No. 3 TECH BRIEF December 2024

Advancing Concrete Pavement Technology Solutions

QUALITY CONTROL FUNDAMENTALS AND TOOLS FOR CONCRETE PAVING

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Federal Highway Administration

Part of Cooperative Agreement 693JJ31950004, Advancing Concrete Pavement Technology Solutions

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Summary and Disclaimers

The purpose of this tech brief is to provide an overview of quality control (QC) fundamentals and to describe quality control tools that can be used on concrete paving projects that feature performance-engineered concrete mixtures (PEMs) or conventional concrete mixtures. The document is intended for highway agency and contractor engineers.

Introduction

Quality control (QC) by contractors, concrete suppliers, and materials suppliers is an integral component of a transportation agency's quality assurance (QA) program and supports the construction of long-lasting concrete infrastructure. Recently, the Federal Highway Administration (FHWA) supported the development and publication of *Quality Control for Concrete Paving: A Tool for Agency and Industry* (Cavalline et al. 2021), which provides an overview of QA and QC for concrete paving and aims to help both contractors and agencies improve or enhance their existing QC programs. Based upon material presented in that document, this tech brief provides an overview of QC fundamentals and describes QC tools that can be used on concrete pavement projects that feature performance-engineered concrete mixtures (PEMs) or conventional concrete mixtures.

Quality Control Fundamentals

QC is defined by the Transportation Research Board (TRB) as the system used by contractors "to monitor, assess, and adjust their production or placement processes to ensure that the final product will meet the specified level of quality. QC includes sampling, testing, inspection, and corrective action (where required) to maintain continuous control of a production or placement process" (TRB 2018). In addition, QC includes the contractor's development of processes to support control of quality and, subsequently, implementation of adjustments to improve those processes.

QC is the first step in a larger process that supports quality construction and is therefore a key component of an agency's QA program (Cavalline et al. 2024). However, QC offers far more to a contractor than simply a checklist for complying with agency requirements. Implementing an effective QC program and enhancing and improving it over time provides the contractor with confidence in the work performed, helps manage risk, and improves profits and reputation.

"What gets measured gets managed" is a common adage in quality management, and it follows that at the core of every QC program is the monitoring of key quality characteristics and a process for the continuous improvement of both those characteristics and the QC process itself. Effective QC does not rely upon the agency to notice quality issues or defective work; rather, issues are identified by the contractor through process control and self-inspection so that adjustments and corrections can be made prior to the agency's acceptance activities.

The Deming cycle, or the plan-do-check-act cycle (shown in Figure 1), is an important quality management approach describing a continuous improvement cycle. This approach originated almost a century ago and helped drive quality improvements in the manufacturing sector throughout the 20th century (Deming 1994), but it is still applicable today and is used in many manufacturing QC settings. This approach can be readily applied to the construction sector and incorporated by contractors into both organizational-level QC programs and project-level QC plans.

The quality improvement process begins with a plan (Step 1 in the cycle) that identifies goals such as achieving a higher production rate, reducing nonconforming material, lowering costs, or accomplishing other outcomes. Once specific goals are identified, policies and procedures that support the achievement of these goals are developed and implemented (Step 2 in the cycle).

Over time, as these policies and procedures become established, training and improvement continue and data are monitored and collected to check on key measures linked to the desired goals (Step 3 in the cycle). Data are analyzed using appropriate methods and presented using tools that enable the quality team to draw conclusions about the reliability of the processes and the quality of the outputs. Upon review of the data, areas for improvement and opportunities for growth or other benefits are identified. Ultimately, the quality team acts on these ideas, implementing corrective actions and continuing the cycle of improvement (Step 4 in the cycle).

> "Any product, process, or service can be improved, and a successful organization is one that consciously seeks and exploits opportunities for improvements at all levels" (Swift et al. 1997).

Tools for Quality Control

The data recorded from a process can be qualitative, quantitative, or both. Qualitative information, captured in tools such as flowcharts or process diagrams, is often used to support planning and administration. Quantitative data can be analyzed using statistical methods, supplemented with qualitative data about any associated processes, and used for decision-making. Technological advancements in construction have led to a substantial increase in the types and quantity of data that can be collected. In fact, cloud-based construction management software has emerged, in part, to help support the use of the vast amount of construction data that can be obtained using modern sensors, data collection devices, and models.

