Sources of Concrete Strength Variation

Part II of Concrete Quality Control Series

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Variation in compressive strength as measured by standard deviation (s) can be used as a measure of a concrete producer's level of quality control (QC). Table 1, which is a reproduction of Table 3.2 from ACI 214R-021, shows that the standards of concrete control based on general construction testing can vary from Excellent (s < 400 psi) to Poor (s > 700 psi). This applies to typical concrete strengths in the range of 3000 to 5000 psi. Part I of this article series addressed possible material cost savings for a producer who attains a lower standard deviation. How does an interested producer go about reducing its standard deviation? To answer this question we have to gain a good understanding of the sources of concrete strength variation.

The sources of strength variation can be broadly categorized into three parts – material, manufacturing and testing. Under each category there are many possible reasons for concrete variability and some of the important ones are listed below:

Material	Variations in characteristics of cement, SCMs, fine aggregate (silt, grading), coarse aggregate (dust/bond), admixtures
Manufacturing	Variations in ingredient weights (water, cementitious, admixture), mixing, transporting, delivery time, temperature, workability, air content
Testing	Sampling, specimen preparation, initial/final curing of specimens, transporting, test procedures and equipment

To put it simply, in order to reduce the strength standard deviation the material, manufacturing and testing variations need to be lowered. Future articles will address each category in depth. In this article let us briefly look at testing variability.

ACI 214R-02 provides a means to judge the quality of testing. Variability due to testing is estimated by the within-test variation based on differences in strengths of companion (replicate) cylinders comprising a strength test result. Typically 2 or 3 cylinder tests comprise a strength test result and these cylinders are cast from the same composite sample of concrete in a wheelbarrow. Since the cylinders are made from the same concrete sample the material and manufacturing variability are assumed to be negligible and the strength difference between the cylinders is due to testing variability. ACI 214 states that the within-test standard deviation (s1) can be estimated from the average range (R) of at least 10, and preferably more, strength test results of a concrete mixture, tested at the same age using Eq. 1. However this process of calculating (s1) does not really capture all of the testing variability and this will be discussed later in this article. In Eq. 2, the within-test coefficient of variation (V1), in percent, is determined from s1 and the average strength (X).

$$S_1 = \frac{R}{d_2} \qquad \textbf{Equation 1}$$

Where d2=1.128, 1.693, 2.059 if the number of cylinders averaged for a strength test result are 2, 3, 4 respectively

$$V_1 = \frac{S_1}{X} \times 100 \qquad \textbf{Equation 2}$$

Table 2, which is a reproduction of Table 3.2 from ACI 214R-021, shows that for field construction testing the quality of testing can vary from Excellent (V1 < 3%) to Poor (V1 > 6%). The last row shows the calculated average range (R) of 2 companion cylinders assuming a case where the measured average strength is 4800 psi. It is seen that the average range can vary from below 162 psi (for excellent testing quality) to over 325 psi (for poor testing quality). Ken Day3 based on his experience states "On normal concrete, average pair differences between 75 psi and 150 psi can be considered as good testing, while that much below 75 psi must be treated with suspicion. Average pair differences consistently above 250 psi are unacceptable and should lead to re-training of testing technicians". As soon as the concrete test reports become available the concrete producer could enter the results in a spreadsheet to keep a running average of R and V1. Comparison between different strength grades becomes possible when it is based on V1 as opposed to R. If V1 goes above 5% testing quality may need to be investigated.

ACI 214R-02 also allows one to calculate the material and manufacturing variability (as measured by the standard deviation (s2)) when the total variability and testing variability is known.

The sample variance—the square of the sample standard deviation—is the sum of the sample within-test and sample material and manufacturing variances

$$s^2 = s_1^2 + s_2^2 \quad \textbf{Equation 3}$$

from which the material and manufacturing variability can be computed as

$$s_2 = \sqrt{s^2 - s_1^2} \quad \textbf{Equation 4}$$

Figure 1 shows calculated material and manufacturing standard deviations (s2 values) for a wide range of overall variability (s values) and testing variability (s1 values). S1 values are calculated from V1 values (corresponding to different levels of testing quality in Table 2) for a case where the measured average strength is 4800 psi. Based on Figure 1 one can make the following conclusions:

1. It is important for a producer to pay attention toward attaining a low material and manufacturing variability. Poor material and manufacturing quality (s2 > 650 psi) even when combined with excellent testing quality (V1 < 3%) will still result in poor overall quality (s > 700 psi).

