presents and discusses what might be called the basic or fundamental tools in this standard. In this section, the tools that help in the application of the standard will be discussed.

Realism and Variability

Acceptance of variability as a fact of life in concrete work makes it impractical and unrealistic to specify minimum strengths. The reason for this is that the cost under such requirement becomes exorbitant. Studies of existing structures serving their purposes adequately indicate no need for such a

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restriction, as these studies indicate that there is always some small proportion of tests that fall below the nominal design strength without detrimental results. However, the percentage of the total concrete in a structure falling below a nominal design strength becomes an important factor in arriving at many decisions in prescribing or specifying the work, and in evaluating the results. This is really the meat of this Standard.

There are several reasons for satisfactory performance, in spite of a small percentage below nominal design strength:

1. The relationship between cylinder strengths and strengths of concrete in structural members is tenuous rather than direct.
2. The gain in strength with time tends to compensate for such low strengths.
3. Concrete batches get intermixed in the forms and average out strengths.
4. Stresses and strains are generally redistributed in a structure.
5. The combination of prevailing designs and construction practices has worked out satisfactorily under these circumstances.

The most effective tool in this kit is nothing but a simple combination of the application of such realism to various possible normal distribution curves representing various degrees of variability or dispersion. This is shown in Figure 2 (next page).

Here realism is shown in that the specified theoretical design strength level, f_c^d , is drawn above the lower end of the universe, thus giving cognisance to the fact that some percentage of the universe may fall below the f_c^d level without reducing the acceptable quality of the structure. The figure shows three normal distribution curves, representing three universes of the innumerable number of possible universes that can fulfill this particular requirement. It is easily seen that the higher the variability or dispersion from the mean, the higher the average strength required to fulfill the limitation that a prescribed limited percentage of the universe may fall below f_c^d . Taking the numbers shown on this figure, it is found that the lowest variability shown requires an average of 3441 psi, while the highest or widest variability requires an average of 4034 psi,

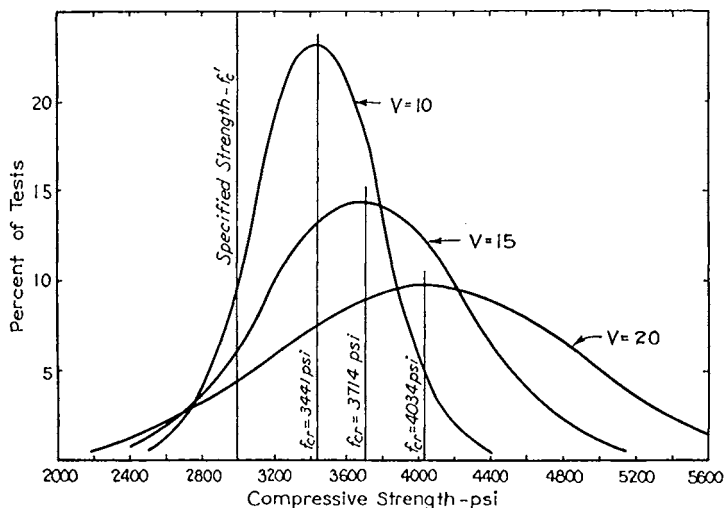


Fig. 2—Normal frequency curves for coefficients of variation of 10, 15, and 20 percent

Required average strength f_{cr} based on a probability of one in ten that a test will fall below a specified strength f_c' of 3000 psi

to meet the requirement. The difference represents 75¢ to \$1 in cement per cubic yard of concrete, roughly 15 to 20 percent of the total cement cost.

Another way to look at this is that it represents this much waste of society's cement resources, and if it could be saved, it represents unnecessary additional costs and environmental pollution. But what makes this tool so effective is that it represents a most powerful incentive for the producer or contractor to reduce his variability by better control of his process, which results in other side benefits of increased efficiency that reduces his costs further and produces more desirable concrete characteristics (3). Figure 3 (next page) conveys essentially the same message, but to this author not in as striking a manner.

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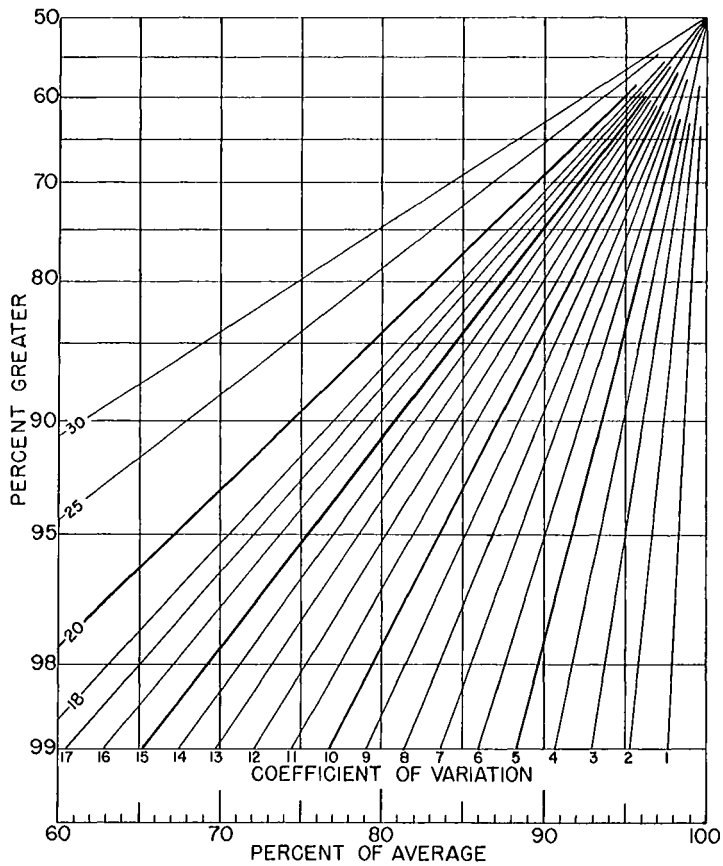


Fig. 3—Cumulative distribution curves for different coefficients of variation

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The above tool, illustrated in Figure 2, is the means for producing modern, realistic, and economical specifications, that provide incentives for more homogeneous concrete, which in turn reduces maintenance, since maintenance rises in direct proportion with variability.