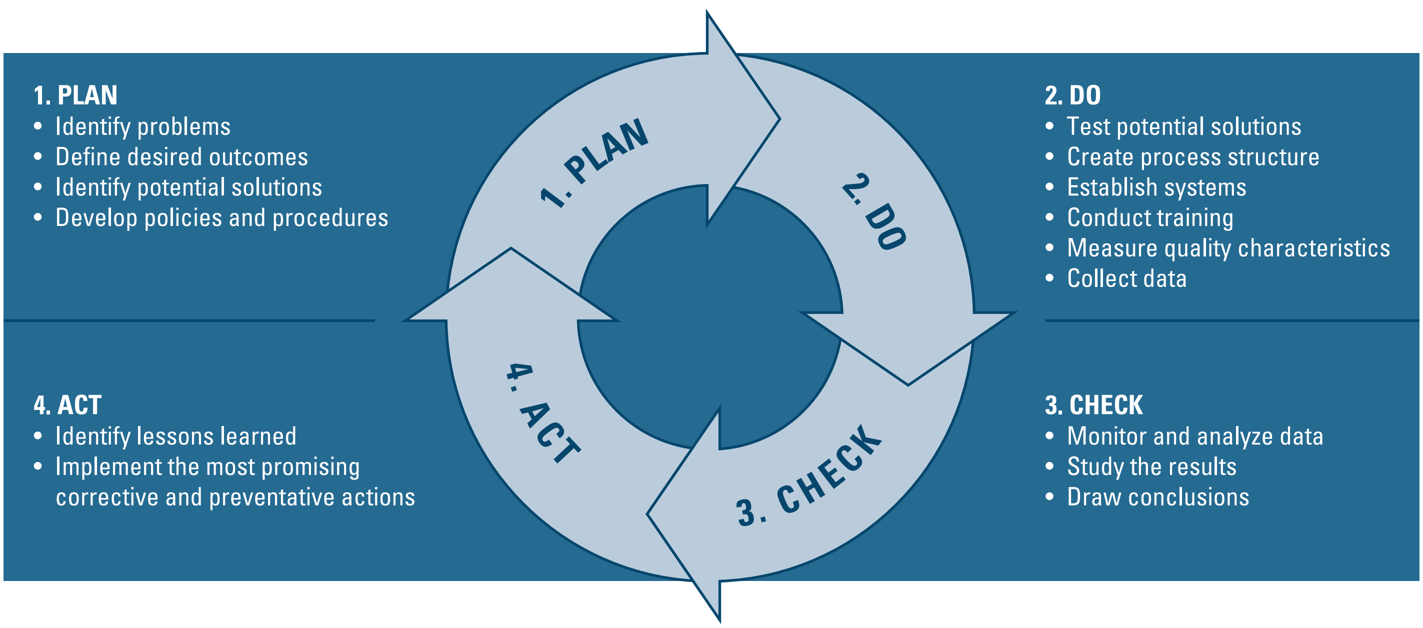

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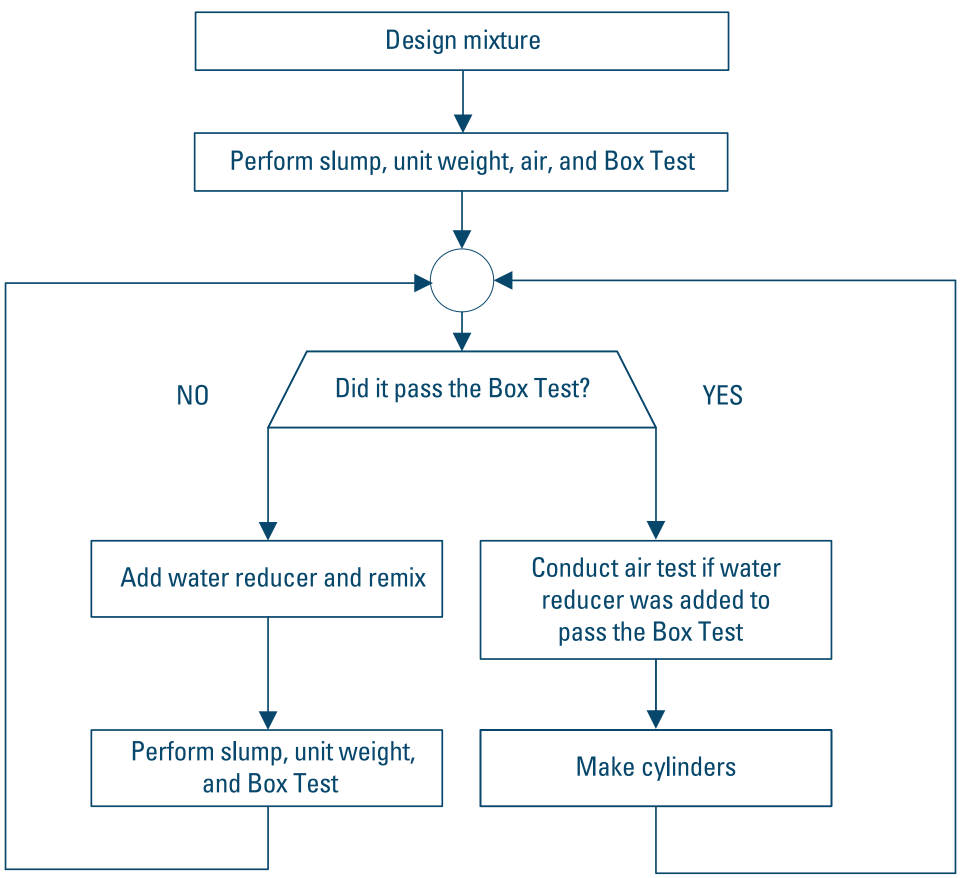
Figure 1. Plan-do-check-act cycle

A variety of tools exist to support quality management and facilitate decision-making and continuous improvement through the recording, processing, and use of data. Many of these tools have their roots in the manufacturing sector and have been adapted for use in construction. These tools can range from simple checklists to complex databases and analysis software. The following sections provide a brief introduction to several tools used to support QC, with an emphasis on control charts, which play an integral role in the monitoring and improvement of QC processes. Additional information on these and other QC tools is provided in *Quality Control for Concrete Paving: A Tool for Agency and Industry* (Cavalline et al. 2021) and in Wadsworth et al. (2001), Besterfield (2009), and Montgomery (2013), among other publications.

Process Diagrams, Check Sheets, and Other Tools

Process diagrams, or flowcharts, are used to graphically display or describe the movement of something of interest (such as a material or information) through a process or system. Flowcharts are useful in QC as a tool to support the planning, communication, and improvement of a process or as a training tool or to provide information to stakeholders involved directly or indirectly with a system. Moreover, flowcharts are highly useful in the troubleshooting process, where they allow stakeholders to observe a system and review interrelationships.

Flowcharts can often be simple, using geometric shapes and arrows to show steps, decision points, and interrelationships. An example flowchart illustrating the process for testing a trial mixture using the Box Test (Cook et al. 2013), a PEM test, is shown in Figure 2. Like many QC tools and documents, a flowchart is a dynamic tool that changes as processes are modified, adapted, or enhanced. Once a flowchart is established, data useful to QC can be appended, such as measurement requirements, performance targets, and other information supporting QC and improvement.



Cook et al. 2013

Figure 2. Flowchart showing process for preparing and testing trial batches of concrete using the Box Test

Large amounts of data are collected as a project progresses, and some portions of the data are often more useful than others. One key QC task is to develop processes to optimize data collection and management so that the right data are obtained, used, and archived efficiently. Check sheets, also known as data sheets, are simple yet foundational QC tools that provide a graphical means (typically as a fillable form) of collecting and displaying information associated with an activity or process and that help users record the necessary data and supporting information. Check sheets can be simple checklists of actions that need to be performed before starting an activity, or they can be more elaborate records of extensive processes being monitored over time. As QC processes are formalized, standardization of check sheets can aid in the consistent collection of data and can provide documentation that a process has been performed.

