Variation in Concrete

Part 8 of Concrete Quality Series

By Karthik Obla, Ph.D., P.E., Vice President, Technical Services

Parts I and II of the Concrete Quality series discussed that a good measure and benchmark of concrete quality is the Standard Deviation (SD) of compressive strength test results. The primary factors that impact the SD are variability associated with materials, production and testing. In order to reduce the strength standard deviation the concrete producer needs to manage those aspects of variability that can be controlled. This article discusses the benefits of controlling accuracy of batching of concrete material ingredients other than water. Effects of batching inaccuracies of water and ways to reduce it have been addressed in earlier articles.

ASTM C94 Scale Accuracy and Accuracy of Plant Batching

ASTM C94-11 states that scales shall be considered accurate when at least one static load test within each quarter of the scale capacity can be shown to be within ±0.15% of the total capacity of the scale or 0.4% of the net applied load, whichever is greater. The NRMCA Plant Certification Check List invokes these requirements through the range of use of scales. The certification requires companies to verify scale accuracy at least once every six months and arrange for prompt recalibration and correction if non-compliance is indicated or if the plant is moved or other maintenance impacts the weighing systems. The accuracy of volumetric measuring devices in the NRMCA Check List for water and chemical admixtures is established by the required batching accuracy. NRMCA certification requires that volumetric measuring devices should be checked for accuracy at least once every 6 months.

ASTM C94 and ACI 117-06 state the tolerances for batching ingredients of concrete. The batching accuracy requirements in the NRMCA Plant Certification program are as required in ASTM C94 and stated in Table 1. For weighed ingredients, accuracy of batching is determined by comparison between the desired weight and the actual scale reading; for volumetric measurement of water and admixtures, accuracy is determined by checking the discharged quantity relative to the target, either by weight on a scale or by volume in an accurately calibrated container. Volumetric measurement is commonly used for water and typically used for chemical admixtures. It is realized that on any single batch, at least one of the ingredients may be out of tolerance, as discussed later. For the NRMCA plant certification, inspectors are advised to review several batch records and to determine that the plant complies with the batching accuracy by reviewing the average of at least 10 batches of concrete.

Two Issues with Batching

The above requirements are essential first steps for ensuring batching accuracy. Concrete producers should continuously review batch records to ensure that batch weights of all the ingredients of concrete are...
within the ASTM C94 batching accuracy requirements. Concrete plants may have to be tuned, continually monitored and adjusted when necessary. If this is not practiced two possible errors may occur:

1. Over batching materials means giving material away and increased material cost per cubic yard produced. Under batching results in under yield causing customer complaints.

2. Batch weights that are highly variable can cause significant variations in yield, strength and other performance characteristics of concrete. It also results in poor inventory control of ingredient materials at the plant.

Over batching

Fig. 1 shows the cement over-batch in dollars from a fairly new concrete plant producing approximately 200 yd$^3$ per day. It is clear that for the first month (June 1 to 30) the plant was on an average over-batching about 10 lbs/yd$^3$ of cement. Between June 30 and September 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 be easily seen at what point the plant fails. It is also apparent that once the plant was repaired to a proper mechanical condition, that 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 November 20.

Fig. 2 represents what can be achieved in batching accuracy when attention is given to all materials. This figure represents five plants producing almost 3000 yd$^3$ per day. Note that this figure represents five months of production totaling over 300,000 yd$^3$. Total material over-batch was reduced to an average of $0.013/yd^3$ for the five-month period. This type of performance requires constant monitoring and constant preventive maintenance.

Another producer reports similar reductions in over batches. Fig. 3 (upper plot) is a timeline graph (over 2 years) of sample averages of cement batch weights of 3 consecutive batches of concrete. Each data point was the average of cement batch weights for 3 consecutive concrete batches for the same mixture. At least 2 such points were collected per day and so the whole plot consists of 663 data points. At the beginning, cement was being over batched on average about 5 lb/yd$^3$ over the target weight.

Figure 2. Significant Reduction in Material Over-Batching After Installation of Improved QC System (5 plants producing total of 300,000 yd$^3$ for that period)
compared with target weights for all the concrete ingredients – cement, fly ash, slag cement, coarse aggregates, fine aggregates, air entraining admixtures and 2 other chemical admixtures (if used). Out of 620 batches 565 batches were 3 cubic yards or higher; the following analysis is restricted to those since short loads (less than 3 cubic yards) are more prone to batching inaccuracies. Table 2 provides the analysis of the out of tolerance batches for just the cementitious weight. 83% of all batches where within the C94 tolerance of ±1%. 95% were within ±2%. When 10 batch records were averaged, 98.5% of the plants met the batching accuracy requirements of ASTM C94. Another aspect of this review is that most batches were out of tolerance on at least one ingredient.