The next tool in the kit is the method of calculating the averages required such as those shown in Figure 2. This tool is provided in Formula 7, which utilizes the factors shown in Table 4.

$$f_m = \frac{f'_c}{(1 - tV)} \dots \dots \dots (7)^*$$

where

f_m = required average strength

f'_c = design strength specified

t = a constant depending upon the proportion of tests that may fall below f'_c and the number of samples used to establish V (Table 4)

V = forecasted value of the coefficient of variation expressed as a fraction

*The required average modulus of rupture for beams can be obtained using Eq. (7) by substituting the specified modulus of rupture (SMR) for f'_c and using an appropriate coefficient of variation for flexure tests.

TABLE 4—VALUES OF t^*

No. of samples minus 1†	Percentage of tests falling within the limits $\bar{X} \pm t\sigma$							
	60	70	80	90	95	98	99	
	Chances of falling below lower limit							
	2.5 in 10	2 in 10	1.5 in 10	1 in 10	1 in 20	1 in 40	1 in 100	1 in 200
1	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657
2	0.816	1.001	1.386	1.886	2.920	4.303	9.955	19.925
3	0.705	0.978	1.250	1.638	2.353	3.182	4.541	6.941
4	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604
5	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032
6	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707
7	0.711	0.896	1.119	1.415	1.895	2.365	2.908	3.400
8	0.706	0.890	1.108	1.397	1.860	2.306	2.805	3.355
9	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250
10	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169
15	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947
20	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845
25	0.684	0.856	1.058	1.310	1.708	2.060	2.485	2.787
30	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750
∞	0.674	0.842	1.036	1.282	1.645	1.900	2.326	2.576

*Values of t extracted from table originally produced by Fisher and Yates, "Statistical Tables for Biological Agriculture and Medical Research."

†Degrees of freedom.

Other values of t for $n - 1 = \infty$

Percentage within $\bar{X} \pm t\sigma$	Chances of falling below lower limit	
40	3 in 10	0.624
68.27	1 in 3	1.000
95.45	1 in 44	2.000
99.73	1 in 741	3.000

Values of t increase for small samples due to the unreliability of small samples to establish a true estimate of σ . The advantage of establishing V in Eq. (7) from a large number of tests becomes apparent in the reduction of t and f_m .

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This is very simple to apply once the percentage below the theoretical or nominal design strength is decided upon and the variability is determined or assumed. If one is not mathematically inclined or does not wish to take the time to go through the mathematics in the formula, the Standard furnishes another tool in the form of Figure 5, where one can look up the average strength to aim at for given variability and proportion below f'_c .

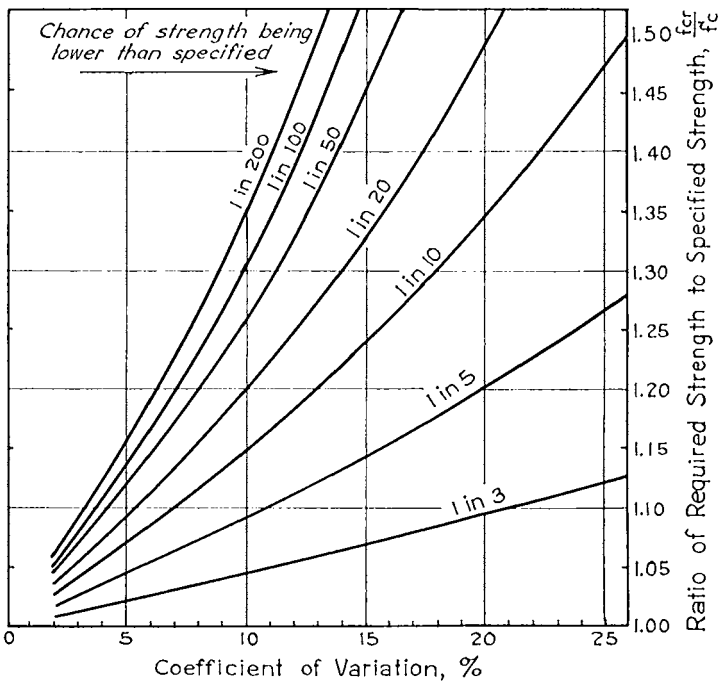


Fig. 5—Ratio of required average strength f_{rr} to specified strength f'_c for various coefficients of variation and chances of falling below specified strength

This chart is based on the distribution of the normal variate while Eq. (7) is based on the distribution of "Student's t ." For a small number of tests Eq. (7) requires a higher, hence a more reliable value for f_{rr} .

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The last tool in this application group of tools is Table 5.

TABLE 5—GUIDE FOR CONCRETE STRENGTH SPECIFICATIONS

Class 1 Concrete: Ultimate strength design structural concrete, with f_{cr} selected to permit one test in ten to fall below f'_c .
 Class 2 Concrete: Working stress design structural concrete—pavements, dams, irrigation works—with f_{cr} selected to permit two tests in ten to fall below f'_c .

Number of consecutive tests to be averaged	Probability of average strength falling below f'_c , percent		Probable minimum average strength if $V = 15$ percent	
	Class 1 concrete	Class 2 concrete	Class 1 concrete	Class 2 concrete
1	10.0	20.0	$0.86f'_c$	$0.79f'_c$
2	3.5	11.7	$0.97f'_c$	$0.90f'_c$
3	1.3	7.2	$1.02f'_c$	$0.94f'_c$
4	0.5	4.6	$1.05f'_c$	$0.97f'_c$
5	0.2	3.0	$1.07f'_c$	$0.99f'_c$
6	0.1	2.0	$1.08f'_c$	$1.00f'_c$

Tabulated values represent the strength level below which the average of the indicated number of tests should be expected to fall only 2 percent of the time.

This table gives the probability of an average strength of any number of consecutive tests falling below f'_c , and the probable minimum average strength for the same number of consecutive tests when the coefficient of variation is equal to 15 percent. These probabilities are given for two classes of concrete and are very useful in setting up specification and acceptance limits.

EVALUATION TOOLS

With the basic tools and application tools in this Standard's tool kit described and discussed in the last two sections, there are only left the evaluation tools.