Concrete paving contractors would benefit from developing a set of QC tools (forms, checklists, data sheets, and so on) to support the practices typically included in their QC program and QC plans. The use of cloud-based tools allows real-time access to data and increases the usefulness of those data.

Check sheets are used extensively in construction for recording both qualitative and quantitative information on activities such as materials tracking, testing, inspection, and many other procedures and activities. A wide range of data collection options can be incorporated into a check sheet to support various QC processes, and a check sheet can be formatted in a manner that guides, documents, and improves the quality of many concrete paving processes. Moreover, entering the data recorded on check sheets into a centralized database allows contractors to analyze past performance and identify potential improvements to QC processes and activities.

An example check sheet for the inspection of an aggregate base course prior to paving is shown in Figure 3, while an example data collection sheet that supports the testing of concrete properties is shown in Figure 4. Although the checklists presented in this tech brief are simple, they can readily be enhanced to be highly useful and meet a contractor's needs.

Historically, check sheets have been paper forms that are completed manually, used, and stored. These types of check sheets are still very valuable and remain widely used. However, paper forms can be cumbersome to manage, data entry issues can occur when information is transferred to databases, and paper forms can be lost or damaged on a jobsite. Because of these issues and others, check sheets are increasingly being developed and used in digital formats. Digital check sheets can be uploaded to cloud-based construction management software systems and readily integrated with other traditional construction management tools (such as scheduling and cost control software). This approach can provide real-time access to data for a variety of stakeholders and allow integrated analysis of QC data with data from other areas of operations.

Check sheets can be used at a stationary point in the QC process (like those shown in Figures 3 and 4) or may travel with a product throughout a process. As an example of the latter, materials tickets are a type of check sheet that moves with a material through the different stages of the construction process. These tickets are used to track the characteristics of a product, along with supporting data that facilitate tracing later. Historically, paper materials tickets have been used in concrete paving. However, e-ticketing systems are increasingly being used to streamline and improve materials ordering, tracking, and data collection for QC (Shilstone 2017, Mulder 2019). E-ticketing systems provide numerous advantages to the paving process, including the ability to optimize and track deliveries, directly obtain information from batch plant software, provide alerts about mixture changes and transport issues, and improve safety by preventing hand-off of paper tickets in construction traffic (Mulder 2019). For an e-ticketing system to be most efficient, it should be compatible and integrated with an agency's automated materials/construction management system.

Performance Paving Company		Project:	Interstate 42, Havelock, NC
Quality Control Plan		**Prepared by:**	Q.C. Smith
Inspection Checklist		**Checked by:**	P.M. Jones
Section	19.31.3b	**Date:**	5/27/2020
	Aggregate Base Course		
Area Inspected	**Description**:		
Item No.	**Description**	**Yes/No**	**Notes**
19.31.3b.a	Approved material source used	Y	Carolina Aggregates ABC, meets Sect 1006 and 1010
19.31.3b.b	Temperature >40°F	Y	73°F and rising, rain 3 days ago
19.31.3b.c	Equipment inspected	Y	
19.31.3b.d	Material inspected and free of defects such as organic matter, clay lumps, and other undesirable substances	Y	
19.31.3b.e	Maximum aggregate size requirement met	Y	Max size 2 in. confirmed
19.31.3b.f	Base material suitable (no soft spots, debris)	Y	Proofrolled afternoon of 5/26
19.31.3b.g	Layer thickness verified per drawings	Y	Min 3 in. lift, not to exceed 6 in.
19.31.3b.h	Nuclear gages calibrated	Y	On file
19.31.3b.i	Testing and sampling frequency confirmed per QC plan	Y	Grade <1/2 in. measured every 50 ft, 95% maximum density at ±2% of moisture content to achieve optimum, sampling at random test site locations per NCDOT Nuclear Density Testing Manual
	Signature	**Date**	
QC Inspector			
Foreman			
Agency Inspector			

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Figure 3. Check sheet for inspection of aggregate base course prior to paving

Performance Paving Company			**Project**:	Interstate 42, Havelock, NC
Quality Control Plan			**Mixture ID**:	Mainline 475
Concrete Testing Report				
Set/Lot ID:	312		**Ambient temp.:**	
Date/Time of batching:			**Concrete temp.:**	
Slump:			**Air content:**	
Required/target (psi):	4500 psi @ 28 days			
Notes:	Adjusting water reducer dosage			
Compressive strength test results				
Cylinder IDs	312-1	312-2	312-3	Average
Test Age (days)				
Load (lb)				
Strength (psi)				
Cylinder IDs				
Test Age (days)				
Load (lb)				
Strength (psi)				
Cylinder IDs				
Test Age (days)				
Load (lb)				
Strength (psi)				
Cylinder IDs				
Test Age (days)				
Load (lb)				
Strength (psi)				
Notes:				
	Signature		**Date**	
QC Inspector				
QC Supervisor				

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Figure 4. Data sheet for recording compressive strength measurements

Run Charts and Control Charts

Run charts and control charts are two process improvement tools that provide insight into the performance of a process. A run chart, also known as a time-series chart, is a very simple chart created by plotting a measurement over time. This type of chart allows the user to observe trends or patterns over time and is helpful in predicting trends or future outcomes. An example of a simple run chart for the flexural strength of a concrete mixture is shown in Figure 5. Although a run chart is useful for identifying trends in a data set, it cannot be used to determine whether a measurement is influenced by chance or assignable cause variation.

Control charts are constructed similarly to run charts in that one or more quality characteristics are plotted over time, but this type of chart also uses statistically derived control limits to help the user evaluate the stability of a process. Due to the use of statistics to establish a line of central tendency and limits, a control chart is considered a statistical process control tool that allows the user to do the following:

- Evaluate the suitability of a material or product
- Identify trends
- Assess whether a process is in control

By allowing the user to review measurements over time along with statistically derived control limits, a control chart provides a clear indication of when a process is in control, out of control, or in control but headed in an unfavorable direction. A control chart also makes it evident to the user when a process is experiencing unacceptable variability or when measurements are trending toward or exceeding specification limits.

