GUIDE

Quality Control for Concrete Paving: A Tool for Agency and Industry

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

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 quality concrete infrastructure.

This guide is intended to serve as a tool that both contractor and agency personnel can use at the batch plant, behind the paver, and at other locations on the job. Contractors can use this guide to improve or enhance their existing QC programs and plans by incorporating the appropriate provisions into their operations. This guide can also help agency personnel become familiar with the components of a comprehensive QC plan for concrete paving projects, the ways such a QC plan benefits agencies, and ways to appropriately incorporate QC requirements into specifications. In addition, this guide provides background knowledge to help agency and contractor personnel understand the elements of an agency's QA program and why QC is an important part of that program.

Topics discussed include common agency QC requirements; the appropriate tools, processes, and procedures to meet these requirements; continuous improvement activities; and the benefits for contractors of good quality control, including higher efficiency and productivity, increased profit, and safer operations.

The material in this guide is presented in a manner that gives contractors the flexibility to develop their QC plans in a way that accommodates their processes and procedures while providing a high likelihood of meeting agency requirements.

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Abbreviations

AAR	alkali-aggregate reactivity
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ASR	alkali-silica reactivity
ASTM	American Society for Testing and Materials
CRCP	continuously reinforced concrete pavement
FHWA	Federal Highway Administration
GGBFS	ground granulated blast furnace slag
IA	independent assurance
LOI	loss on ignition
NETTCP	NorthEast Transportation Training and Certification Program
NRMCA	National Ready Mixed Concrete Association
PEM	performance-engineered mixtures
PWL	percent within limits
QA	quality assurance
QC	quality control
SAI	slag activity index
SAM	Super Air Meter
SCM	supplementary cementitious material
TRB	Transportation Research Board
VKelly	vibrating Kelly ball
w/cm	water-to-cementitious materials
WRA	water-reducing admixture

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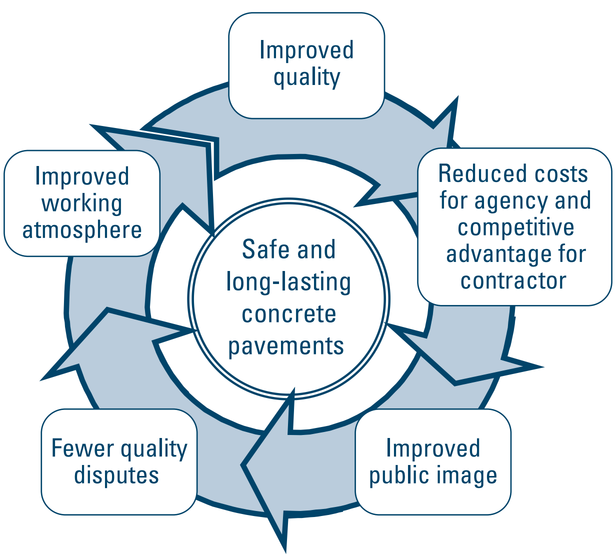
Chapter 1

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 quality concrete infrastructure. QC encompasses the personnel, equipment, and practices required to control the quality of the product(s) being produced and work being performed. Central to QC are organizational-level quality management programs and project-level QC plans. Jointly, these activities and processes ensure that the appropriate elements of QC are implemented to meet the quality requirements or standards for the product(s) produced and work performed.

At the project level, the implementation of a comprehensive QC plan provides confidence to agencies and other stakeholders that when the plan is followed, specification provisions will be met. The benefits of a QC plan are not limited to agencies, however. A well-implemented QC plan provides many benefits to contractors, including increased profitability, reduced rework, greater pay factors, improved public image and customer satisfaction, and, in some cases, improved safety (Figure 1.1). Contractors can achieve these benefits through incorporating appropriate provisions into their operations and QC plans.