The first tool in the evaluation group is the control chart, shown in Figure 4 (next page). This is a very simple control chart, but such a chart is an indispensable tool to enable the producer or contractor to evaluate his process control and is of great help for the owner who is monitoring an operation for acceptance and needs to evaluate the concrete for acceptance or

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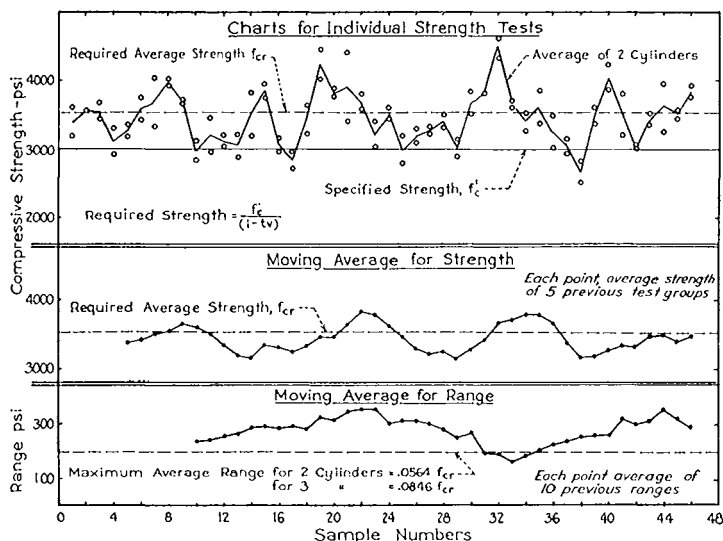


Fig. 4—Quality-control charts for concrete

rejection. The chart shown in this figure is divided into three sections. In the top section, the individual cylinder strengths or their averages are plotted against consecutive sample or test numbers to indicate graphically the overall variations in the process and in sampling and testing. If the process is under control and the strengths come close to the outer limits designated for the work, or if several test results remain together on one side of the average or mean central trend line, then it is an indication that some assignable cause is interfering with the process and the cause needs to be investigated and corrected in order to re-establish the controlled process variability before it is too late and the process gets out of control thus leading to rejection.

Inasmuch as these charts portray test results that are obtained after the fact, with the concrete in question already in the structure (even for charts based on accelerated 24-hour strengths), it is, therefore, advisable to add to the chart warning and action limits, to assure one that concrete can be accepted without hesitancy and to provide lead time for correcting assignable causes before the process gets out of control. This makes the chart more sensitive and useful. But it must be

remembered that unnecessary interference with the process is most undesirable. The chart should be designed in each case to interfere with the process as little as possible and yet to be sensitive enough to raise a warning sign when action is needed before it is too late.

With such a balanced chart, once the process is under control, one need not worry about it getting out of control as long as the warning and action signs are heeded. Under such circumstances acceptance should be automatic, and the chart becomes meaningful to assure those concerned that the process continues under control and also to serve for future record.

The middle section of the chart shows the changes in the averages of successive sets of 5 tests (see discussion of Table 5). This tends to smooth out the variations and indicates trends, or it can be used for acceptance purposes where the specifications are couched in terms of an average of a certain number of successive tests (Table 5 again).

The third section of the chart shows a plot of the moving average of ranges of successive 10 sets of cylinders. This provides a check on the variability of sampling and testing procedures. If this indicates sloppy testing, then it must be corrected rather than penalize the producer or contractor. Many problems investigated by the author have been found to be due to improper sampling or testing and not the fault of the process being studied.

A tool in the kit to evaluate the adequacy of testing is given in Formula 8:

$$\bar{R}_m = f_{rr} V_1 d_s \dots \dots \dots (8)$$

The within-test coefficient of variation V_1 should not be greater than 5 percent for good control (Table 2), and the estimate of the corresponding average range will be:

$$\begin{aligned} \bar{R}_m &= (0.05 \times 1.128) f_{rr} = 0.05640 f_{rr} \text{ for groups of two companion cylinders} \\ \bar{R}_m &= (0.05 \times 1.693) f_{rr} = 0.08465 f_{rr} \text{ for groups of three companion cylinders} \\ \bar{R}_m &\text{ becomes the maximum for average range in control chart (c) of Fig. 4.} \end{aligned}$$

This ties in with the third section of the control chart in Figure 4.

And finally the last tool in the evaluating group is found in Table 2 (next page):

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TABLE 2—STANDARDS OF CONCRETE CONTROL

Class of operation	Coefficients of variation for different control standards			
	Excellent	Good	Fair	Poor
Over-all variations:				
General construction	Below 10.0	10.0 to 13.0	15.0 to 20.0	Above 20.0
Laboratory control	Below 5.0	5.0 to 7.0	7.0 to 10.0	Above 10.0
Within-test variations:				
Field control	Below 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory control	Below 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

Note: These standards represent the average for 28-day cylinders computed from a large number of tests. Different values for other than average concretes can be expected.

This gives an idea of the levels of variability for the combination of currently used design and construction procedures. It gives an overall judgment of the degree of control attained.

And finally, a word of caution is in order. For any of the tools discussed in all these sections to produce valid results, one has to have random sampling in order to justify the assumption that variations are randomly distributed. Biased sampling can provide very erroneous results and lead to misleading conclusions that may lull one into a sense of false security, and in some cases even produce failures.

DISCUSSION AND CONCLUSIONS

This tool kit, like any other tool in any facet of life, is subject to abuse, misuse, and wrong use. The advantages from its realistic use, however, outweigh by far those from any other available tools, which also fall into the same trap of misuse or wrong use at one time or another. It is hoped that the descriptions and discussion of the various tools in the kit have made it clear to everyone by now that there are worthwhile reasons why a symposium should be devoted to the realistic application of these tools--this answers the second question raised in the introduction.

As for conclusions, it has been shown that this tool kit comprising ACI Standard 214-65:

1. Provides indispensable help in the realistic approach to concrete technology.
2. Helps the designer in understanding the realistic variability of the material he is dealing with and

how this fits in his overall quality.

3. Permits the designing of realistic specifications, with proper tolerances to take into consideration the unavoidable variations, and at the same time allows the introduction of incentives that motivate the producer or contractor to control his process and reduce its variability, as it improves his efficiency and increases his profit.
4. Provides a means for the producer to evaluate his process control.
5. Helps the owner evaluate the quality for acceptance.
6. Through reduced variability, results in reduced maintenance.
7. Thus it stretches society's resources and reduces potential pollution--most valuable aims in this day and age.

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ACI 214 RECOMMENDED PRACTICE -- WHAT PRACTICES DOES IT RECOMMEND AND WHAT DOES IT MEAN?