> Quality is achieved for a given process if the following is true (Fick 2008):
>
> 1. The process is stable, and only common cause (expected) variability is present.
> 2. The common cause variability present in a process is small enough to allow products to remain within specification tolerances.
> 3. The process is consistently performing near the target values.

If the control chart used to monitor a given process is constructed well and reviewed periodically, issues with the process can be identified quickly and addressed in a timely manner. Contractor experience and companion records (if available) can be used to identify ways to address the issues and bring the process back into control. Once corrective actions are taken or adjustments are made, continued use of the control chart will allow the contractor to observe the impact of the changes to the process. If the adjustments bring the process back into control, the attempt was a success. If the process does not return to a controlled state, the contractor can develop a plan for other changes or improvements to the process.

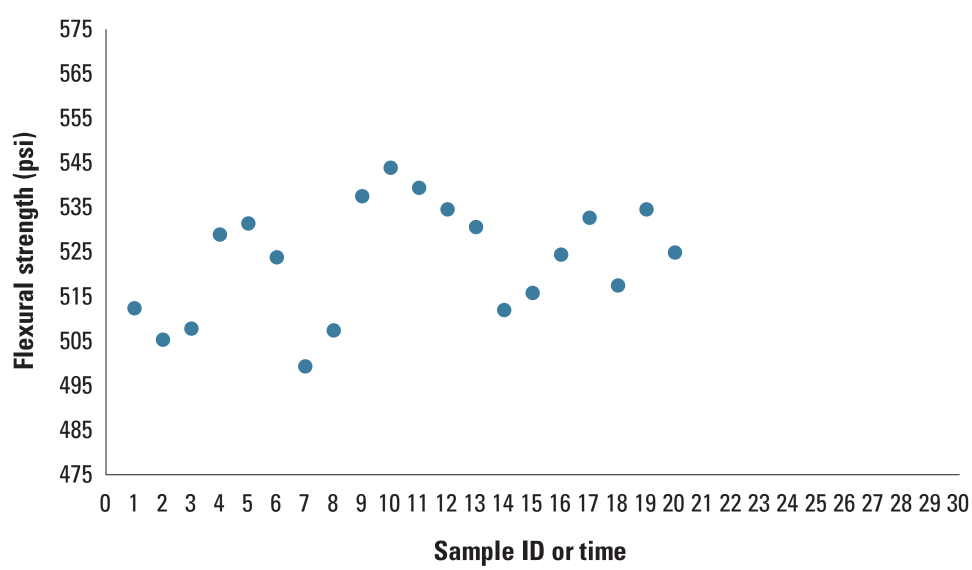

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Figure 5. Run chart for the flexural strength of a concrete mixture

Run charts and control charts are not intended to be tools for formal acceptance of work. Instead, these charts are easy-to-use tools that allow contractors to gain insight into their processes. Control charts use the power of statistical analysis to assure both agencies and contractors that their processes are in control and work will likely comply with specifications.

Constructing Run Charts and Control Charts

Run charts and control charts are constructed using measurements for one or more selected quality characteristics. For concrete, charts can be prepared for measurements of both fresh and hardened concrete properties. Measurements such as unit weight, air content, and Super Air Meter (SAM) number provide good quality indicators for monitoring fresh concrete properties over time. Measurements of hardened concrete properties such as compressive strength, flexural strength, and surface resistivity are also often used in run charts and control charts to assess quality. In addition to using charts to monitor concrete, charts can be constructed for other materials used in concrete paving applications, such as aggregates (tracking characteristics such as moisture content or fineness modulus). Other quality characteristics of interest could also be used in run charts or control charts, if desired.

Once a quality characteristic is selected, a sampling plan should be determined. (Note that this sampling plan should be separate and independent from the agency's acceptance sampling plan.) The sampling plan will need to identify the number of samples to be taken, the number of measurements to be made, and the frequency at which the sampling/testing is to be performed. The level of reliability of the control chart will be heavily influenced by this sampling plan. Sampling and testing should be performed at a frequency capable of providing confidence that the results represent the whole of the work. However, the sampling plan should be readily implementable without placing an unacceptable burden on personnel or adversely interfering with production. The sampling plan should consider the following:

- The time it takes to obtain the sample, run the test(s), and turn around the test results
- The safety of the personnel involved in obtaining/testing the sample
- In the case of destructive tests, the impact to the construction process or to the completed work
- The risk associated with the amount of work proceeding while waiting for test results

A sampling plan is often based on (1) lots of material produced, (2) a volumetric quantity of material produced, or (3) a number of linear feet or square yards of material placed. Sublots or subunits can also be used. Statistical control charts require the use of random sampling, where tools such as random number generators are used to assign sampling locations or material sublots in a manner that minimizes bias that may affect test results. Regardless of the procedure used to establish the sampling plan, the location of each sample should be documented. The ability to link a sample measurement to a specific location on the constructed pavement is critical to knowing the area of pavement associated with a certain test result and correctly applying any corrective actions that may be needed.

To construct either a run chart or a control chart, sample IDs or sampling times and measurements (or averages of measurements representing a single sample) are plotted over time. The sample IDs or sampling times are shown progressing with time along a central line on the x-axis of the control chart or run chart, with the measurements of the quality characteristic (or characteristics) plotted on the y-axis (or y-axes).

Additional information can be plotted on run charts and control charts to assist the user in analyzing the processes under consideration. On a run chart, a central line showing a selected value, such as a specification target, can be plotted, along with additional lines representing upper and lower specification limits. Lines representing upper and lower action limits, selected without statistically derived calculation, can also be plotted on run charts. Control charts similarly have a central line and one or more sets of upper and lower limit lines, but these lines are established through statistical methods using the data available to date.

In summary, the central line on a run chart or control chart can be established as follows:

1. On a run chart, the central line is established as a selected value, such as a specification target.
2. On a control chart, the central line is established as a measure of central tendency (moving average) of the measurements to date.