Moreover, contractors that have instituted robust QC programs throughout their organizations will be better prepared for an upcoming shift in the highway construction industry. In recent years, some agencies have begun moving toward performance specifications and performance-engineered concrete mixtures (PEMs)



Adapted from Fick et al. 2012

Figure 1.1. Benefits of improved quality for transportation facilities

as part of the Federal Highway Administration's (FHWA's) PEM initiative. In contrast to mixtures based on prescriptive specifications, PEMs (discussed in Chapter 4 of this document) allow contractors and suppliers to use their knowledge to produce better quality concrete. As agencies implement performance-type specification provisions, contractor QC programs and plans will become an increasingly important component of project QA. During the transition to performance specifications, many of the prescriptive contractual requirements and responsibilities related to quality will be transferred to the contractor, along with some of the performance risks.

Due to the unique nature of highway construction, the measures that need to be taken to ensure quality differ for each project. Contract documents (including plans, specifications, and special provisions) define the quality standards that an agency expects. However, it is up to contractors to specify the means and methods necessary to provide confidence that quality is attained by their own personnel, equipment, and processes.

Overview of This Guide

This document is intended to serve as a tool that can be used at the batch plant, behind the paver, and at other locations on the job. The primary target audience is contractors desiring to improve or enhance their existing QC programs and plans; this document presents the means for contractors to achieve the benefits of well-implemented QC through incorporating the appropriate provisions into their operations. However, this document can also help agency personnel become familiar with the components and approaches that comprise a comprehensive QC plan for concrete paving projects, the ways such a QC plan benefits an agency, and ways to appropriately incorporate QC requirements into specifications.

In addition, this document provides background knowledge to help agency and contractor personnel understand the elements of an agency's QA program and why QC is an important part of that program. As part of the development of this document, the QC requirements related to concrete paving for 15 agencies were reviewed; a list of commonly and less commonly specified requirements is presented in Appendix A. The reader should be mindful that agency QC requirements are *minimum requirements*, and additional QC activities are very often needed to support the success of a project.

The QC guidance in this document is presented in a manner that provides flexibility for contractors to develop their QC plans in a way that accommodates their own means and methods (frequently referred to as "processes and procedures" in the quality management field) while providing a high likelihood of meeting agency requirements.

This document includes information necessary for contractors to do the following:

- Understand common agency QC requirements
- Develop and implement the appropriate tools, processes, and procedures to meet agency QC requirements
- Develop and implement continuous improvement activities to more effectively and efficiently meet agency requirements
- Recognize that good quality control offers several benefits for contractors, including higher efficiency and productivity, increased profit, and safer operations

The material presented in this document is outlined below.

Chapter 2 presents a brief introduction to QC. The chapter describes the components of an organizational-level QC program that supports QC across operations and projects. Because people are the foundation of quality management, the chapter emphasizes the importance of communication, with Appendix B providing example QC plan provisions that demonstrate "poor," "fair," and "good" language and level of detail. The chapter also introduces the fundamental components of QC plans and the topics of variability, sampling, and statistical process control.

Because constructing quality concrete pavements requires materials that meet quality standards, Chapter 3 describes QC for suppliers of concrete pavement materials, including cementitious materials, chemical admixtures, and aggregates. Readers seeking additional information on this type of QC are referred to other key resources.

Chapter 4 describes the characteristics of PEMs, the benefits that can be achieved through the use of PEMs and associated tests, and QC processes and provisions that support PEMs. The move toward PEMs by many agencies provides opportunities for contractors and suppliers to more fully capitalize upon their knowledge and experience to produce quality concrete pavements, but the use of PEMs often requires contractors to implement an enhanced QC program.