BY
HOWARD T. ARNI

Synopsis:

ACI Standard 214 is a Recommended Practice for Evaluation of Compression Test Results of Field Concrete. The primary function of such tests, as stated in the document, is "to insure production of uniform concrete of desired strength and quality." The following represent some of the problems connected with this field of testing:

- (1) The quality of concrete in a structure is assumed in the design of the structure to have a certain strength. However, the actual strength of the concrete in the structure can never be known directly, but must be inferred from companion specimens cast from the batches of concrete that went into the structure.
- (2) The strength of the companion specimens is not obtainable until some-time after the concrete in the structure has already hardened into place. This leads to problems in deciding what course of action to follow if the test specimens seem to show evidence of a significant degree of probability that the concrete in the structure has not reached the desired strength.
- (3) Assessment of the level of strength indicated by the companion specimens is complicated by the fact that the strengths of individual test specimens vary widely both because of actual differences in strength in the portions of the concrete mass from which the specimens came, and because of a whole complex of factors connected with the sampling, molding, curing, and testing of specimens.

The only way that complicated evaluation situations like this can be dealt with rationally is by the judicious use of statistical principles. The purpose of ACI 214 and of this symposium is to provide guidance in the use and understanding of the statistical concepts involved for the benefit of technical people who are in the position of having to evaluate strength tests. Emphasis is on understanding of the basic ideas in ACI 214 rather than on the mechanics of computation.

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Concepts discussed include the following:

- (1) What is a "normal distribution" and why do groups of test results so often follow such a distribution curve?
- (2) Single test results or a small group are of interest not just for the specific values obtained but as representatives of some larger group, and for what can and cannot be inferred about the larger group from the small number of tests taken.
- (3) The value of accumulating information over a period of time rather than evaluating results as isolated pieces of evidence and of following trends of results as they are obtained by means of various techniques.
- (4) The reasons for aiming at a certain average for the strength tests and allowing a certain percentage of the test strengths to fall below the so-called design strength.

Keywords: average; coefficient of variation; compression tests; compressive strength; concretes; distribution functions; moving average; quality control; range (extremes); standard deviation; standards; statistical analysis; statistical distributions; statistical samples.

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ACI Member, Howard T. Arni is a Highway Research Engineer in the Materials Division, Federal Highway Administration. He joined the National Bureau of Standards in 1942 and later, as a Materials Engineer, served at that agency until transferring to his present position in 1969. He is a member of ACI Committee 214 and is active in the Highway Research Board and in ASTM C09.

INTRODUCTION

The planning for this Symposium arose out of a concern on the part of Committee ACI 214 and of other interested parties that many people who are faced with the problem of Evaluation of Compression Test Results of Field Concrete are not making adequate or "realistic" use of ACI Standard 214-65, and thus that potential large-scale benefits to the entire concrete industry are not presently being realized. Other authors in this Symposium present examples in which ACI 214 has been properly used and illustrations of the benefits that resulted. The purpose of this paper is, by an examination of some features of the document itself, to explore the reasons why it is not being used properly, and to deal with some of the objections and prejudices that are responsible for preventing its use.

Most of the obstacles to effective use of the techniques in ACI 214 arise from two main systems of causes: (1) the peculiarities of concrete tests themselves, ignorance about the characteristics of the results of tests (especially their variability), and what these factors mean in relation to making judgments about the strength of concrete in structures, and (2) the reluctance that many practical concrete people display toward statistical terms and the use of statistical procedures. A major portion of this paper is devoted to an effort to convince such people that the statistical procedures described in ACI 214 are sound and are really not complicated or difficult to understand and apply, and it is hoped that the result of the entire Symposium will be to convince people who are not now using ACI 214 effectively, that the benefits that accrue from its realistic use are worth the effort.

CHARACTERISTICS OF CONCRETE STRENGTH MEASUREMENTS

Many of the fundamental problems connected with evaluation of concrete strengths seem self-evident or have already been discussed many times in the literature. An excellent example of the latter is Mr. Abdun-Nur's paper, "How Good is Good Enough?" which appeared in the January 1962 ACI Journal and is reprinted as Appendix B in this volume (1), and I strongly recommend rereading of that paper to anyone interested in the subject. Nevertheless, the tendency to act as though the unknown limitations

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connected with evaluations of concrete strength do not exist persists and still needs to be dealt with.

Concrete in a structure is assumed in the design of the structure to have a certain strength. However, the actual strength of the concrete in the structure can never be known directly, but must be inferred from companion specimens cast from the batches of concrete that went into the structure. It is universal practice to refer to the "strength" of concrete as though it really meant the strength at a given age in the structure, and even ACI 214 refers to "Variations in Strength" (2) when what is really meant is variations in the numbers obtained when cylinders cast from the same batches of concrete that went into the structure are subjected to certain arbitrary procedures of curing and handling and are broken in a testing machine.

Thus, a whole series of questions revolves around the single question, "What information do these numbers give us about the actual load-supporting capabilities of the concrete in the structure, and how reliable is that information?" The basic assumptions upon which evaluations of strength tests are based have validity insofar as the materials, proportions, and processes that go into a certain batch of concrete can be assumed to be capable of developing a definite degree of strength when allowed to set and harden under a given set of conditions, and the fact that they do have validity is attested by the large number of structures designed and built under these assumptions that are standing and are successfully fulfilling the functions for which they were built. The individual numbers obtained by testing, however, differ from the fundamental characteristic strength due to a host of superimposed influences having to do with characteristics of the particular configuration of concrete being considered, age, curing conditions, handling, environment, etc., and these influences differ not only between the companion cylinders and the structure, but also between cylinders from different batches made with the same materials and procedures, and even between cylinders from the same batch.

A second problem connected with so-called strength testing is that whatever indication of the strength in the structure test specimens provide only becomes available some time after the concrete in the structure has already hardened into place, usually 28 days. This leads to problems in deciding what course of action to follow if the test specimens seem to show evidence of a significant degree of probability that the concrete in the structure has not reached the desired strength. This does not directly affect our discussion of the techniques involved in dealing with the numbers, but does eventually color our thinking about the meaning of the results.