Upper and lower limit lines on a run chart or control chart can be established as follows:

1. On a run chart, upper and lower limit lines can be established as the specification limits for the process under consideration and/or as nonstatistically determined action limits that lie within the specification limits but indicate cause for concern.
2. On a control chart, upper and lower limit lines are plotted based on a standard deviation of the data (such as at two or three times the standard deviation).

Decisions on how to establish the central line and upper/lower limits are at the discretion of the user, and the examples presented subsequently in this section illustrate the thought process behind the creation of several run charts and control charts for different measurements of interest for concrete paving. However, it should be noted that the use of a statistically derived central line and limits on a control chart allows the user to capitalize on a broad range of analytical techniques to assess whether the variation observed is due to chance cause versus assignable cause.

In a control chart, the goal of establishing upper or lower limits using statistical methods is to ensure that the user can identify when the variability associated with a measurement is the result of chance cause or natural process variation or is the result of assignable cause variation, the latter of which indicates an issue that needs to be addressed.

If a control chart is to be constructed (Figure 6), establishing control limits three standard deviations (3σ) greater than or less than the average of the data set (represented by the central line on the control chart) can provide a reasonable boundary that helps distinguish natural variation from assignable cause variation. Measurements exhibiting natural variation will most likely be within ±3σ from the average measurement.

If a measurement is greater than +3σ or less than -3σ from the average measurement, it is most likely due to assignable cause variation. Assuming a normal distribution of measurements exhibiting natural variation, 99.73% of measurements (or 9,973 out of 10,000) should fall within ±3σ from the average measurement. Therefore, it is highly likely that measurements outside of 3σ from the average are due to assignable causes. It is possible that a measurement outside of 3σ from the average is due to natural causes, but this would only be expected to occur in 0.27% of cases (or 27 times out of 10,000) (Besterfield 2009).

Ideally, the average and control limits should be established when the process is stable and in control, or at least when the contractor does not suspect that assignable causes or atypical issues have affected the measurements. When a control chart is initially developed, limits can be determined after as few as 10 data points are obtained but should be revised again as additional data are collected (for example, after each set of 5 consecutive measurements is added to the control chart). Once a significant number of measurements have been made (Fick [2008] recommends 25 measurements), the control limits do not necessarily need to be changed again unless a change is made to the process (Fick 2008) or points associated with an assignable cause are identified and removed from the calculation of the limits.

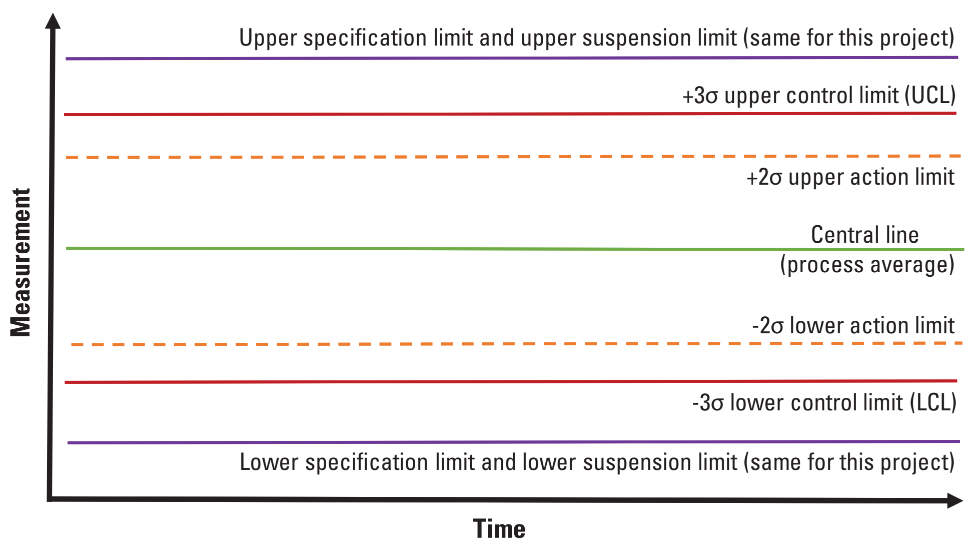

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Figure 6. Typical central line (process average) and limits on a control chart

In some instances, multiple measurements are used to compute an average value for a sample. When this is possible, additional statistical techniques can be used to provide improved control limits and more reliability to a control chart. Although the use of more advanced statistical methods to establish control limits is a common practice in manufacturing environments (where a large number of measurements can be collected for each sample lot), such methods are not often used in construction applications, where replicate testing is limited due to time and production considerations. Appendix E of *Quality Control for Concrete Paving: A Tool for Agency and Industry* (Cavalline et al. 2021) provides an example illustrating the use of advanced statistical methods.

In addition to control limits, upper and lower action limits can also be established on both control charts and run charts to alert the user to appropriate points at which to adjust a process. On a control chart, action limits that signal that a process is trending in a certain direction of concern may be warranted for a single data point and could be established at values such as $\pm 2\sigma$ or $\pm 2.5\sigma$ at the discretion of the user. (In Figure 6, the action limits are set at $\pm 2\sigma$.) On a run chart, action limits can be established at user-selected points within the specification limits. Using this approach provides a "safety net" but does not provide statistical confidence. On both types of charts, if test results fall outside the action limits but within the control limits, the material being produced is still within the specification limits, but early action to address potential issues and prevent the production of out-of-specification materials is prompted. However, the user is cautioned to avoid making unnecessary process changes in response to a single data point, which may lead to increased variability.

Agencies typically establish the suspension limits for a process at the specification limits. If the action and control limits are established using statistical methods, they may be farther from or closer to the central line than the specification limits. In Figure 6, the specification limits and suspension limits are shown to be the same and, for this example, are plotted outside of the control limits.

