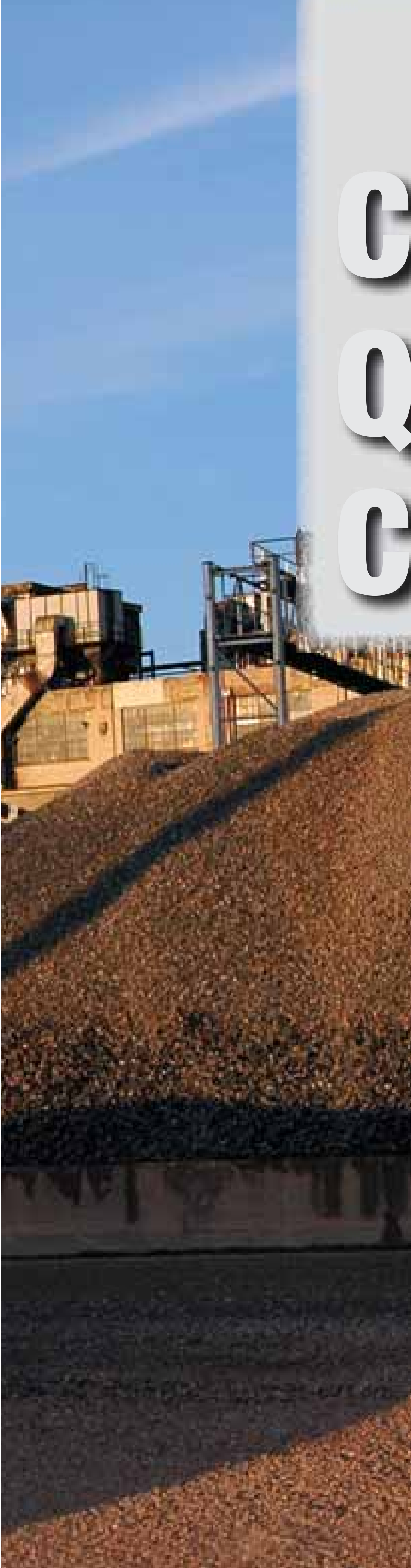
As Seen in Concrete inFocus, Fall 2007



Concrete Quality Control

The Untapped Profit Center

By Don Bain and Karthik Obla

It has been said that quality control (QC) does not matter once the project specifications have been satisfied. QC has been treated as a cost center, with not much thought as to how it can benefit the bottom line of the ready mixed concrete company. For some, QC is endless comparative testing with a testing laboratory to evaluate the quality of testing, while for some others it is to add extra cement to minimize their risk. It is the authors' view that concrete QC, if properly approached, can be a tangible profit center for the company. Many companies are already practicing good QC and are prospering as a result.

What is QC?

A QC program is much more effective if rather than trying to catch the defective loads that might be produced, it endeavors to ensure that no defective loads are in fact produced.[1]

Concrete is a variable product. Each and every day, the product is slightly different. The main thrust of any good QC system is to attempt to control and minimize this variability. A lower variability will result in a lower standard deviation (σ) and a reduced target average strength (f'_{cr}) for a specified strength (f'_c). ACI 318-05[2] requires that the target average strength should be the maximum of the following two equations:

$$f'_{cr} = f'_c + 1.34\sigma$$

$$f'_{cr} = f'_c + 2.33\sigma - 500$$

Table 1, which is a reproduction of Table 3.2 from ACI 214R-02,[3] shows that the standards of concrete control for general construction testing can vary from excellent ($\sigma < 400$ psi) to poor ($\sigma > 700$ psi). This applies to typical concrete strengths in the range of 3,000 to 5,000 psi.