**Cementitious Batch Weight Variation and Its Effect on Strength Variation**

For a given concrete mixture, variations in cementitious batch weights can be expected to lead to strength variations. A commonly used rule of thumb is that 1 pound of cementitious material equates to a compressive strength between 8 to 12 psi. (This is a simplistic assumption that is valid only for w/cm around 0.50 to 0.60 or for concrete with 28-day compressive strength ranging from 4000 to 5000 psi). This means that a ±1% variation in cementitious batch weight will result in a ±1% compressive strength variation. If the cementitious batch weight varies by ±1% of the target value 95% of the time, the effect is that the resulting compressive strength variation should be within ±1% of the average strength 95% of the time. For the purpose of this analysis it is also assumed that the cementitious batch weight and the resulting compressive strength of the concrete are normally distributed. If 95% of the time it is within tolerance then it follows that 97.5% of the time the cementitious batch weight is more than the lower tolerance limit and as a result 97.5% of the time the compressive strength of the concrete should be greater than the strength corresponding to the cementitious batch weight at the lower tolerance limit.

So, for the 97.5% probability, it follows that:

\[ X - 1.96s = (1-y)X \]

where \( X \) is the average compressive strength; \( y \) = variation in cementitious batch weight (0.01 for 1%; 0.02 for 2% etc.); \( s \) = standard deviation of resulting compressive strength test results.

Simplifying, we get

\[ s = \frac{y}{1.96}X \]

If \( X=5000 \) psi, \( s \) can be calculated as given in Table 3 for the various cementitious batch weight variations. Table 3 shows that the resulting strength standard deviation varies linearly with the cementitious batch weight variation. ACI 214R-02 states that for laboratory trial batches the overall standard deviation for excellent standard of concrete control should be below 200 psi. To attain an overall standard deviation of 200 psi, assuming very good testing standard deviation of 140 psi (COV of 2.8% for average 5000 psi concrete which corresponds to Very Good testing control), one would have to target a standard deviation of less than 140 psi for material and manufacturing and initial curing variations! Cementitious batch weight is one of numerous variables affecting compressive strength variability. Considering this, the standard deviation of more than 25 psi due to cementitious batch weight alone may be too high. The analysis of the NRMCA batching survey in Table 2 shows that for cementitious material 95% of the batches are within ±2%. If a concrete producer is reviewing these records, a suggested target for improvement would be to ensure that the cementitious batch weights should be within ±1% in 95% of the batches. As a process of continuous improvement, once the 95% target level has been attained producers can aim for 99%. One company has reported to have attained batching accuracy of 99.9999% or only 1 in a million batching failure rate and has quantified significant material cost savings as should be expected!

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. Batching inaccuracy can be cumulative. A 2% reduction in cementitious batch weight in addition to a 2% increase in aggregate batch weights in the same batch can lead to a 4% reduction in cementitious weight when concrete is adjusted for yield thus resulting in significant concrete performance variation. Also, admixture dosage...
C94 cement batching tolerance is ±1%

Table 1. Batching accuracy requirements per ASTM C94 and NRMCA Plant Certification

<table>
<thead>
<tr>
<th>Check List Section</th>
<th>2.5.1</th>
<th>2.5.2</th>
<th>2.5.3</th>
<th>2.5.4</th>
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</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>Cementitious Materials</td>
<td>Aggregates</td>
<td>Water, Vol. or Wt.</td>
<td>Admixtures</td>
</tr>
<tr>
<td></td>
<td>Individual Batchers</td>
<td>Cumulative Batchers</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Basic Tolerance</strong></td>
<td>± 1% of desired weight</td>
<td>± 2% of desired weight</td>
<td>± 1.5% of desired value or</td>
<td>± 3.0% of desired value or</td>
</tr>
<tr>
<td></td>
<td>Intermediate and cumulative</td>
<td>Intermediate and cumulative</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Small Batch Tolerance</strong></td>
<td>-0 to +4% of desired weight</td>
<td>± 0.3% of scale capacity for loads below 15% of scale capacity</td>
<td>Whichever is greater</td>
<td>Whichever is greater</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum dosage rate per 100 lb. cement</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Analysis of Cement Batching from a NRMCA Batching Accuracy Survey

<table>
<thead>
<tr>
<th>Tolerance Limits, %</th>
<th>Percent within Tolerance, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>±1%</td>
<td>83</td>
</tr>
<tr>
<td>±2%</td>
<td>95</td>
</tr>
<tr>
<td>±5%</td>
<td>98</td>
</tr>
<tr>
<td>±10%</td>
<td>99</td>
</tr>
</tbody>
</table>

C94 cement batching tolerance is ±1%

Table 3. Cementitious Content Variation and its Effect on Concrete Strength Variation

<table>
<thead>
<tr>
<th>Cementitious Batch weight Variation, %</th>
<th>Calculated Concrete Strength Standard Deviation, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>±1%</td>
<td>26</td>
</tr>
<tr>
<td>±2%</td>
<td>51</td>
</tr>
<tr>
<td>±5%</td>
<td>128</td>
</tr>
<tr>
<td>±10%</td>
<td>255</td>
</tr>
</tbody>
</table>

How can a company improve batching accuracy?