Ultimately, if the specification limits provide reasonable boundaries between acceptable and unacceptable performance, the user can choose to establish the central line and upper/lower control limits at values that are useful for ensuring that the variability in the measurements remains within a safe distance from the specification limits. Figure 7 shows an example run chart where the user has chosen to establish the upper and lower specification limits, suspension limits, and control limits at the same values. Action limits can be computed or selected at values determined at the discretion of the user based on the contractor's risk tolerance. Integrated into a QC plan, these action limits and specification and/or suspension limits could be used to guide the process by which a contractor resumes full production after a suspension. The QC plan should define the number of data points that should fall within the control limit in order to proceed out of suspension.

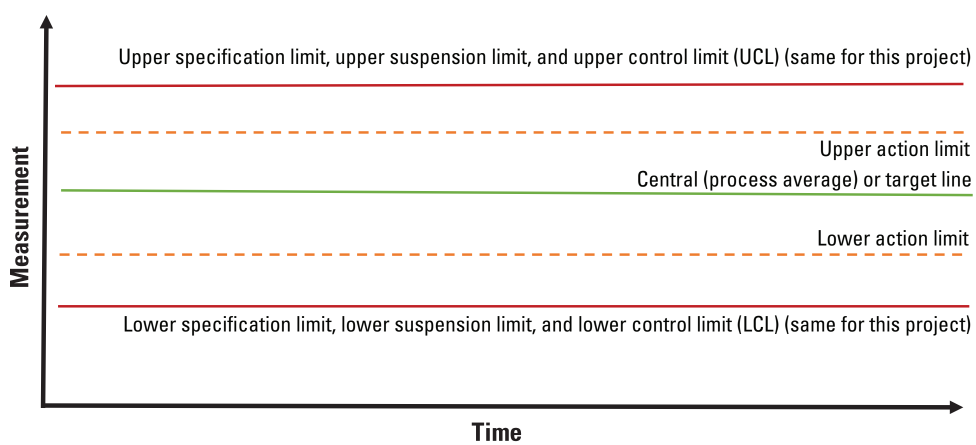

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Figure 7. Typical central line (target line or process average) and limits on a run chart, where statistical methods are not used to establish limits

Example Control Chart: Central Line and Limits Established Using Statistical Methods

Quality Control for Concrete Paving: A Tool for Agency and Industry (Cavalline et al. 2021) provides an example demonstrating the generation and use of a control chart for the 7-day flexural strength of a concrete mixture where the central line and limits are established using statistical methods. A similar example of a control chart for average 28-day compressive strength is shown in Figure 8.

For this control chart, the user decided to use statistical means to establish the central line and upper and lower limits (both the control and action limits). The central line was established at the average compressive strength of 20 samples taken over time, 4,814 psi. The user decided that the control limits would be established at ±3σ while the action limits would be established at ±2σ.

Using the standard deviation of the 20 measurements (117.8 psi), the upper and lower control limits were established at 5,167 psi and 4,460 psi, respectively. Compressive strength measurements greater than 5,167 psi or less than 4,460 psi would likely indicate that an assignable cause of variation (an issue with the process) was associated with that measurement. The upper and lower action limits were established at 5,049 and 4,578 psi, respectively. Measurements that trended above 5,049 psi or below 4,578 psi would prompt the contractor to consider taking action to move the measurements of the process closer to the established (or desired) average to improve control of the process.

In the control chart for this example (Figure 8), statistical methods were used to establish the central line and the action and control limits using data obtained over a period during which the contractor believed the process was in control. Note that, in this example, all points indicate a stable process (no points are outside of the ±3σ control limits), confirming the contractor's assumption that the process was in good control during the timeframe used to produce the control chart and establish the central line and limits. Only one point (Sample 7) is approaching an action limit, but this does not indicate that the process was out of control at that time. If statistical methods are used to establish control limits and one or more points are outside of the control limits, the contractor could (1) remove the data point and recompute the central lines and control limits or (2) address the issue associated with the out-of-control data point, restart the measurement process, and use the new data to re-establish the control chart.

Over time, additional measurements will be obtained, and the central line and control limits can be re-established to represent the current process. It is not necessary to re-establish the control limits if the contractor feels that they are providing reasonable insight into the process, that is, that the measurements that fall within the control limits indicate a controlled process and the measurements that fall outside the control limits can be linked to an issue with the process. However, recomputing the central line and control limits periodically as material is produced and data are collected should allow the contractor to better understand the process and ensure that control limits truly reflect the conditions of the process at that point in time.

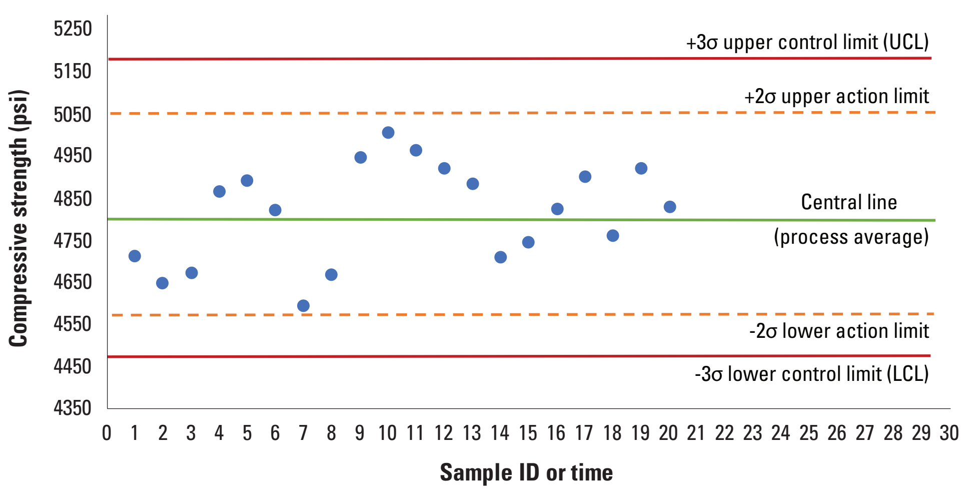

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Figure 8. Control chart for concrete compressive strength, with central line and control limits established using statistical methods

Processes often become more stable over time. With experience and with efforts to address issues and implement improvements, there is a strong likelihood that the standard deviation will decrease and the control limits will move closer to the central line. This "tightening" of statistically computed control limits indicates that good QC practices are being implemented, the process is becoming increasingly stable, and the risk of producing out-of-specification material is being reduced.

