

# Variation in Concrete Strength Due to Cement

## Part III of Concrete Quality Series

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Parts I and II of the Concrete Quality series<sup>1,2</sup> discussed that to attain good concrete quality a concrete producer needs to target a low standard deviation of compressive strength. In order to reduce the strength standard deviation, the material, manufacturing and testing variations need to be lowered. This article discusses concrete strength variability due to variation of cement from a single source.

### Cement from a given source varies between shipments

It is well understood that there are significant differences in strengths of Type I cements from different sources. How variable is the strength of different cement shipments from the same source? One of the most exhaustive studies to address this question was conducted by Walker and Bloem back in the 1950s at the NRMCA/NSGA Joint Research Laboratory<sup>3</sup>. Cement samples were secured from each of 5 sources every 2 weeks from October 1955 to October 1956 and

stored in sealed containers. A sixth cement consisting of a blend of 5 cement brands from the Washington area was thoroughly mixed at the start of the program and stored in sealed containers for use as a control. Three principal series of tests were conducted at different times. The first series involved standard mortar strength tests (ASTM C109) on all samples; the second, concrete tests on selected samples; and the third, concrete and mortar tests on selected samples. In the first series five mortar batches were made on different days with each cement sample including the control; each round including all sources was made on the same day. All work was performed by the same operator. Nine cubes were molded from each batch for strength tests in triplicate at 3, 7 and 28 days age. The series involved testing of approximately 7000 2-in. mortar cubes. In the second series concrete batches with a cement factor of 517 lb/yd<sup>3</sup> and mixed to a constant slump of 3 to 5 in. were made using samples of cement which had produced the

highest, median and lowest mortar strengths from each of the 5 cement sources in Series 1. Concrete cylinders of size 4x8 in. were tested in triplicate at 3, 7 and 28 days. Due to the space restrictions only series 1 and 2 are discussed below. Series 3 findings were in line with Series 1 and 2.

Figure 1 shows the percentage distribution of mortar strengths about the average for all 3 test ages. The percentage strengths at each age have been arranged in order of descending magnitude. If the different shipments from the same source were absolutely identical and the cement was essentially uniform, one should observe a perfectly horizontal line at 100%. Source 1 (control) approaches that and the small variability is primarily due to variation attributed to testing. All the cement sources showed a greater variation than the control with some of them better than the others. Table 1 summarizes some of the statistical data of the 28-day mortar strength test results of the 5 sources. On the basis of sample-to-sample

Table 1. Statistical Summary of 28-day Compressive Strength Tests of Mortar<sup>3</sup>

Data represents 26 samples taken every 2 weeks over a year,  $s_1$ ,  $s_2$ ,  $s_3$  are, respectively, standard deviations in psi, within batch, batch-to-batch and sample-to-sample;  $n_1$ ,  $n_2$ ,  $n_3$  are corresponding coefficients of variations

	Control (Source 1)	Source 2	Source 3	Source 4	Source 5	Source 6
Average, psi	5198	5355	4950	3674	5434	4582
$s_1$ , psi	133	132	125	79	137	111
$s_2$ , psi	119	131	127	81	137	114
$s_3$ , psi	123	339	362	244	520	245
$n_1$ , %	2.6	2.5	2.5	2.1	2.5	2.4
$n_2$ , %	2.3	2.4	2.6	2.2	2.6	2.5
$n_3$ , %	2.4	6.3	7.3	7.3	9.6	5.3

