Concrete

Q&A

Evaluation of Strength Results

Q. *The 28-day cylinder breaks were initially fine, but now they're coming in low. The concrete supplier blames the testing lab and the testing lab blames the supplier. Who can we believe? Can ACI 214R be used to sort this out?*

A. The quick answer is yes, ACI 214R-11[1] can be used to help sort this out. But without specific information regarding the cylinder test results, we have to start by referring to ACI 301-10[2] or ACI 318-11[3]—the ACI documents that define strength acceptance requirements for structural concrete.

From Sections 1.6.5 and 1.6.6 of ACI 301:

1.6.5 *Evaluation of concrete strength tests*

1.6.5.1 Standard molded and cured strength specimens—Test results from standard molded and cured test cylinders will be evaluated separately for each specified concrete mixture. Evaluation is valid only if tests have been conducted in accordance with procedures specified. For evaluation, each specified mixture shall be represented by at least five strength tests. When strength test results do not meet the requirements of 1.6.6.1, take steps to increase the average of subsequent strength test results. Submit documentation of actions to increase strength test results.

1.6.6 *Acceptance of concrete strength*

1.6.6.1 *Standard molded and cured strength specimens*—The strength of concrete is satisfactory provided that the criteria of 1.6.6.1.a and 1.6.6.1.b are met.

1.6.6.1.a Every average of three consecutive strength tests equals or exceeds the specified compressive strength f_c'.

1.6.6.1.b No strength test result falls below f_c' by more than 500 psi when f_c' is 5000 psi or less, or by more than $0.10f_c'$ when f_c' is more than 5000 psi. These criteria also apply to accelerated strength testing unless another basis for acceptance is specified in Contract Documents.

Section 5.6.3.3 of ACI 318 states the same requirements.

We will assume that the breaks called "fine" met these requirements and the breaks called "low" did not. So for the "low" breaks, the real question becomes: Were the "low" test results caused by changes in the delivered concrete, poor or inadequate testing procedures, or both?

This is where ACI 214R can be helpful. As Table 3.1 of ACI 214R indicates, variability in test results can be caused by many factors, but, basically, variation in strength tests will be related to variability in batching during production or variability in testing. ACI 214R provides methods for quantifying these two components of variability, using either the sample standard deviation or the sample coefficient of variation (simply the sample standard deviation divided by the sample mean). Either can be calculated with the aid of functions provided with spreadsheet software, statistical analysis packages, and many calculators.

Overall standard deviation (or, for concretes with specified strengths greater than 5000 psi [35 MPa], the overall coefficient of variation) is used to assess the batch-to-batch variability. The within-batch coefficient of variation is used to assess the testing variability.

Each cylinder break provides an estimate of the average strength of the concrete in the batch from which the cylinder sample was taken. For example, if we made, cured, handled, and tested 100 cylinders from a single batch of concrete in exactly the same way, we would not expect them all to break at exactly the same compressive strength. We would, however, expect them to break somewhere near the average of all 100 cylinders. A histogram of the 100 individual cylinder strengths would likely be distributed about the average, following a bell-shaped curve resembling the normal distribution curve (Fig. 1). The variability of the results is representative of the within-batch variation.

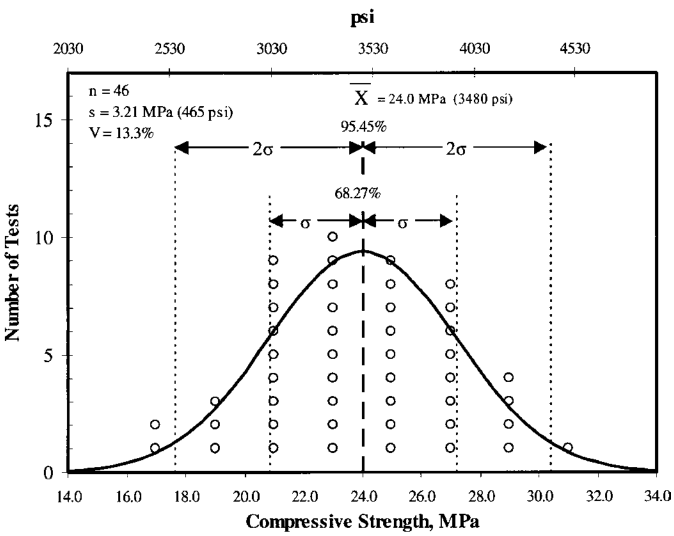

Fig. 1: Frequency distribution of strength data and corresponding assumed normal distribution (Fig. 4.1 in ACI 214R-11[1]) (Note: 1 MPa = 145 psi)

Going further, if we made 100 batches of concrete in exactly the same way, using the same materials, the same mixer, and the same personnel, and molded 100 cylinders from each batch, we would not expect all 10,000 cylinders to have the same strength. We also would not expect the average of the strengths of the 100 cylinders from each batch to be the same as the average of the strengths of every other batch. We would expect a histogram of the averages of the batches to be distributed about the average of all the batches in a similar bell-shaped curve. This variability among all the batches under consideration is the overall variability.