Table 2 shows the cost savings due to

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

Overall variation					
Class of operation	Standard deviation for different control standards, MPa (psi)				
	Excellent	Very good	Good	Fair	Poor
General construction testing	Below 2.8 (below 400)	2.8 to 3.4 (400 to 500)	3.4 to 4.1 (500 to 600)	4.1 to 4.8 (600 to 700)	Above 4.8 (above 700)
Laboratory trial batches	Below 1.4 (below 200)	1.4 to 1.7 (200 to 250)	1.7 to 2.1 (250 to 300)	2.1 to 2.4 (300 to 350)	Above 2.4 (above 350)
Within-test 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

*$f'_c \leq$ 34.5 MPa (5000 psi).

improved QC for concrete with f'_c = 4,000 psi. Different standards of QC are assumed as per ACI 214R-02 and f'_{cr} calculated for each case as the maximum of the above two equations. Assuming that each 200-psi increase in f'_{cr} results in an increase in concrete materials cost of $1/yd[3] (due to higher cementitious materials content and/or increased admixture dosage), the cost savings due to the lower f'_{cr} can be estimated. It is instructive to note that with improved QC, i.e. reducing σ from 750 psi to 350 psi, can result in a savings of $3.9/yd[3] in concrete materials' cost due to a reduction in f'_{cr} from 5,250 psi to 4,470 psi. A producer who can achieve this will be more competitive and is more likely to be successful in getting the job.

The immediate question is how to improve QC or reduce σ. ACI 214R-02 reports that variability can be due to batching, mixing, sampling, testing and properties and characteristics of the ingredients. This article will suggest a procedure employed by the first author to control the variability due to some of the above factors and achieve concrete with a low σ.

Improving Batching Accuracy

Most producers take for granted that modern, computer-controlled concrete batch plants are capable of sustained, repeatable and accurate concrete production. In fact, they are, if they are tuned to do so and continually monitored and adjusted when necessary. All computerized batch panels have some form of error-monitoring and alerting system, and all of them make errors from time to time. There are two types of batching errors that can occur – an under-batch of materials or an over-batch of materials. Both types of errors typically will generate the same type of alert, and both may be overridden and accepted with a keystroke even though an under-batch is often easily corrected.

It is extremely important that QC personnel are familiar with and in control of the batching process. One of the easiest ways to do this is with an automated evaluation and alerting system.[4] Such systems integrate with the batch computer and in effect look over the shoulder of the plant operator. When a load is batched, it is evaluated based on criteria established by QC that may be different from that of the batch panel itself. If a load is found to be outside the prescribed limits, an alert in the form of an e-mail to a computer, cell phone or other handheld device is generated. Parameters for these alerts can be set by recipient, region, plant, material and magnitude of the error. These alerts arrive in the hand of the intended recipient in ample time to correct the error and prevent that particular batch of concrete from ever arriving at the jobsite.

Most companies measure their batching accuracy by cumulative end-of-day, week or month method. If at the end of some time period the total amount of material used in the concrete more or less equals the amount that should have been used, then all is deemed to be well. This type of control is more often than not the responsibility of the accountants and not QC or operations. This "inventory-based" method is not useful enough to adequately establish the true performance of a concrete plant or to predict the performance of individual concrete batches. A cumulative ending number only tells a small part of the story. It is necessary to determine the path to that number.

A concrete plant typically will print out the ingredients of each batch and the difference between the target amount and actual amount batched. With the average plant producing 50 to 200 loads per day,

Table 2. Cost Savings Due to Improved QC for $f'c$ = 4,000 psi

QC Standards (ACI 214)	Excellent	V. Good	Good	Fair	Poor
σ, psi	350	450	550	650	750
$f'cr$, psi	4470	4600	4780	5020	5250
Cost savings, $/yd^3	3.9	3.2	2.3	1.2	0.0

it is not hard to see that vast amounts of paper are generated. It has been said that if you have the time to read what is contained in the boxes of batch reports, you probably are not qualified to understand them! The lack of the true batching picture can and often does lead to misleading conclusions about concrete performance.

Small, persistent errors, especially with cement, can lead not only to erroneous conclusions about concrete performance at the mix-design stage but also to a substantial waste of money and resources. Uncorrected or unrecognized batching errors are one of the fundamental causes of concrete variability. While cement is usually the primary focus of any plant analysis, all materials are subject to variations in batching, and all have an effect on the quality of the concrete. It is pointless to attempt a tuning of the batch plant computer if the plant itself is not in perfect mechanical condition or, more correctly, if the condition of the plant has changed with time. In fact, a real-time reporting of batching errors is one of the best ways to monitor the changing mechanical condition of a plant. If multiple consecutive alerts are received from the same plant, it can safely be assumed that a breakdown has just occurred or is about to occur. This type of system is often just as valuable as a maintenance tool as it is a QC tool.