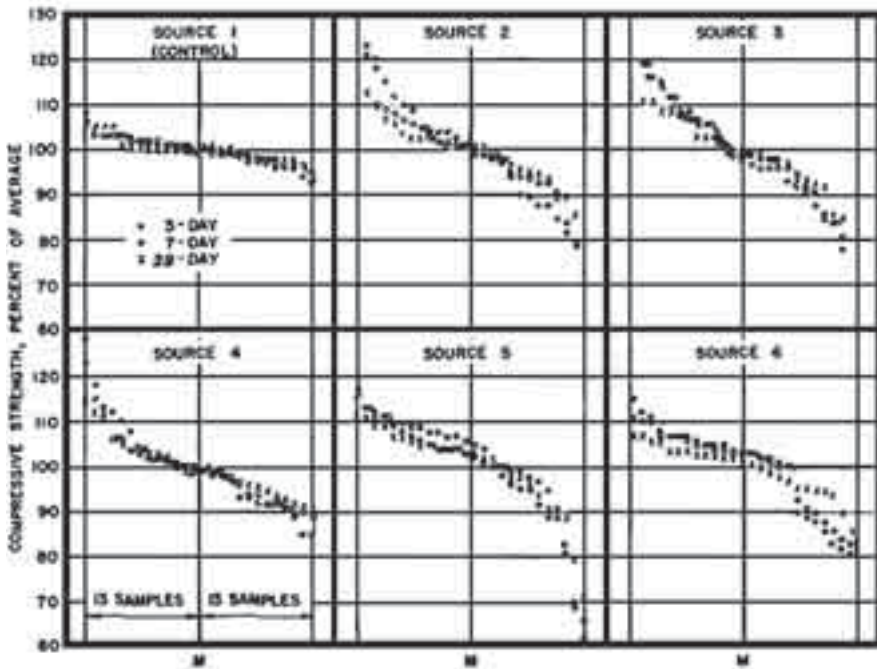


Figure 1. Percentage Distribution of Mortar Strengths about Average<sup>3</sup>

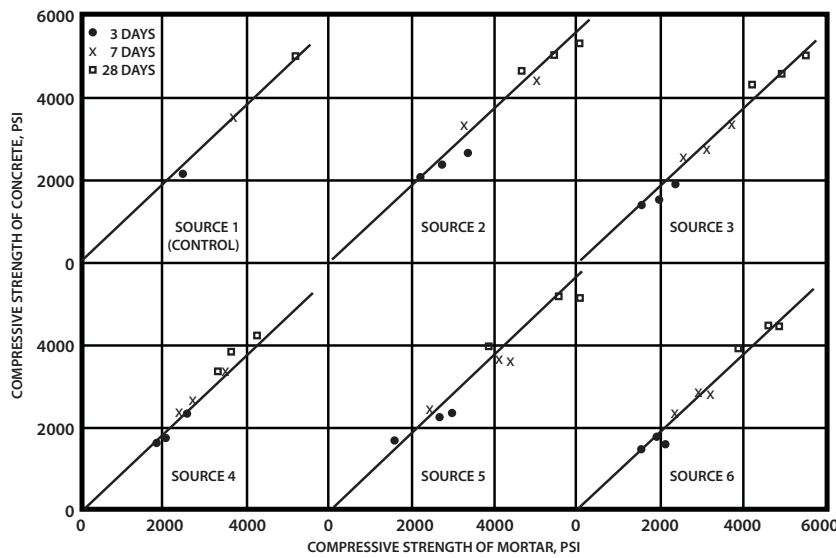


Figure 2. Relationship Between Compressive Strength of Constant-Slump Concrete and C109 Mortar for Control and the 5 Cement Sources<sup>3</sup>

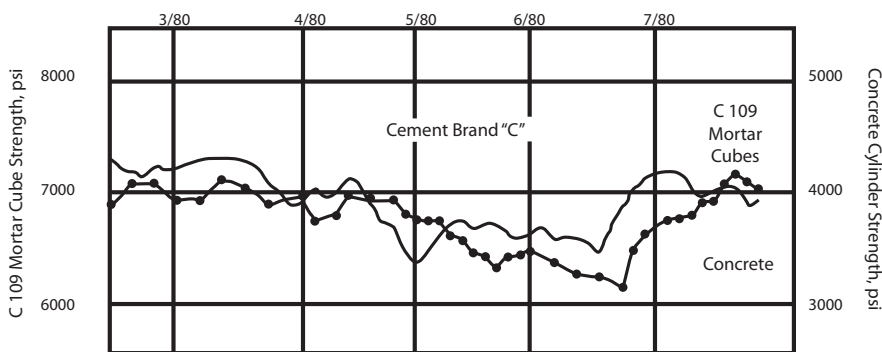


Figure 3. Running 5 Test Average of C109 Mortar Cubes (C917 Report) Vs Running 5 test Average of Concrete Cylinders Tested at 28 days<sup>7</sup>