The only way that complicated evaluation situations involving the kind of data we are talking about can be dealt with rationally is by the judicious use of statistical principles. ACI 214 is an attempt to provide the necessary statistical tools and guidance in their use and understanding for

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the benefit of technical people who are in the position of having to evaluate strength tests. We hope the ensuing discussion in this and other papers in this volume will be of help.

VARIATIONS IN STRENGTH

The outstanding characteristic of the numbers derived from the testing of cylinders that underlies the whole problem of evaluation of strength is that the numbers vary even though they arise from tests on specimens of concrete that presumably ought to have the same strength. The problems about these variations that plague technical people and are responsible for much of the misuse or lack of use of ACI 214 are mainly related to: (1) insufficient understanding of the inevitability of, reasons for, and magnitude of the variations in the individual results, and (2) insufficient understanding of the characteristics of the distribution of the measurements.

Table 1 of ACI 214, (see Appendix A) under the headings "Variations in the properties of concrete" and "Discrepancies in testing methods," lists a number of "Principal Sources of Strength Variations" such as the following: poor control of water content, nonuniform materials, inconsistent sampling procedures, excessive handling of sample, etc. This table gives the impression to some that the variations are mainly caused by bad practices, which could be eliminated, thus removing the variation in the results, and this is the way many people usually view the variations in individual results. The fact is, however, that some variation is inherent in the process, and control of all the influences listed in Table 1 plus others that might be added, to the maximum degree of precision possible, reduces the variability, but can never eliminate it entirely. The implication of this fact is that the desired information about the strength represented by the results must be derived from the pattern of the results, or what the statisticians call their frequency distribution.

The next stumbling block is the form of the distribution taken by the variable results. ACI 214 states (3), "The strength of concrete test specimens on controlled projects can be assumed to fall into some pattern of the normal frequency distribution curve." The stumbling block here, I believe, is not so much misunderstanding of the normal distribution itself, but disbelief in its applicability. I cannot document this out of the published literature, but from contacts I have had I am convinced that many practical people have a hard time really believing deep down that a function such as:

$$Y = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[-\frac{(X - \mu)^2}{2\sigma^2} \right]$$

has anything to do with their data.

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The point that is often overlooked here is that the normal distribution does not describe measurements themselves. It describes the frequency with which groups of individual measurements of given magnitude occur, when repeated tests are made. Thus the same kind of bell-shaped curve can apply to the frequency distribution of widely varying types of measurements, from the location of charges in an atom to measurements of the speed of light.

In a pamphlet on the Theory of Errors and Their Treatment, the following quotation from another reference is given, "Everybody believes in the exponential law of errors; the experimenters because they think it can be proven by mathematics, and the mathematicians because they believe it has been established by observation." (4) So far as strength tests of concrete specimens are concerned, experience supports the belief that the normal frequency distribution describes the frequency distribution of strength tests sufficiently well that realistic and reasonably reliable conclusions concerning the strength of concrete can be derived on the basis of the assumption that populations of strength test results, within limits, are normally distributed (See Figure 1 and Appendix Tables A3, A4, and A5 in ACI 214).

It may be well here to take a moment to illustrate (without going into a mathematical proof, which would be quite beyond the scope of this article) how a bell-shaped distribution resembling the normal curve can arise from combinations of individual deviations such as those that occur in concrete strength testing. We begin by assuming, as mentioned earlier, that a given set of concrete-making materials and of rules for combining, handling, and testing specimens produced from those materials and under those conditions, can be expected to produce test measurements of a certain characteristic magnitude, which we will call the average strength, without for the moment defining what is meant by average. Thus any given measurement on a cylinder has a value which is fundamentally a measurement of the average strength, but departs from that average due to certain disturbing influences. For instance, temperature at the time of mixing, during curing, at the time of testing, etc., may cause an individual measurement to be higher or lower than the average. Slight variations in water/cement ratio, even under the best of control, may cause increase or decrease in strength in a given case, and so on through a whole host of items, each of which can add a small positive or negative increment to the fundamental strength value.

Figure 2 illustrates how a hypothetical measured value is built up by addition to a so-called true or average value of a number of deviations due to different causes. Here ten different deviations were selected from a table of random numbers. Each of the deviations could take any value from -10 to +10 with equal probability. The ten individual deviations are shown on the left. Deviation No. 1, which might be due to a variation in temperature, for example, is -4.6. No. 2, due to some other cause, is -9.7. On the right is shown the result of the cumulative addition of these deviations to a basic measurement of 100. (Each bar in the right-hand diagram represents

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the cumulative total of all the individual deviations up to that point). The final result with all ten deviations added is a measured value of 104.4.

This process can be repeated indefinitely, of course, and Figure 3 shows a histogram of 42 hypothetical measurements built up in the same way, each measurement being the result of ten hypothetical deviations added to a basic measurement of 100. The interesting thing to note is how close an approximation to the normal distribution results from the accumulation of deviations which are not in themselves normally distributed. The average of the 42 measurements is 101.4, very close to the "true" value of 100 on which all the deviations were superimposed. Also 71 percent of the measurements are between 80 and 120, a range of slightly more than plus or minus one standard deviation, which, for a normal distribution, includes approximately two-thirds of the measurements, and 95 percent are between 60 and 140, which is approximately plus or minus two standard deviations.

Another argument that is used in support of the contention that the normal frequency distribution does not apply is that the theoretical normal distribution covers a range from minus infinity to plus infinity. No physical measurements, of course, have this wide a range, and usually, as with concrete strengths, measurements less than zero make no sense. Mr. Abdun-Nur dealt with this point very well in his paper mentioned above (1). The answer briefly is that the probability of ridiculously far-out measurements in a normal population is so small that the assumption that they are impossible introduces negligible error. Note that in the hypothetical example given above the physically possible range for each single measurement is from 0 to 200. However, the probability of getting one of these two results is 10^{-20} , and in the example it can be seen that out of 42 cases, none was outside the range 50 to 140. Let us take a hypothetical normal distribution which looks more familiar in terms of concrete strength; for example, an average of 3000 and a standard deviation of 300 (coefficient of variation equals 10 percent). The following table shows the probability of getting numbers outside three different ranges from such a population:

Population with average = 3000

Standard deviation = 300

Range of values	Probability of a measurement outside (above or below) range
2100-3900	0.00135
1800-4200	0.0000317
1500-4500	0.000000124

It can easily be seen that assuming that the population does not extend below 2000, let alone ignoring all the infinity of negative numbers, has

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negligible effect.