Table 1. Standards of Concrete Control (adapted from ACI 214R-02 Table 3.2)

Overall Variation					
Class of Operation	Standard Deviation for Different Control Standards, psi				
	Excellent	Very Good	Good	Fair	Poor
General Construction Testing	< 400	400 to 500	500 to 600	to 700	> 700

Table 2. Standards of Concrete Control (adapted from ACI 214R-02 Table 3.2)

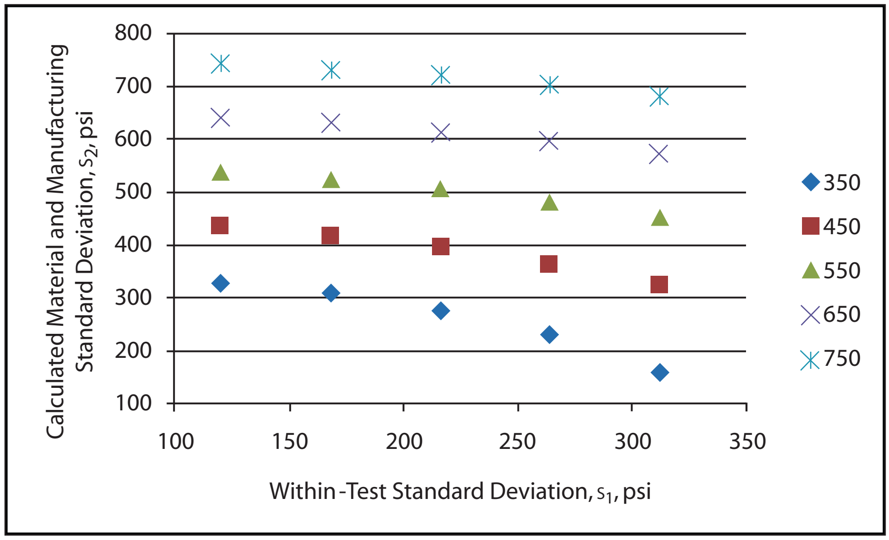
Within-test Variation					
Class of Operation	Coefficient of Variation for Different Control Standards, %				
	Excellent	Very Good	Good	Fair	Poor
Field Construction Testing	< 3	3 to 4	4 to 5	5 to 6	> 6
Calculated Average Range of 2 Companion Cylinders	< 162	162 to 217	217 to 271	271 to 325	> 325

2. If the aim is to attain an overall variability that is Very Good (s = 400 to 500 psi) it is important to attain a testing variability that is at least Good (V1 < 5%) and preferably Very Good or Excellent.
3. If the aim is to attain an overall variability that is Excellent (s < 400 psi) it is important to attain a testing variability that is at least Very Good (V1 < 4%) and preferably Excellent (V1 < 3%).

Is the ACI 214R-02 process of calculating within-test variabilities accurate?

According to ACI 214, the within-test standard deviation (s1) estimated from the average range (R) of companion test cylinders is supposed to account for variations in curing (including the variations in initial curing at the job site for the first 48 hours). Is this really the case? ASTM C31-094 states that for standard curing, immediately after casting the cylinders shall be stored for a period up to 48 hours in a temperature range from 60 to 800 F and in an environment preventing moisture loss from the specimens. Also the cylinders should be shielded from direct sunlight. Unfortunately, this is not always practiced in the field as curing boxes with temperature and humidity controls may not always be available. It has been reported5 that non standardized curing during the first 48 hours can cause more than a 1000 psi loss in 28-day compressive strength for a typical 4000 psi concrete mixture. Job site conditions (temperature, humidity) are expected to vary from day to day; therefore cylinders cast on different days are expected to experience different initial curing conditions. ***However companion cylinders cast from the same batch of concrete should experience identical initial curing conditions.*** That being the case it is logical to expect that variations in initial curing conditions do not influence the range of compressive strength of companion cylinders prepared from a batch; yet variations in initial curing conditions will impact the overall compressive strength variability. Therefore, s1 calculated according to ACI 214 does not take into account variations in initial curing even though ACI 214 states otherwise. This means that the calculated material and manufacturing standard deviations (s2 values) based on Equation 4 (plotted in Figure 1) for given s and s1 values will have to be even lower in order to accommodate the variations in initial curing.

Figure 1. Calculated material and manufacturing standard deviations (s2 values) for a wide range of overall variability (s values) and testing variability (s1 values)



A similar argument can also be made for delays in transporting cylinders to the laboratory, and beginning of standard curing. ■

References

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