Coefficients of Variation (COV) over the duration of the shipments all five cement sources showed considerably greater variability than the control, as should be expected. These COVs ranged from 5.3 to 9.6% as compared with only 2.4% for the control – the COVs for the various sources was even higher with early age strengths. The average 28-day sample-to-sample standard deviation for the 5 sources of cement was 342 psi. ACI 214R-02 states that a good standard of concrete control for general construction testing is a standard deviation of 500 to 600 psi. Even though the cement strength standard deviation may not translate directly to a concrete strength deviation of the same magnitude, cement variation plays an important role in concrete strength variability and it should be clear that variation in strength producing property of cement from a single source cannot be ignored.

Figure 2 shows that C109 mortar strengths correlate very well with concrete strengths from the Series 2 work for all sources. This confirms that for a given source, variation in cement strengths between shipments causes variations in concrete strengths. For the 28-day tests the average strengths of the five sources ranged from a high of 4880 to a low of 4060 psi, an overall spread of 820 psi. This variability in concrete strengths will necessitate an increase in cement content to achieve a higher target strength to accommodate this variability. Contrary to this Weaver et al.<sup>4</sup> reported that for the same cement source as shipments changed there was no correlation between the C109 mortar strengths and corresponding concrete strengths. Gaynor<sup>5</sup> conducted an exhaustive study of past NRMCA research. He states that variations associated with testing of C109 mortar strength, as well as with concrete strength, are not insignificant. When the cement is very uniform and real cement strength variations are small, the testing variation is large enough to mask the variability that can be attributed to variation of the cement source. Additionally, when only single batches of mortar or concrete are tested correlation between these strengths are not obvious because of testing variability. However good correlations were obtained<sup>3,6,7</sup> if several batches of mortar and concrete are prepared from the same sample or enough consecutive samples (5 or 10) are averaged. Gaynor concluded that there was indeed an excellent correlation between

C109 mortar strengths and concrete strengths made from the same cement sample.

Walker and Bloem<sup>3</sup> attempted to attribute the cause for the variability in mortar strengths of the 5 cements sources. Barring two instances for cement source 5 the mortar mixing water contents remained fairly constant and therefore could not explain the reasons for the variability in mortar strengths. Mortar sand grading was repeatedly checked and was found to be consistent as well. Good correlation between cement tri-calcium silicate contents and mortar compressive strengths was noted for sources 2-5. For source 6 such a correlation was not observed but the fineness was found to vary significantly. The authors concluded that variation in the tri calcium silicate (C<sub>3</sub>S) content was a primary factor that can be attributed to variability in mortar strengths between shipments from a given source. The authors did not notice any correlation between cement strength performance and the changing seasons.

A 1962 study<sup>6</sup> by the same researchers looked at 14 cements sources with 2 different operators and came to similar conclusions as the earlier study. In 1977 over 100 cement plants in the U.S. and Canada participated in a year-long grab sample testing program. Cement companies collected 10 grab samples every month from shipment containers. Grab samples better represent the cement received by the concrete producer. The data from the 1977 study was statistical evaluated<sup>8,9</sup> by a joint NRMCA/PCA Technical Liaison Committee and led in 1980 to the development of ASTM C917<sup>10</sup>, Standard Test Method for Evaluation of Cement Strength Uniformity from a Single Source. In a later article Gaynor<sup>11</sup> analyzed the data and reported the variation in the monthly moving average strength (10 sample moving average) during the course of the year. This is reproduced in Table 2. A typical overdesign for concrete furnished under the ACI 318 Building Code is about 20%. Table 2 shows that about 40% of the cement plants experienced changes in strengths exceeding 15%. Half of these plants had an increase in strength. This again confirms that that variation in strength producing property of cement from a single source cannot be ignored.