The point to be borne in mind in connection with application of the normal distribution to strength measurements (as well as to other aspects of the over-all problem) is that, although much of the reasoning behind the whole subject is based on assumptions that we know are not strictly true, the error introduced by the assumption that they are is sufficiently small (especially when considered in relation to all the other possible errors in the process) that realistically useful results can be obtained by the use of techniques based on those assumptions. In addition the use of rational techniques does not make the problems more complicated; in reality it simplifies them.

Another set of problems connected with the use of the normal frequency distribution to characterize the results of strength tests has to do with the small number of results that are often available for analysis. In some cases this problem is ignored, either through ignorance of its existence or lack of appreciation of its importance. The result in these cases is that computed values based on small numbers of measurements are often treated as though they told the whole story about a complete population of results and unwarranted conclusions are drawn from those values.

In other cases awareness of the limitations of conclusions based on small samples serves as the basis for another claim that use of the normal frequency distribution is not valid. The statement is sometimes made, "You cannot have a normal distribution unless you have at least 30 measurements."

The problem with both of these attitudes is lack of understanding of the relationship between a complete population and a sample from that population. The information from any finite set of test results is of interest only for what it tells about the whole set of measurements characteristic of the specific testing situation of interest. Specifically, what we are concerned about when we make any given number of strength tests and average the number obtained is some kind of knowledge about the fundamental "true" value of the underlying average strength that belongs to the hypothetical total population of tests. Referring to our hypothetical example again, the underlying true average was 100.0. Our sample of 42 measurements from the infinite population of all the measurements that might have been made gave us an estimate of the true average of 101.4, which is not bad.

It is obvious that the larger the sample we take, the better estimate we have of the so-called true value. The statement that you do not have a normal distribution unless you have at least 30 measurements is true in the sense that the group of 30, more or less, measurements is not by itself a normal population, but overlooks the fact that that group is a representation of the population from which it came. If we have no information about what the form of the distribution of the population is, and wish to test whether the distribution does in fact fit the normal curve, 30 is a meager

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amount of data for doing this. Usually, however, we have more previous knowledge about our data than this, and, as in the case of strength measurements, we assume, on the basis of experience and rationalization that the characteristic form of the distribution of the data, if we do not try to push it over too wide a range of different conditions, is normal. Thus we seek, from the data in our sample, information about what the average and standard deviation (the parameters of the distribution as the statisticians call them) of the normal distribution are. This requires less information for a reliable estimate than the case where nothing can be assumed about the form of the distribution.

There is one more misconception about statistical techniques in general that sometimes prevents their use. That is the idea that statistical techniques are of little value in cases where variation is large. The fault, of course, is not with the statistics, but with the data themselves. All that the statistics can do, when applied properly, is mirror the actual characteristics of the data, and where the variability is large, understanding use of statistics is essential to a proper understanding of the data and of what can and cannot be inferred from the study of small groups of measurements. Often this misconception arises when statistics show a wider variation in data than has previously been supposed to exist. Usually, after the experimenters get over their first panic, they can learn to live consciously with situations which have obtained all along without being recognized.

ANALYSIS OF STRENGTH DATA

Details of how the normal distribution is used in the analysis of the numbers obtained by the testing of standard cylinders are given in ACI 214 and are illustrated in other papers in this volume. The significance of some of the techniques will be discussed here.

The first thing ACI 214 says under the heading of Analysis of Strength Data is, "To obtain maximum information, a sufficient number of field compression tests should be made to be representative of the concrete produced and appropriate statistical methods should be used to interpret the test results. Statistical methods provide the best basis for assessing from such results the potential quality and strength of the concrete in a structure and expressing results in the most useful form." (5)

These two sentences, which appear to say some pretty obvious things, also raise some fundamental questions, and could be the basis for a symposium by themselves. Questions raised are the following: What is a "sufficient number of field compression tests?" What does "representative of the concrete produced mean?" What are "appropriate statistical methods?" How are those methods "used to interpret the test results?" How do statistical methods provide a basis for assessing "the potential quality and strength of the concrete in a structure" from the results of strength tests? and What is the "most useful form" for expressing results?

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Starting with the last of these questions, we will agree to accept the hypothesis that the distributions of strength measurements obtained under proper conditions conform to the normal frequency distribution curve, and, therefore, the most useful form of expression of the results is by calculation of the average and standard deviation. The coefficient of variation and range of a sample are introduced, respectively, as a means of expressing the variation on a relative basis, and a simplified means of indicating the variation.

The statement that "statistical methods provide the best basis for assessing -- the quality and strength of the concrete in a structure" from field compression tests needs qualification. Obviously the methods, statistical or otherwise, used in analysis of the numbers obtained by testing companion specimens, have nothing directly to do with how well the strength tests describe the actual strength in the structure. The statement is true only in the sense that statistical methods do provide the best basis for a rational description of what the test results themselves show about their own characteristics, and the quality of the information so obtained has a bearing on the validity of any projection from strength tests to strength in the structure.

The questions of what are the appropriate methods and how those methods are used to interpret test results derive their answer from the assumption of normal distribution of test results and from known methods of analyzing data having the characteristics of that distribution. We will not consider these questions further except as they come up in connection with special problems related to ACI 214.

The first two questions concerning a "sufficient number of tests" and a definition of "representative" need some consideration here, however. Many people operate on the assumption that most, if not all, problems can be solved by getting more data. This often results in merely adding more misinformation to the misinformation one already has and drawing wrong conclusions from the results. Even with valid data, properly taken, the appropriate number depends on the characteristics of the data and on the use to which the information contained in the data is to be put. Consideration of the amount of data and how they should be handled is dependent on two concepts, (1) the idea of a "controlled project." and (2) the concept of "representative measurements."

Such terms as "controlled project," "statistical control," "process in (or out of) control," appear frequently in ACI 214, in the ASTM Manual on Quality Control of Materials (6), and in the literature on evaluation of strength tests. "Control" in these contexts means that the measurements come from a group of measurements whose magnitude are the result of some more or less constant set of underlying conditions and the variations in which conform to some logical pattern. It further means that the measurements conform not only to a normal distribution but to a particular normal distribution with a particular average (or mean) and standard deviation.