Once a target has been established there are different ways companies can go about to improve batching accuracy. One producer has used a real time error monitoring system with great success. Control systems available to the industry allow for the notification to responsible company personnel, in the form of an e-mail, whenever the set batch tolerances are exceeded. 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 (quality personnel) in real time so that a decision can be made as to whether to correct the error, prevent that particular batch of concrete from being delivered to a project, divert the load to another customer or to discard the load. Real time reporting of batching errors is a good way to monitor the changing mechanical condition of a plant as well.

Another producer has had significant success in improving batching accuracy using statistical process control charts (Fig. 4). The upper chart is a timeline graph of sample averages of ingredient batch weights of 3 consecutive batches of concrete; 2. The lower chart is the corresponding range within the sample. In the upper chart, the straight line labeled X̄ is the process average. The lines labeled UCL and LCL are upper and lower statistical control limits, set three standard deviations above and below the process average. The upper chart is sensitive to shifts in process average and the bottom chart is sensitive to process variation. The charts depict a process said to be in a state of statistical control - that is a process showing random variation with no points falling above or below the control limits. Process variation originates from many random common causes. When a process is operating in this manner, the probability that all points will fall within the control limits is 0.997 probability or 99.7 percent. Points that plot outside the control limits are said to come from special or assignable cause variation; these causes of variation can be easy to locate and correct. So in this respect, the charts provide a decision-making tool to identify when an assignable cause for the variation occurs that then generates an action as to correct the situation or not.

In the process described the plant operator was asked to plot two points each of three consecutive batches a day from the batch weight data being reported by the batch control computer. A top-selling concrete mix was picked for the evaluation. The first two batches of the day were not used as plant equipment had not yet warmed up. When the data collection was initiated quick changes were avoided. Changes were made methodically and involved resetting constants in the batch computer without any hardware changes. Fig. 3 shows control charts for the cement batching process. The point “S” on the charts in Fig. 3 is the point where this process was brought into statistical control most of the time. The points under A, B, C and D were caused by the batch control computer changing its own constants, reacting to assignable cause variation as though it were a shift in the process average.
and adjusting, where no adjustment was warranted. Initially, there were differences as high as 40 lb/yd³ between batches that could have led to significant variation in concrete performance. Similar control charts were developed for all the ingredient materials. Fig. 5 shows the control charts for the fine natural dune sand batching process. Changes to batching such as tolerances, jog timing, jog duration, time in air fall, etc. were made methodically by the plant operator. The overall result was an 80 percent reduction in the average range. In the beginning there was difference as high as 80 lb/yd³ between batches, significant enough to cause quite a bit of variation in yield, strength etc. In the lower chart the four “out of control” points under the letter A are caused by one batch in the sample going way over target batch weight just after the plant ran out of material on the previous batch. The “out of control” point under the letter B was from a modification tried. Overall for all the ingredient materials the average range was reduced by about 60%. For ingredients that are batched at very low weights (< 100 lb/yd³) it was found harder to achieve large reductions. By methodically following the process and reducing the standard deviations, the producer was able to operate at a variation less than half of the C94 tolerance for cement and aggregate batch weights thus ensuring that tolerance limits will be exceeded less than 1 in a million batches! The producer reports success in implementing statistical process control in aggregate production and paperwork as well.

The producer states that an environment of trust that is free of fear is essential for statistical process control to succeed. Initially, rapid progress can be made by making simple changes and it is important not to resort to blame someone or some group as then many of the low hanging fruit will not be accessed. The producer states that a plant operator who achieved most of the improvements shown in Figs 4 and 5 has become an advocate of continuous improvement and pride in workmanship, traits very beneficial to the company.

Another way of doing batching accuracy is 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 is a business side argument. Unfortunately, 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. There needs to be a quality side of the argument too. A cumulative ending number only tells a small part of the story, it is necessary to determine the path to that number.

Summary

Improving batching accuracy can help reduce material over-batching and thus reduce material costs per cubic yard produced. It can also help reduce material under-batching and thus under yield that could result in poor customer relations. Improving batching accuracy can help attain more consistent performance for fresh concrete properties that is important to the contractor and to reduce variation of compressive strength of concrete. The intangible benefits of improving batching accuracy are also considerable. There will be fewer loads batched in error, and a reduction in rejected loads. 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.

There is a cost to improving batching accuracy. It may require plant operator time for developing and tracking control charts or investing in error monitoring alerts. It may increase the time for batching materials into the ready mixed concrete truck. But the benefits far outweigh the additional costs.

References

2. 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.
3. Obla, K.H., “Variation in Concrete Strength due to Water and Air Content Variation – Part IV of Concrete Quality Series”, Concrete InFocus, January-February 2011, Vol. 10, No. 1, NRMCA, pp. 29-32.

“The standard deviations of the compressive strengths are calculated by assuming that the cementitious batch weights are within the noted variation 95% of the time, and the cementitious batch weights and resulting concrete compressive strengths are normally distributed.