Table 2. Changes in Cement Plant Monthly Moving Averages of Mortar Strengths<sup>11</sup>

(100 cement plants participated in yearlong grab sample program in 1977 at 10 samples every month)

Percent Change in 10 samples 28-day strength, %	% of plants exceeding
5	97.1
10	86.4
15	38.8
20	17.5
25	4.9
30	1.0

### ASTM C917

ASTM C917 is the standard test method for Evaluation of Cement Strength Uniformity from a Single Source. C917 is typically done on the predominant cement sold at a cement plant. Grab samples of cement are taken from normal delivery units, either

trucks or rail cars or some other point of the loading/unloading process. Grab samples reflect the properties of cement as shipped and will more closely explain what true variation is likely from shipment to shipment. On the other hand the sampling process of a single mill test report may be applicable to many different cement shipments to the same concrete plant.

Typically 10 test samples are collected in a month. All samples are tested for 7- and 28-day mortar compressive strength in accordance with ASTM C109 on standard 2-in. cubes. The test report includes number of samples tested, average strength, total standard deviation, standard deviation corrected for testing and the moving average of the five most recent test results. The report will contain test data that covers a period of 3 to 12 months. At its discretion a cement manufacturer may decide that a consistent change in strength-producing property of cement has occurred and may start a new set of calculations; in such a case the values calculated before as well as after the change should be reported.

The appendix of C917-05 has plots that summarize test data collected from 87 cement plants in the U.S. and Canada in 1991. It shows that some cement plants can produce more consistent strengths than others. About 10% of the plants had a 28-day standard deviation of more than 380 psi; 10% of plants had a 28-day standard deviation less than 180 psi; the median standard deviation of all plants tested was 280 psi.

### C917 – How Should a Ready Mixed Concrete Producer Use it?

#### Cement Choice

Cement strength uniformity (ASTM C917 test data) can be considered in cement purchase decisions by the ready mixed concrete producer. Apart from ASTM C150 mill test reports concrete producers should request to see ASTM C917 test reports over the past 12 months. Everything else being equal, a cement that has a lower standard deviation as measured by ASTM C917 will be more uniform and will generally result in a lower concrete strength standard deviation. This can result in a lower target average strength and a lower cementitious content for a given strength level.

#### Better Understand Concrete Variability and lower it

ASTM C917 test data can be used to lower overall concrete variability and hence improve quality. If periodically (once a week) standard concrete mixtures (the most commonly sold mix at that plant for example) are cast and strength properties evaluated it becomes possible to correlate the cement strength variation to concrete strength variation. Figure 3 shows how a concrete producer<sup>7</sup> tracked the five-test running average of C109 mortar cube strengths from the C917 test report. Superimposed is a five-test running average of concrete cylinders test results made from a standard 450 lb/yd<sup>3</sup> cement factor, 3000 psi concrete mixture. Both the mortar and concrete strength curves show a downward trend from mid March to mid June followed by a sharp increase. A typical 2- to 5-day time lag for rail shipments to the ready mix plant would explain some of the apparent shift in peaks. A good understanding of the concrete strength variation due to cement strength variation is a first step in understanding the causes of the overall concrete strength variation. Such an understanding can help find ways to lower the concrete variability, reduce cement factors in concrete and attain improved quality.