If a change to the process has been intentionally made or is known to have occurred, the statistically established central line and control limits should be recomputed. Specifically, the central line and control limits should be re-established in the following cases:

- A material source changes or material characteristics change.
- An adjustment to mixture proportions is made.
- An admixture is added.
- The batching sequence is changed.

Example Run Chart: Central Line and Limits Established Using Nonstatistical (Specification-Based) Targets

In lieu of using statistical methods, the central line and the control and action limits can be established on a run chart based on specification limits or preferences. To illustrate this approach, an example run chart showing the results of air content tests of fresh concrete is presented in Figure 9. The air content for this project was specified to be 6.0% ±1.5%, so the user established the central line at 6.0%. Upper and lower limits were established at the maximum and minimum specification limits of 7.5% and 4.5%, respectively. To help ensure that the contractor would have time to make changes before the process trended in a direction that may have exceeded specification limits, upper and lower action limits were established at 0.5% within the specification limits, or at 7.0% and 5.0%, respectively.

In this example, the upper action limit was reached at Sample 8, and in response the air-entraining admixture (AEA) dosage was reduced slightly. As the process continued, the air content trended downward until an out-of-control point (an air content of 4.4%, below the lower specification limit of 4.5%) was reached at Sample 16. The process was adjusted to increase the AEA dosage, and afterward the air content trended toward a more stable reading by Samples 18 through 20.

Observing and Understanding Trends in Run Charts and Control Charts

Ultimately, the goal of the QC team should be to maintain a given process in a manner that results in measurements falling within the desired range of values on the run chart or control chart. Adjustments should be made as necessary to address assignable cause variation and to reduce the amount of variation between the data points and the central line. Whenever possible, only one variable should be changed at a time to ensure that the impact of that change on the characteristic of interest can be most clearly observed. Adjustments in a given variable may also impact other characteristics, whether anticipated or not. For instance, in the example presented above, adjustments to the AEA dosage could affect slump as well as air content.

If measurements exhibit concerning trends, such as several consecutive points trending upward or downward toward an action limit, QC personnel should consider identifying a potential adjustment to the process, implementing this adjustment, and continuing to closely monitor the subsequent data points to observe the impact of the adjustment.

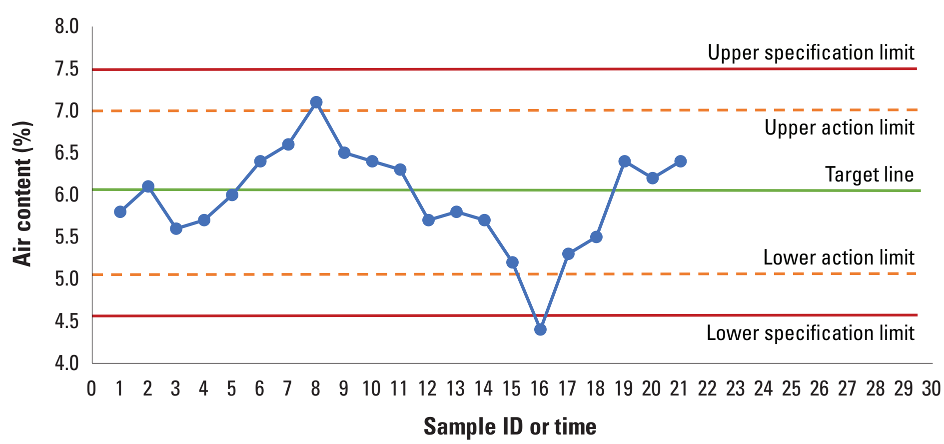

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Figure 9. Run chart for air content in fresh concrete, with control limits established using specification limits

Measurement variability is likely attributable to an assignable cause (indicating an issue in the process) if even a single data point falls outside of statistically computed control limits. However, assignable causes may also affect a process in a manner that does not appear as a measurement spike outside of the control limits. Drift or other issues in a process, often due to an assignable cause, can be identified on a run chart or control chart using the following rules of thumb (ODOT 2003, Besterfield 2009):

- Six consecutive test results are increasing or decreasing.
- Nine consecutive test results are on one side of the central line.
- Fourteen test results are alternating above and below the central line (acting as two populations).
- Two of three measurements are more than two standard deviations from the central line.
- Four of five test results on the same side of the central line are more than one standard deviation from the central line.
- Fifteen test results are within one standard deviation from the central line.
- Eight consecutive test results are more than one standard deviation from the central line.

These trends are illustrated in *Quality Control for Concrete Paving: A Tool for Agency and Industry* (Cavalline et al. 2021) using unit weight as an example measurement.

Using Two Measurements on a Run Chart or a Control Chart

Multiple characteristics can be plotted on the same run chart or control chart, providing an even better understanding of the state of a process. Theoretically, any two measurements could be plotted on the same chart. However, in concrete paving applications, only certain pairings of measurements provide useful insights into the concrete production and paving process. An example involving the fresh concrete measurements of unit weight and air content is presented in Figure 10 to demonstrate the unique understanding gained when two measurements are plotted together.

The fresh concrete measurements of unit weight and air content are related: as the entrained air content of concrete increases, the unit weight decreases. Since these properties are inversely related, one axis can be inverted (or reversed) to show the relationship more directly, as demonstrated in Figure 10, where the secondary y-axis for unit weight has been inverted.

Different trends in the relationship between these two measurements can point to specific potential issues with the process. If the unit weight changes while the air content remains relatively uniform, issues with the process are likely present, such as problems with materials proportioning or control of the water entering the mixture from the aggregates. Similarly, if the unit weight remains relatively constant while the air content changes, other issues may exist, such as admixture incompatibilities or the loss of air during transit.