Chapter 5 presents QC methods for concrete pavement construction. The chapter describes the establishment and implementation of a QC program that includes mixture design (prequalification), mixture verification (field setup), mixture and construction QC, and mixture and construction acceptance. QC provisions for concrete batching and paving are then presented, with an emphasis on the measurements and observations required for a successful paving project. Best practices to support the development of a QC plan are described throughout the chapter, along with guidance to help contractors distinguish between specified requirements and QC responsibilities. An overview of typical acceptance testing approaches and a brief discussion of corrective actions close the chapter. The guidance provided in this chapter is supplemented by a QC plan outline (Appendix C) and a model QC plan (Appendix D) for concrete paving based on the Typical Model Quality Control Plan developed by the NorthEast Transportation Training and Certification Program (NETTCP).

Chapter 6 describes the development and use of QC tools, including checklists, statistical control charts, and graphical data used for reporting certain material properties, and the benefits these tools can offer. The basics of process control are presented using several examples of run charts and control charts for concrete paving data, and means of identifying and implementing appropriate process adjustments are described. Appendix E provides an additional, more detailed example demonstrating a statistical process that can be used to develop and enhance the utility of control charts. Chapter 6 closes with a description of strategies for records management.

Definitions

The key terms used in this document are defined below.

The following definitions are presented as they appear in the seventh edition of the Transportation Research Board's (TRB's) Transportation Research Circular E-C235, *Glossary of Transportation Construction Quality Assurance Terms* (TRB 2018). The seventh edition of E-C235 reflects efforts to align the definitions of key terms presented in the TRB glossary with the definitions used in publications from the American Association of State Highway and Transportation Officials (AASHTO). For additional clarity, the following definitions incorporate commentary originally presented in brackets in the TRB glossary.

- **Quality assurance (QA)**: (1) All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service, or (2) making sure the quality of a product is what it should be. QA addresses the overall process of obtaining the quality of a service, product, or facility in the most efficient, economical, and satisfactory manner possible. Within this broad context, QA includes the elements of quality control (QC), independent assurance, acceptance, dispute resolution, laboratory accreditation, and personnel certification. The use of the term QA/QC or QC/QA is discouraged, and the term QA should be used. QA involves continued evaluation of the activities of planning, design, development of plans and specifications, advertising and awarding of contracts, construction, maintenance, and the interactions of these activities.
- **Quality control (QC)**: The process specified by the agency for a contractor 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. QC may or may not be specified by the agency. Even when it is, the specified QC requirements or activities may not be adequate to ensure the final product will meet the specified level of quality. Thus, a contractor may elect to conduct activities in addition to specified QC activities to ensure the specified level of quality. These additional activities are referred to as process control (PC) activities. QC measurements (sampling, testing, and inspection results) may or may not be used with other factors as a basis for acceptance or payment. PC measurements are not used by the agency in acceptance.
- **Process control (PC)**: A method for keeping a process within boundaries and/or the act of minimizing the variation of a process. PC activities may include sampling, testing, inspection, and corrective action performed by a contractor in addition to QC requirements to improve the likelihood that the final product will meet the specified level of quality. For example, a contractor may measure, monitor, and control the gradation of individual aggregates as a PC activity, when QC or agency acceptance measurements are required on blended gradations of fine, coarse, and intermediate aggregates.
- **Quality control plan (QC plan)**: A project-specific document prepared by the contractor that identifies all QC personnel and procedures that will be used to maintain all production and placement processes "under control" and meet the agency specification requirements. The document also addresses actions to be taken if a process goes "out of control."
- **Acceptance**: The process whereby all factors used by the agency (i.e., sampling, testing, and inspection) are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value for a given product. Owner acceptance measurements (sampling, testing, and inspection) are always considered in the acceptance decision process. QC measurements (sampling, testing, and inspection results) may or may not be used in the acceptance decision process. PC measurements are not used by the agency in the acceptance decision process. Where contractor test results are used in the agency's acceptance decision, the acceptance process includes contractor testing, agency verification and validation, and possibly dispute resolution.
- **Independent assurance (IA)**: Activities that are an unbiased and independent evaluation of all the sampling and testing (or inspection) procedures used in the QA program. IA provides an independent verification of the reliability of the acceptance (or verification) data obtained by the agency and the data obtained by the contractor. The results of the IA testing or inspection are not to be used as a basis of acceptance. IA provides information for quality system management. The IA program can be set up on a project basis, which is the traditional approach, or on a system basis. Frequencies for the project approach are based on project quantities while the system approach is typically administered on a statewide basis and frequencies are based on time with the intent of covering all active personnel over multiple projects.