### Reduce Low Breaks and Optimize Mixture Proportions

This is perhaps the most important use of ASTM C917 test data and it can help the producer lower costs. If a process variable in cement manufacturing has changed and the cement strength is trending upward timely communication from the cement manufacturer can help the concrete producer optimize concrete mixture proportions. On the other hand if the cement strengths are trending downward mixture proportions may have to be changed to prevent low strength test results. To be effective, communication should occur as soon as 7-day mortar test results are available or even earlier if process changes have occurred at the cement plant that are known from experience to change the strength producing property of cement in a certain manner. In periods of high volume use, it is also possible that cement producers might switch the cement source shipped to the concrete producer.

It is important not to be alarmed by a single low or high cement 7- or 28-day strength test result. 7-day test results are preferable as they provide a quicker opportunity to make changes as needed. A single low strength could be because of testing or genuine material variation. However if there is a pattern of low strength results then it suggests a “change point” has occurred; the average strength has reduced; and that reduction in cement strength has to be managed by changing the concrete mixture proportions to avoid low concrete strengths. The change point could be due to a testing bias but that is generally unusual and the cement manufacturer can rapidly investigate that. Most likely the change point is due to a genuine change in the strength producing property of the cement itself. Control charts of running averages of 3 or 5 consecutive test results and Cusum charts<sup>12</sup> can help understand if change points have occurred. The concrete producer can choose to adjust mixture proportions if certain control charts limits are exceeded. If running average of 5 consecutive test results are plotted on a control chart, statistically there is only a 2% chance that test results will fall outside limits set at  $1.042 \times V_t$  percent from the average; where  $V_t$  is the total coefficient of variation of the cement strength.  $V_t$  is calculated in percent as the ratio of the standard deviation ( $S_t$ ) and average strength ( $\bar{X}$ ) reported in a C917 test report.

Example: For  $\bar{X} = 4000$  psi,  $S_t = 240$  psi,  $V_t$  can be calculated as 6%. Limits for the 2% chance can be calculated as 6.25% from  $\bar{X}$  which gives an upper control limit of 4250 psi and a lower control limit of 3750 psi.

### Troubleshoot Low Strength Problems

When C917 data is available, concrete producers can also use it to troubleshoot low concrete strengths in evaluating whether the cause for the low concrete strength can be attributed to a reduction of the cement strength. Other factors, such as mixing water, air content, batching errors, testing errors etc., should also be considered. Concrete producers should also keep 5-lb samples of cement from each shipment in sealed containers so that these can be tested if necessary. It is advisable to retain cement samples for 3 to 6 months from the date the shipment was received.

### **C917 – How Should a Cement Producer Use it?**

Cement manufacturing is an intensive process of using naturally available (variable) resources and manufacturing process variables. The cement manufacturer clearly has a goal of minimizing

variability and has access to various tools and methods to monitor cement variation. A large cement producer can look at the annual COVs measured according to C917 at various cement plants and try to better understand the reasons for lower variability at certain plants and duplicate them elsewhere. Sometimes the higher COV attained at a plant is because of a wider variability in the raw materials of the cement itself. This was referred to by a cement producer<sup>13</sup> while discussing the 1958 research study. He says that some plants had a wider variation of silica content in their raw materials. If those plants attempted to control their composition of raw mixes by just the analysis for the carbonate portion they could end up with wide variations in tri-calcium silicate contents. The cement producer can target a lower COV as measured by ASTM C917 by identifying the key strength producing characteristics, such as tri-calcium silicate content, fineness, gypsum content, etc. and attempt to control them. It has been suggested that ASTM C150 itself should have limits on the extent to which some of these properties can vary<sup>13-15</sup>. In 1975 Bryant Mather then president of ASTM discussed the lower-limit-only cement strength specifications: “We need to do something about the variability. We need to put into the ASTM standards some way by which the user can require not just compliance with the minimum, but an assurance of some degree of uniformity”. An attempt at this was to incorporate a cement strength range concept in ASTM C1157, but it was dropped because of significant confusion on how cement could be ordered.