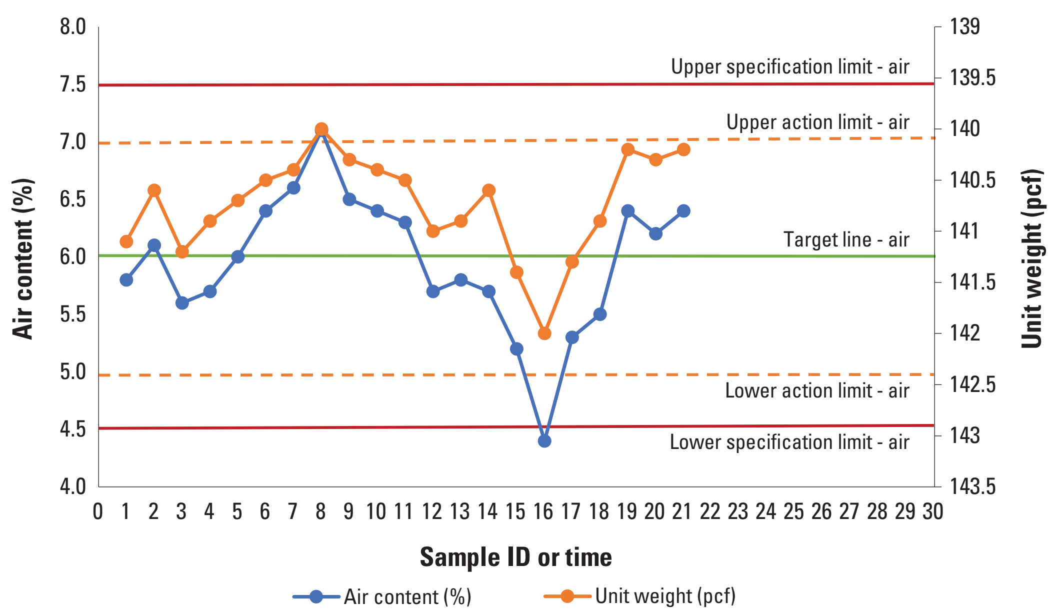

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Figure 10. Run chart for air content and unit weight, with secondary y-axis inverted

The following pairs of measurements can also be shown on a single run chart or control chart to illustrate useful relationships:

- Air content and SAM number
- Microwave water-to-cementitious materials (w/cm) ratio and unit weight
- Compressive strength and surface resistivity (shown in Cavalline et al. 2021)

Using Run Chart and Control Chart Data to Improve Processes

Run charts and control charts allow visualization of data trends and are therefore powerful tools for QC. Paired with a contractor's understanding of a given process, the information obtained from a run chart or control chart can allow the contractor to identify data trends that may indicate issues with the process, determine potential causes for those issues, and implement any corrective actions needed to address the issues. When issues are not identified before a process becomes unstable or out of control, finding the issues and determining corrective actions can be much more challenging.

The information from run charts and control charts can be supplemented with information from other resources on a project. For example, the QC team will often need to rely upon the experience of and feedback from personnel involved in a given process to fully understand the observed trends. Additionally, good recordkeeping is critical to allowing the contractor to respond quickly to potential issues and adjust a process in light of information from a run chart or control chart. Records pertaining to changes in materials, personnel, equipment, or weather can provide clues to the assignable causes that are negatively affecting a process, and these records should be adequately maintained.

If a run chart or control chart identifies a problem for which a short-term fix is available, the fix should be applied while permanent solutions are evaluated and implemented. The QC team should be hesitant to change a process to accommodate an assignable cause identified in a run chart or control chart because this approach is not guaranteed to improve the process (or improve performance) in the long term and has typically been found to increase costs (Fick 2008).

Run charts and control charts also provide a clear, graphical means of displaying data and communicating issues to stakeholders other than QC personnel. To be most effective, control charts must be used not only by the QC team but also others involved in production and construction. If control charts are posted where they can be seen, all personnel involved can observe trends and feel responsible for their own role in quality management and process improvements. Obtaining stakeholder buy-in in this way may help reduce both natural cause variation and assignable cause variation. Control charts can also be used to support the identification of quality targets and goals and to monitor the effectiveness of quality improvement initiatives.

Additional guidance on preparing and utilizing control charts, as well as example uses of control charts during a project, is presented in *Testing Guide for Implementing Concrete Paving Quality Control Procedures* (Fick 2008).

Closing

QC describes the system used by contractors to monitor, assess, and control their work to ensure that quality standards are met. Understood more broadly, QC is also the first step in a larger process that supports quality construction. Not only is QC a key component of an agency's QA program, but data obtained through QC sampling, testing, and inspection also inform continuous improvement efforts and actions for all processes.

This tech brief has provided a snapshot of the fundamental continuous improvement cycle driving QC activities and a brief overview of tools that can be used to support good QC practices. These tools, though initially developed in the manufacturing sector, are highly useful for construction QC.

Simple tools such as process diagrams and check sheets allow data to be collected, organized, and used to inform decisions. Process diagrams, or flowcharts, provide a graphical means of displaying or describing the movement of material or information through a process. Check sheets, or data sheets, are used to optimize the collection and management of data associated with an activity or process at various points in the materials production and construction operations. Check sheets can be customized to ensure that the qualitative and quantitative data collected can be used to guide, document, and improve the quality of a process. Digital and cloud-based construction software programs allow these tools to provide real-time data to inform QC personnel and other stakeholders.

Run charts and control charts provide insight into the performance of a process. These tools are useful for identifying and understanding data trends that may indicate issues with the process, determining potential causes for those issues, and implementing corrective actions needed to address the issues. Control charts prepared using statistically based methods provide advantages both over run charts and over control charts prepared using specification-based targets. Over the long term, the values resulting from the analysis of these control charts will tend to approach the best estimates of population-standard values as the data set increasingly reflects only natural process variation. Trends evident in these charts can be used to explain problems and solicit input from individuals within a contractor's organization, such as paving superintendents, or from outside personnel, such as suppliers and agency representatives. Ultimately, the data from run charts and control charts help support and justify changes to a process.

A range of other tools are used in QC, including histograms, scatterplots, Pareto charts, and other graphical and statistical tools. For more information on these tools, the reader is referred to the references provided in *Quality Control for Concrete Paving: A Tool for Agency and Industry* (Cavalline et al. 2021).

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.