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Furthermore, in most cases of interest to us, the concept of control involves also the idea of a continuing process of some kind in which measurements are taken at the beginning. From these measurements, estimates are established of what the characteristics of the underlying pattern of the measurements are. Subsequent measurements are examined for conformity to the originally established pattern. If the evidence indicates that something has happened within the process to change the average or the standard deviation, the process is then said to have "gone out of control" and something may have to be done to bring it "back into control."

Control, then, implies that a pattern, once established, does not change, but it does not necessarily mean, as some people seem to feel, small variability. Control can exist between narrow limits or between wide limits, and a degree of variability of results that would be intolerable in some situations may be quite acceptable in others. This in no way invalidates the statistical approach to dealing with the data. It merely changes the numbers.

"Representative" has to do not only with the number of measurements but the manner of taking them, and this is an area where programs for the evaluation of concrete strengths frequently fall down. No amount of careful handling or testing or statistical manipulation of the numbers is going to produce meaningful results if the samples have not been taken properly to begin with. Mr. Abdun-Nur has discussed this question pretty thoroughly in his paper mentioned above, including examples of practices he has encountered that would make the data useless. It is so important, however, that we will take a look at it here.

Our fundamental assumption about strength tests again, is that for a controlled project, the measurements fit a pattern that conforms to an underlying normal distribution with a particular but unknown average and standard deviation. The function of the test results taken is to give us information about what the average strength and variability, as represented by the standard deviation, are. In order to fulfill this function, it is necessary that each measurement have a chance to be affected by the same causes of variation that are operating to cause the total variation characteristic of the population. Referring to our hypothetical example, if we take our samples in such a way that one of the ten individual contributors to the over-all variation is eliminated or reduced somehow in the samples, but not in the over-all testing situation, then the results in our sample will show a smaller variation than they should. This can happen by such practices as taking several samples out of a single batch, instead of out of different batches at different times of day, and selecting batches to be sampled on the basis of the way they look. Sampling must be done by a completely random procedure determined before the samples are taken. No sample should be rejected by the inspector because he does not think it looks representative, if the concrete goes into the structure.

The four statistical functions recommended to be used in ACI 214 are the

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average or mean, $\bar{X}$; the standard deviation, σ ; the coefficient of variation, V ; and the range, R . In general the methods of calculating these statistics and the method of their use are adequately explained in ACI 214 and in many examples of its use. I will only discuss some aspects of their interpretation.

The average is self-explanatory. The standard deviation, σ , however, needs some consideration. Eq. 2 (p. 214-5) in ACI 214, and Eqs. (3) and (3a) derived from it give the standard deviation as the sum of the squares of the deviations from the average divided by n , the number of measurements. In a footnote it is stated, "Some texts on statistics refer to σ as the standard deviation of the universe (infinite number of tests) and s as the standard deviation of a sample. In computing s instead of σ in Eq. (2), n is replaced by $(n-1)$." Most texts now seem to use $n-1$ as giving what is known as an "unbiased" estimate of the variance, or standard deviation. For the most part, ACI 214 is consistent in assuming that large enough numbers of tests, or long enough series of tests, are available so that the estimates of σ (and of V) obtained and used are reliable estimates characteristic of the population. However, the values given in Table 4 for numbers of samples less than infinity, apply to standard deviations calculated using $n-1$ in the denominator. Thus, to use the factors in Table 4 for 1 through 30 degrees of freedom, with σ 's calculated by the formulas given in ACI 214, σ would have to be multiplied by $\sqrt{n/(n-1)}$. (7).

The factors given in Table 3 for computing within-test standard deviations are also figures which give unbiased estimates of σ . One thing that is pointed out in ACI 214, but is sometimes overlooked in connection with calculating an estimate of σ from ranges is that one batch of concrete does not provide enough data to calculate a reliable estimate of σ , and $\bar{R}$ obtained from companion cylinders from at least ten batches is needed.

The coefficient of variation, V , has become generally accepted as the appropriate measure of variability of concrete strength measurements. It is presented in ACI 214 and is generally thought of as merely a way of expressing the variability on a percentage rather than an absolute basis. This is not strictly a correct view, since the use of coefficient of variation rather than standard deviation statistically is based on certain characteristics of the data. There has been considerable discussion in ACI Committee 214, and in the literature on evaluation of strength tests on the question of whether coefficient of variation or standard deviation should be used as the basis for evaluation of strength tests, or whether some other method of evaluation is appropriate (8, 9). However, the coefficient of variation has served pretty well for a long period of time in practical situations, and its use does not cause significant trouble if a particular V calculated from concrete tests obtained under certain conditions and at pretty much the same strength level is not assumed to apply under widely different conditions and at widely different strength levels.

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STRENGTHS BELOW DESIGN STRENGTH

One of the main stumbling blocks in the way of wider acceptance and use of ACI 214 has been reluctance to accept the idea that not only some, but a certain definite percentage of, test results should be not only permitted, but expected to fall below the design strength, f'_c . This idea, however, is an inherent and inescapable characteristic of the whole data-producing process. Once again, Mr. Abdun-Nur has covered this subject admirably, and I have already touched on it under Variations in Strength, but it is so important and seems so hard for some people to accept, that it needs re-emphasis in different words.

First, it is obvious that, not only in concrete strength testing, but in a whole series of measurement situations, we get different numbers when we repeatedly measure supposedly identical properties. It is further obvious that, once we accept that all measurements on a particular system are not going to be the same, we must accept that some are going to be lower than others, and that this does not mean they should be rejected as not belonging with the others.

Second, once we accept the idea that the measurements not only differ from each other, but differ in some logical pattern whose characteristics we know, then we are in a position to state what proportion of the results should be expected to fall below (or above) any given value in the range of possible values of the variable we are measuring, or between any two given values. We have accepted, we hope, the idea that the frequency distribution of strength tests fits sufficiently well for our purposes, what is known as the normal probability curve, any particular form of which is completely specified by two parameters known as the mean or average and the standard deviation. We know that this distribution has been thoroughly studied and we have tables which tell us what proportion of the results in any given population of normally distributed measurements departs from the average by any given multiple of the standard deviation.

Much of the discussion in ACI 214 is devoted to the question of how to determine an average strength, f_{cr} , which the distribution of results must have (if a given coefficient of variation prevails) to insure that no more than a certain percentage of the results falls below f'_c .