Figure 1. Significant Cement Over-Batching Prior to Installation of Improved QC System (1 plant producing 200 yd³/day working five days/month)

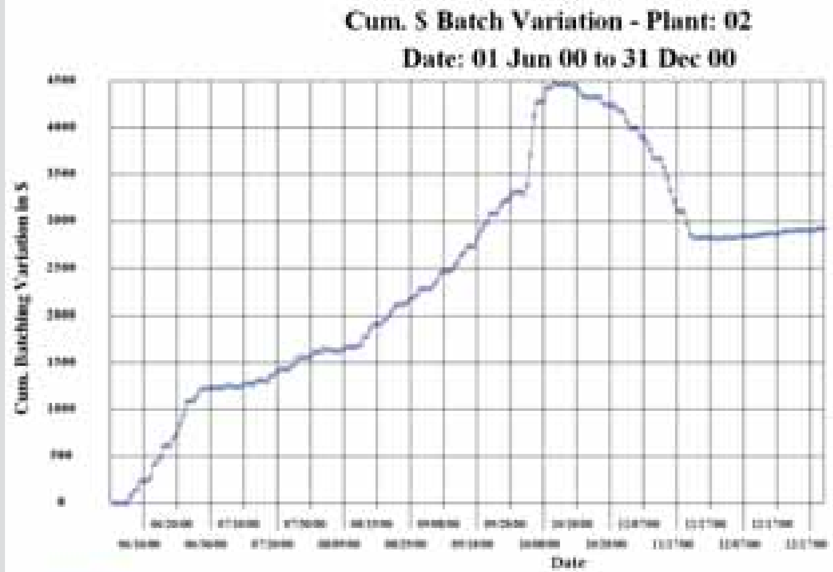


Figure 1 shows the cement over-batch in dollars from a fairly new concrete plant producing approximately 200 yards³ per day. It is clear that for the first month (June 1-30) the plant was on an average over-batching about 10 pounds/yard³ of cement. Between June 30 and Sept. 30, the over-batching continues upward in a series of ever-shortening steps. This is due to attempts to tune the plant using the batch computer as the plant continued to become more and more mechanically unsound. It can easily be seen at what point the plant fails.

It also is apparent that once the plant was repaired to a proper mechanical condition, the batch computer had in fact been tuned to an under-batch condition in order to correct a deteriorating mechanical condition that had been causing the plant to over-batch. Once the plant was repaired and the computer properly tuned, more accurate batching was possible, as reflected by the almost flat line starting about Nov. 20.

Figure 2 represents what can be achieved in batching accuracy when attention is given to all materials. This figure represents five plants producing almost 3,000 yards³ per day. Note that this figure represents five months of production totaling more than 300,000 yards³. Total material over-batch has been reduced to an average of $0.013/yards³ for the five-month period. In comparison, the average concrete plant over-batches by more than $0.50/yards³. This type of performance requires constant monitoring and preventative maintenance.

Material savings of $0.50 per yard³ or more are not at all unusual for the company that practices effective batch monitoring and control. This cost savings is purely due to the reduction in material over-batch. In addition, high batching accuracy will translate to a much lower σ of strength test results, thus requiring a lower f'_{cr} and lower materials cost to attain that. This phenomenon is especially important in situations where statistical data from two or more plants are combined to determine the σ. If one plant had been over-batching while the other plant had been under-batching, the σ would be much higher, resulting in high materials costs at both plants. In the experience of the first author, the cost savings due to a lower f'_{cr} as a result of batching accuracy is an additional $0.70 per yard³.