Strength Acceptance

For strength acceptance, typically two or three cylinders are molded from a single batch of concrete. A strength test is defined in ACI 318 as the average of the individual cylinder strengths and so is an estimate of the average strength of the batch. The strength of each cylinder represents an estimate of the average strength of the batch from which it was sampled. The difference between the highest strength and lowest strength in a set of two or three cylinders is called the range.

ACI 214R advises that the range of individual strength tests from a batch can be used to estimate the within-batch coefficient of variation. The strength test results for all batches being considered are used to estimate the average strength and the overall standard deviation (or overall coefficient of variation). These estimates of within-batch

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

Fig. 2: Standards of concrete control (Tables 4.3 and 4.4 in ACI 214R-11[1])

coefficient of variation and overall standard deviation (or coefficient of variation) are used to categorize the standard of quality control using Tables 4.3 and 4.4 of ACI 214R (Fig. 2). If the within-batch coefficient of variation corresponds to a category of "Fair" or "Poor," this may be an indication of inadequate sampling and testing procedures. If the overall standard deviation or coefficient of variation corresponds to a category of "Fair" or "Poor," this may be an indication of inadequate batch plant production controls.

Control charts similar to those shown in Fig. 6.1 of ACI 214R (Fig. 3) can be used to help determine if there is a sudden change in the range corresponding to the lower strength test results. Such a change, regardless of category, may be indicative of a change in batching, sampling, or