If f_{cr} equals f'_c , obviously, half the results will fall below f'_c . This is illustrated in Figure 4, Curve A. If it is desired to have less than 50 percent of the results fall below f'_c , then f_{cr} , the center of the distribution, must be greater than f'_c , (Figure 4, Curve B), and the greater the amount by which f_{cr} exceeds f'_c , the smaller will be the proportion of tests that fall below f'_c .

So far nothing we have assumed rules out the idea that theoretically the concrete could be designed so that its average strength would be high enough

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to insure that, for all practical purposes, none of the strength tests would fall below f'_c . Our friend Abdun-Nur, again, has done a fine job of illustrating that, in practice, the idea is absurd. Since the interval between plus or minus 3σ from the mean of a normal distribution contains about 99.7 percent of all the results, the error introduced by assuming that the limit 3σ below the mean is a minimum is negligible. Thus, if it is desired to have f'_c as a minimum below which no results should be expected to fall, f_{cr} needs to be at least 3σ above f'_c (Figure 4, Curve C).

Coefficients of variation for field concrete tests appear to be generally 15 percent or higher, and 20 percent is sometimes given as the one to be used when sufficient data have not yet been obtained to calculate $V(1, 10)$. If an f'_c of 3000 psi is assumed and $V = 20$ percent, the standard deviation is 1500 psi and the average strength required is 3000 plus 4500 or 7500 psi. This is obviously not being obtained on concrete jobs aimed at a design strength of 3000 psi. Abdun-Nur states that in his experience jobs designed for 3000 psi generally have averages around 3500 psi. For a coefficient of variation of 20 percent, this means that about 24 percent of the strength results will be below 3000 psi, the so-called design strength.

Thus "Realism in the Use of ACI 214" is really the same thing as "Realism in the Interpretation of Strength Tests," even if ACI 214 did not exist, and one of its most basic elements is recognition of the fact that a certain percentage of strength tests are going to fall below f'_c (without necessarily impairing the strength of structures) and the designing of concrete mixes with a view to obtaining a specific percentage. ACI 214 recommends the use of 1 in 10 below f'_c . Abdun Nur recommends 1 in 10 for structural concrete and 2 in 10 for pavement concrete (1). Experience will teach any user what proportion he can live with and still obtain the kind of structures he wants at a reasonable cost.

The experience of many people indicates that the best method for monitoring control of a concrete production is the use of the control chart technique, and I believe that this subject deserves more emphasis than it receives in ACI 214. Properly maintained control charts give a continuing easy-to-read picture of the process. With their use it is easy to establish that a certain desirable pattern of results has been achieved, and then to monitor the results as they are obtained on the basis of accumulating information over a period of time to see that they are sticking reasonably close to that pattern. If the results show signs of departure from the desired pattern, it can be determined whether the departure is temporary or permanent, and whether it is of such a degree that it is required that something be done to correct the situation.

Other papers in this symposium describe the use of Control Charts in more detail and provide examples.

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Other topics related to realistic Use of ACI 214 could be explored in more detail if space permitted, but I hope that what has been said will be helpful to some who have been shy about using ACI 214 for one reason or another, and that this symposium and future symposiums and publications will provide further stimulus and result in better concrete construction.

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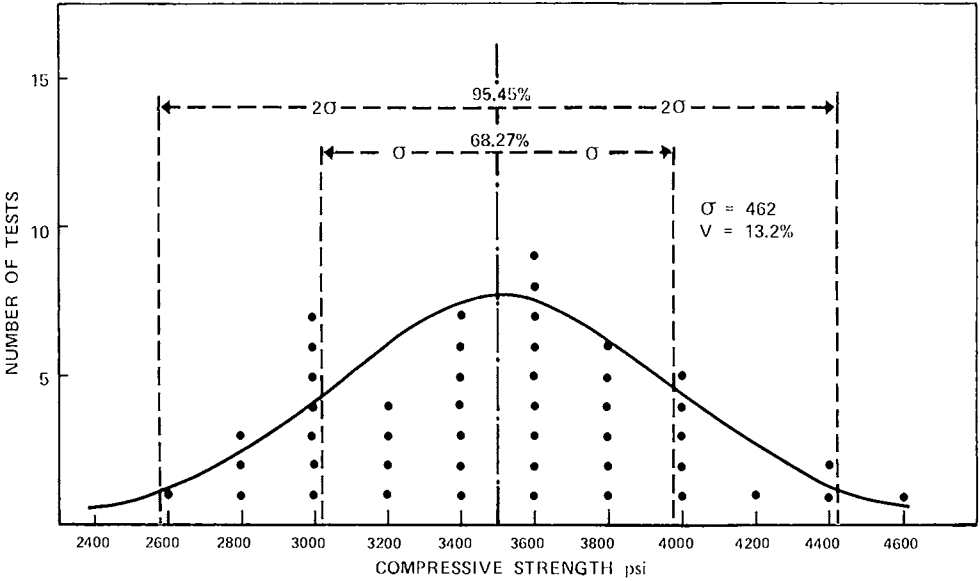


Fig. 1 -- Distribution of data from 46 strength tests
 (after Fig. 1, ACI 214-65)

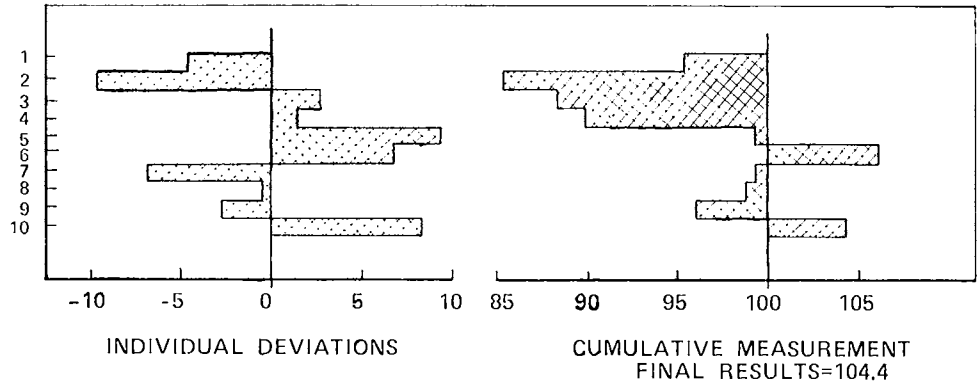


Fig. 2 -- Hypothetical measurement built up from individual deviations