Minimizing Variability Due to Changes in Material Characteristics

Even though a concrete producer may always receive materials from the same source, it is well known that the material properties and characteristics change with every shipment. Some of these changes can significantly influence the concrete performance and lead to higher σ of compressive strength. The easiest and perhaps most popular way to handle material changes is to put additional cement into the mix so that low-strength problems can be avoided. A better approach is to track concrete performance and material characteristics and make suitable, timely adjustments to mixture proportions to balance the impact that the change in material characteristics may have on the concrete performance. A CUSUM

Figure 2. Significant Reduction in Material Over-Batching After Installation of Improved QC System (five plants producing a total of 300,000 yd³ for that period)

graph is an effective tool to track concrete performance and material characteristics.

A CUSUM graph works in the following manner. With any large data set (the larger the better), an average is calculated. The difference between each individual value and the average is cumulatively summed and graphed against a timeline. A CUSUM graph begins and ends at zero and is very effective in highlighting change. As long as the slope of the graph is constant, whether positive or negative, the performance of the concrete for that property plotted is constant. If the slope of the graph changes, it indicates a change in that property. Figure 3 shows a CUSUM graph for strength. A positive increase in slope indicates an increase in strength, while a negative increase in slope indicates a decrease in strength. In a CUSUM graph, the Y-axis denotes the cumulative sum of the property measured, and the X-axis denotes time. Different properties with different magnitudes can be plotted on the same graph. For instance, slump multiplied by 1,000, concrete temperature multiplied by 100 and compressive strength can be plotted on the same graph at the same scale, as illustrated in Figure 4.

With commercially available software,[4] as many as eight variables can be plotted on the same graph. Common change points can highlight a cause-and-effect relationship, and therefore any variable (fineness modulus of sand, Blaine fineness of cement, etc.) whose change has a known effect on concrete performance can be monitored, and potential changes in concrete performance can be predicted at the earliest possible moment.

Figure 4 shows the characteristic CUSUM relationship between 28-day concrete strength, concrete temperature and slump. A common change point occurs on or about Oct. 22. From the start of the plot on July 1 to this point, the values of slump, temperature and strength are more or less constant, as indicated by the relatively constant slope of each of the variables plotted. On Oct. 22, concrete temperature turns downward, stabilizes and remains constant to the end of the plot on March 31. Slump has also turned downward, probably in response to the cooler concrete having a higher slump life and thus and thus not requiring higher slumps for ease of placement.

At the same point, concrete strengths have turned upward. A cause-and-effect relationship is established, and a change in temperature is clearly seen as a good predictor of concrete strength performance. By watching the temperature CUSUM and reacting to changes in it, whether up or down, it is most advantageous to begin heating or cooling the concrete. Producing concrete year-round at a temperature that is as consistent as possible will reduce the concrete strength variation and lower the standard deviation.

On a CUSUM graph, characteristics of aggregate and cementitious materials must be plotted over time against concrete performance. The most expensive and most influential ingredient, cement, is often ignored due to lack of data. It has been the experience of the first author that the cement companies are interested in the performance of their product in concrete, but short of doing their own concrete testing, have not had an easy method of compiling the data. Most concrete companies receive from their cement supplier monthly or sometimes weekly certifications that verify that cement produced complies with applicable ASTM standards regarding chemistry, physical properties and strength requirements. These certifications are based on averages of all cement produced and may vary from the characteristics of cement shipped.

In order to properly control the quality of concrete produced, it is vital to have access to the material characteristics for each individual shipment of raw material. A report on the uniformity of cement from a single source, as per ASTM C 917, can be a useful resource to the concrete producer.

By continuously monitoring concrete performance over time and making rapid adjustments to mixture proportions, it is possible to reduce the σ for concrete strength test results. The first author has achieved cost savings of about $0.35 per yard³ just by this technique.

Water Addition After Batching

Truck drivers and customers may alter the concrete after it is batched. This usually is in the form of water being added to the concrete after it is batched. Modern concrete is usually designed based on a water-to-cementitious-materials ratio (w/cm), but it is ordered, delivered and accepted based on a slump that is either specified or needed by the contractor to facilitate placement and finishing. In order to comply with required slump, the driver may add water to the concrete prior to leaving the plant for the jobsite at the "slump rack." This is sometimes done with water on the truck but is more often done through a hose or overhead source at a slump or temper stand. The customer may add water at the jobsite, either to bring the load to the ordered slump or to make it even more fluid. This water usually is not measured and often is not included in the batch water. It is an unknown variable contributing to the variability of the concrete.