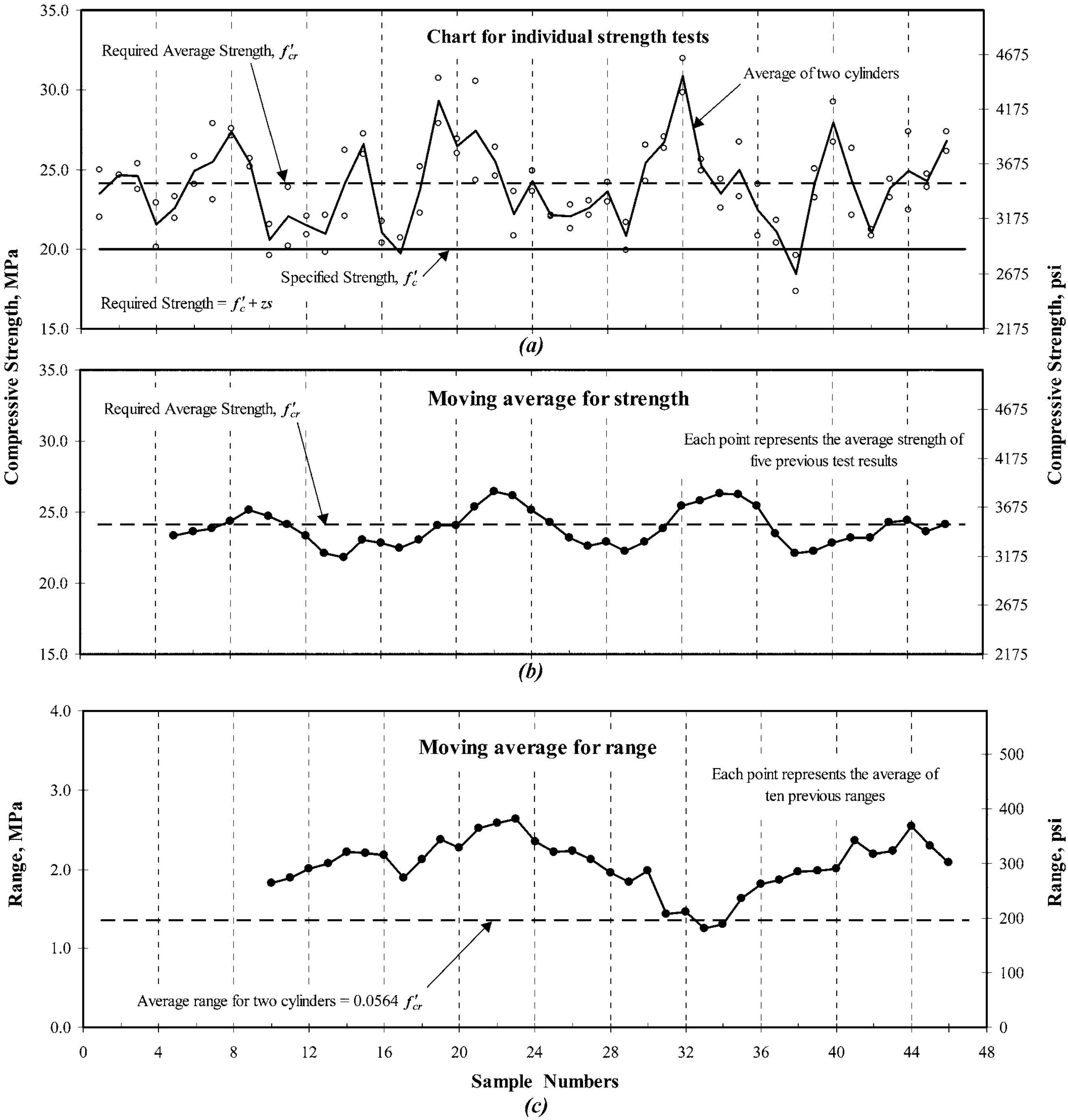

Fig. 3: Three simplified quality control charts: (a) individual strength tests; (b) moving average of five strength tests; and (c) range of two cylinders in each test and moving average for range (Fig. 6.1 in ACI 214R-11[1])

testing procedures. Careless or sloppy sampling and testing procedures will most likely increase the within-batch coefficient of variation. Systematic deviations from standardized test methods will affect all of the cylinders from a batch the same way and therefore will not affect the range adversely. Examples of systematic deviations include using a test machine that is out of calibration, curing cylinders at nonstandard temperatures, and failing to continue loading each cylinder to failure.

Limiting sources of testing variability is important for the test results to be meaningful. Consistent application of the methods provided in standards (for example, ASTM C31/C31M-12, "Standard Practice for Making and Curing Concrete Test Specimens in the Field") helps minimize variability of testing. Other standards, such as ASTM C39/C39M-12a, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," generally include precision and bias statements that can be used to help determine if the variability of test results from a test are reasonable. It is rarely possible to assess strength variations if proper sampling and testing procedures are not being followed. Using ACI-certified field and laboratory technicians on your project, however, can go a long way toward assuring that the sampling and testing are being performed in accordance with the applicable standards.

If your ACI 214R evaluation fails to shed any light on the low strengths, a thorough review of the testing laboratory sampling and testing procedures and a thorough review of the concrete supplier's quality processes are warranted.

References

1. ACI Committee 214, "Guide for Evaluation of Strength Test Results of Concrete (ACI 214R-11)," American Concrete Institute, Farmington Hills, MI, 2011, 16 pp.

2. ACI Committee 301, "Specification for Structural Concrete (ACI 301-10)," American Concrete Institute, Farmington Hills, MI, 2011, 77 pp.

3. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary," American Concrete Institute, Farmington Hills, MI, 2011, 503 pp.

Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

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Request for Concrete Cylinder Test Data

ACI Committee 214, Evaluation of Strength Test Results of Concrete, is conducting a study to verify or update the values listed in ACI 214R-11, Tables 4.3 and 4.4, to qualify concrete control. The values listed in Table 4.3 are identical to values published in the 1977 edition of the ACI 214 report—one might hope that the standards of concrete quality control have improved over the past 35 years!

The study is being led by Mike Bartlett at the University of Western Ontario in London, ON, Canada, with the assistance of Senior Undergraduate Student Jason Daplyn. After preliminary results were presented at the ACI Committee 214 meeting in Toronto on October 22, 2012, it was agreed that additional data should be solicited.

Therefore, ACI Committee 214 is asking readers to provide data for this study. Data must be for production covering 30 or more tests of the same mixture design, obtained by qualified persons on calibrated equipment, and it should be submitted in a Microsoft® Excel file. The data should include:

- Individual cylinder breaks for each test result, so that within-test variation may be computed;
- Specified strength of the concrete tested;
- Cylinder size and concrete age at time of testing;
- Indication of whether the mixtures represent laboratory trial batches or general construction testing;
- Indication of whether the data are from a single testing company or a composite set from several firms; plus
- Any other information that may have influenced the quality of testing.

Other data about the fresh concrete, such as slump, temperature, air content, or unit weight, should be included if available. These data will be analyzed to determine the correlation (or lack of it) between these properties and the strength.

All information received will be confidential. All organizations that provide data will be acknowledged, but the source of any particular data set will not be identified.

Please send data to f.m.bartlett@uwo.ca. Please send questions to luke@njit.edu.