As discussed in the previous section as soon as the 7-day running average of 5 consecutive C917 strength test results fall outside previously agreed upon control limits the cement producer could communicate that to the concrete producer so that suitable actions can be taken. Communication can even be earlier if process changes have occurred at the cement plant that are known from experience to change the strength producing property of cement in a certain manner. Timely communication can reduce low strength problems in the field and the accompanying investigating costs.

It is important that the concrete producer and the cement manufacturer work as a team as it is in the best interests of both that concrete of good quality with low variability and reduced low strength problems are made and placed. A good understanding of cement strength variations through effective use of ASTM C917 is essential in this regard. ■

### **References**

- <sup>1</sup> Obla, K.H., “How Good is your QC – Part I of Concrete Quality Series,” *Concrete InFocus*, May-June 2010, Vol. 9, No. 3, NRMCA, pp. 17-18.
- <sup>2</sup> Obla, K.H., “Sources of Concrete Strength Variation – Part II of Concrete Quality Series,” *Concrete InFocus*, July-August 2010, Vol. 9, No. 4, NRMCA, pp. 21-23.
- <sup>3</sup> Walker, S., and Bloem, D.L., “Variations in Portland Cement,” Proceedings, ASTM International, West Conshohocken, PA, Vol. 58, 1958, pp. 1009-1032.
- <sup>4</sup> Weaver, W.S., Isabelle, H.L., and Williamson, F., “A Study of Cement and Concrete Correlation,” *Journal of Testing and Evaluation*, ASTM International, West Conshohocken, PA, Vol. 2, No. 4, July 1974, pp. 260-303.

- <sup>5</sup> Gaynor, R.D., "Cement Strength and Concrete Strength - An Apparition or a Dichotomy," *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 15, No. 2, Winter 1993, pp. 135-144.
- <sup>6</sup> Walker, S., and Bloem, D.L., "Variations in Portland Cement - Part 2," *Proceedings, ASTM International*, West Conshohocken, PA, Vol. 61, 1961, pp. 1059-1077.
- <sup>7</sup> Scott, B.M., "Cement Strength Uniformity - A Ready-Mix Producer's View", NRMCA

Publication No. 165, NRMCA, Silver Spring, MD, December 1981.

- <sup>8</sup> Davis, R.E., Jr., "Uniformity of Portland Cements - Facts and Fantasies," Presented at the 45<sup>th</sup> Annual NRMCA and 59<sup>th</sup> Annual NSGA Convention, New Orleans, January 1975.
- <sup>9</sup> Klieger, P.L., "Description of NRMCA-PCA Cement Strength Uniformity Test Program," Presented at the NRMCA Opening Session, Annual Convention, Houston, February 1976.

- <sup>10</sup> ASTM C 917-05, "Standard Test Method for Evaluation of Cement Strength Uniformity From a Single Source," Volume 04.01, ASTM International, West Conshohocken, PA, 2005, 11 pp.
- <sup>11</sup> Gaynor, R.D., "Cement Strength Variability and Trends in Cement Specifications in the U.S.," Eighth Congress of the European Ready Mixed Concrete Organization (ERMCO), Rome, May 1986, 8pp.
- <sup>12</sup> ACI Committee 214, "Evaluation of Strength Test Results of Concrete (ACI 214R-02)," American Concrete Institute, Farmington Hills, MI, 2005, 20 pp.
- <sup>13</sup> Floor Discussion of Paper on "Variations in Portland Cement," *Proceedings, ASTM International*, West Conshohocken, PA, Vol. 58, 1958, pp. 1033-1043.
- <sup>14</sup> Peters, D.J., "Evaluating Cement Variability - The First Step" A Discussion of the New ASTM Method C917-80 and the Past, Present, and Future for Cement Uniformity Evaluation, NRMCA Publication No. 161, NRMCA, Silver Spring, MD, April 1980.
- <sup>15</sup> Mather, B., Interview in *ASTM Standardization News*, ASTM International, July 1975.



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