Figure 3. CUSUM Graph for 28-Day Compressive Strength Over 10 Months of Production

The ready mixed concrete producer has for years relied on the driver's judgment as to how much water was added and relies on him to remember to write it on the delivery ticket before it is signed. Even though some specifications prohibit the addition of water, it is not advisable to eliminate the addition of water by the driver or customer. ASTM C 94-04[5] does allow for a single addition of water at the jobsite as long as the w/cm is below the specified level.

Technology now exists to accurately measure all the water that is added to the concrete prior to discharge. Meters on the slump or tempering stands can measure the amount of water added by the driver and include this water in the batched water amount. Such measurements, if displayed in front of the batch plant operator, can have the bonus effect of shortening the time the truck has to remain at the plant, tempering the load for target slump. Truck-mounted meters can measure jobsite additions of water and, given a compatible truck-tracking system, can transmit this data back to a central database or even e-mail the additions to the customer. New technology now exists that controls and records the addition of water in the truck mixer based on the torque on the PTO (slump meters) so that the customer gets a consistent product with every load.

Variability in Testing

The final variable is the testing itself. It is felt that the only way to combat substandard testing is endless comparative testing, which may be the sole purpose of some QC departments. Testing variability is due to sampling, specimen preparation, curing and testing. These common errors will manifest themselves as differences between the two 28-day cylinder strengths, the average of which constitutes a single concrete test result. In order to at least be aware of the differences between technicians, it is necessary to track the 28-day pair difference of each technician. Figure 6 shows a comparison typically conducted by the first author through the use of commercially available software.[4]

Most modern laboratories do a good job of storing, curing and breaking the cylinders once they receive them. By far the most common lab-related problem is a failure to conduct initial curing of the cylinders at the jobsite and to transport them to the lab in a timely manner as required by ASTM C 31-03.[6] This type of mishandling has the effect (usually) of lowering the test result of all of the cylinders. It is therefore necessary to record and monitor the time in field before transport to the lab.

Overall lab performance can only be quantified in a lab-to-lab comparison of "like" concrete. An almost unknown but surprisingly common error is simply a typographical misrepresentation of the results obtained. It should be noted that the first author's ongoing informal study of typos on testing reports indicates that as much as 11 percent of all test results have at least one identifiable typographic error, such as a lack of correlation between date and ticket number or truck number or load date. However, it is impossible to identify typos relating to measured values such as slump, strength, etc. Nevertheless, it exists and contributes to the overall variability.

There is little that the concrete producer can do to minimize the effect of testing variability on the quality of concrete produced. Making the labs aware of the ability to monitor and measure testing

Figure 4. CUSUM Graph for 28-Day Compressive Strength, Strength and Temperature Over 12 Months of Production Showing Common Change Points

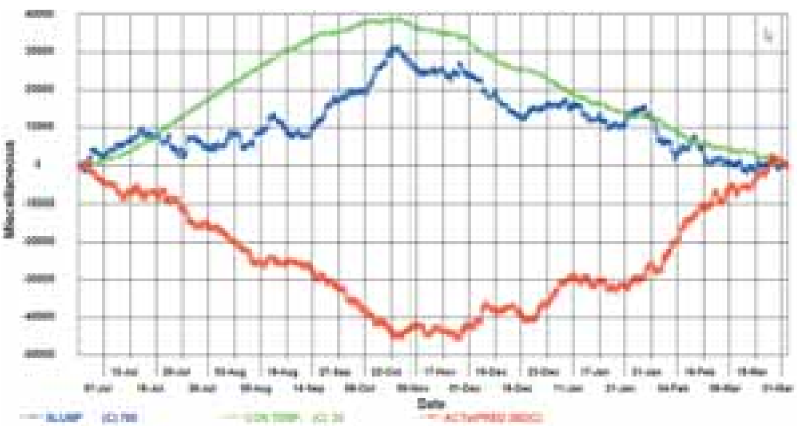


Figure 5. Tracking Testing Variability by Technicians

QC Testing Statistics for Testers

From: 1/1/2006 to 1/1/2007

Tester Number	Pair Diff All	Max. Pair Diff	No of Excess RNG
1	109	330	1
2	82	210	0
3	130	130	0
4	127	200	0
5	111	300	1
6	330	330	1
7	100	100	0
8	17	40	0
9	320	440	1
10	450	450	1
11	108	200	0
12	77	180	0
13	100	100	0
14	205	570	1
15	137	300	1
16	50	50	0
17	153	280	0
18	99	260	0
19	90	260	0
20	0	0	0
21	115	220	0
22	133	370	1
23	162	400	1
24	160	160	0
25	88	190	0

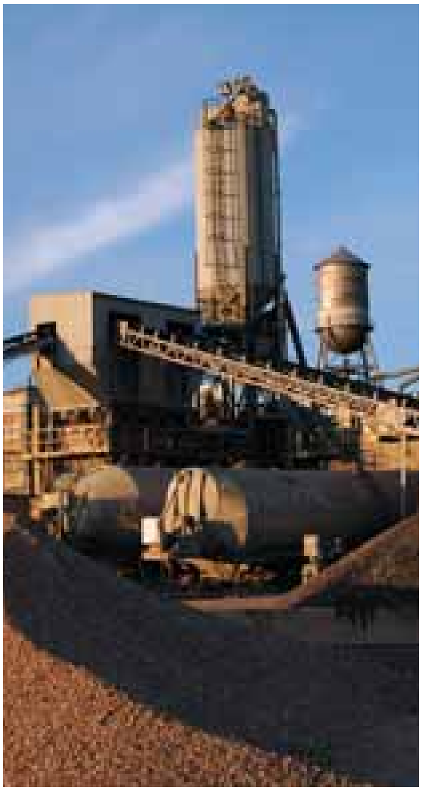
variation (as shown in Figure 5) generally motivates the lab to improve its testing standards and helps identify technicians who tend to attain greater testing variability.

Intangible Benefits from Improved QC

The intangible benefits of QC are considerable and perhaps more valuable than the tangible benefits in the long run. A common excuse for the adoption of a QC system is simply the lack of time to do data entry and evaluation. A good system will create its own time because you simply will not be dealing with the common time-consuming issues typical of today's QC professional. The first and most obvious benefit is a reduction in customer callbacks both for QC and sales. There will be fewer loads batched in error and a reduction in rejected loads. There also will be a reduction in low-concrete tests, which translates into less remedial testing and the time it takes to deal with them. There also will be fewer back charges by the customer for defective concrete. Because of the constant tracking of material batching, it is possible to quickly detect plants that have just had a breakdown or where one is about to occur. This helps reduce plant downtime and maintenance.

The excellent database developed also can come in handy for mixture design submittals and as a means to go back and troubleshoot potential problems that may occur several years into the future.

By far the greatest benefit is the perception of competence. If the customer believes he will get a better product, he can be convinced to pay more for it. When the inevitable problems do occur, the customer is more willing to look at himself, the lab or other factors beyond the concrete producer. The owner, engineer and architect are more willing to trust and even take the advice of the concrete producer when problems do occur. They may even consult and seek the help of the concrete producer on matters of specification and desired concrete performance. The bottom line is a happier, satisfied customer, which will inevitably lead to more business and a higher profit.



Summary

By improving concrete quality control it is possible to significantly reduce the variability of concrete performance, such as the standard deviation for strength. The first author consistently averages σ lower than 400 psi and has attained a net cost savings of $\$1.55/\text{yard}^3$ due to the improved QC. For a different company, if the initial σ is much higher, the cost savings as a result of improved QC can even be as high as $\$3.9/\text{yard}^3$. In addition, improved QC also provides substantial intangible benefits. Although examples have been provided, this article should not be construed as an endorsement of any commercial software product. ■

References

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