- **Verification sampling and testing**: Sampling and testing performed by the agency, or its designated agent, to evaluate the acceptability of the final product.
- **Validation**: The mathematical comparison of two independently obtained sets of data (e.g., agency acceptance data and contractor data). For example, using statistical tests such as *F*- and *t*-tests to determine whether it can be assumed the data set came from the same population. Validation of test results includes the verification test results.
- **Dispute resolution**: Also called conflict resolution. The procedure used to resolve conflicts resulting from discrepancies between the agency's and contractor's results of sufficient magnitude to impact acceptance and payment. The procedure may include the testing of retained split (or "referee") samples, an investigation to identify equipment or procedural deficiencies, resampling, retesting, or use of third-party arbitration.

For the purposes of this document, the terms "quality management program," "QC program," "QC plan," and "QC process" are differentiated as follows:

- **Quality management program**: A planned series of activities by an organization (such as an agency, contractor, consultant, third-party testing company, or other stakeholder) that supports the achievement of a long-term goal of providing high-quality work and/or services.
- **QC program**: A planned series of activities by a contractor or supplier that support the achievement of a long-term goal of providing high-quality materials and construction on all projects. A QC program includes quality-related activities that are not specific to a project but support quality on all projects and within company operations.
- **QC plan**: A detailed proposal, specific to a project, describing the resources, practices, and other actions necessary to meet the agency's quality standards and requirements.
- **QC process**: A series of actions or steps to achieve a specific goal associated with control of quality.

In addition to the terminology listed above, the terms "base" and "subbase" require clarification because they have had different meanings in different applications and locales. Historically, concrete pavements have been designed with a single constructed layer beneath the concrete, referred to as the "subbase." "Base" has often referred to the layers beneath asphalt concrete pavements. In recent years, pavement rehabilitation and reconstruction activities have resulted in composite pavements with more than one layer below the pavement surface layer and above the soil. Therefore, in this document "base" is used to refer to any constructed layer below the pavement surface layer and above the roadbed soil. "Subbase" is used to refer to a layer constructed below the pavement surface and base layer(s).

Elements of a Quality Assurance Program

Federal regulation 23 C.F.R. § 637 requires state highway agencies to have a QA program. Although agencies are permitted to develop, and have developed, QA programs that meet their specific needs and risk tolerances, all QA programs are required to have six core elements (Dvorak 2019). These six core elements—contractor QC, agency acceptance, personnel qualification and certification, laboratory qualification, independent assurance (IA), and dispute resolution—are shown in Figure 1.2.

All six elements of a QA program work together to support the construction of quality projects. Each entity within a QA program has certain roles and responsibilities that support the success of the program, although interdependencies among these six elements require collaboration among the agency, contractors, suppliers, and other industry stakeholders on a regular basis.

Adapted from an image provided by Dennis Dvorak, FHWA, used with permission

Figure 1.2. Core elements of a quality assurance program

QC is an important component of QA. In a QA program, agencies are primarily responsible for acceptance of the work performed by contractors. To support the acceptance process, agency personnel are responsible for monitoring the contractor's QC activities to ensure that they meet the agency's (minimum) requirements, measuring and evaluating the quality of the final product, and determining the final payment value of the completed work (Fick et al. 2012). The contractor's QC testing may be included in the agency's acceptance decision if the agency has independently verified the QC testing. This approach is important when statistical acceptance procedures, such as percent within limits (PWL), are used by an agency.

Contractors maintain autonomy of and responsibility for their production and processes. QC includes sampling and testing by contractors so they can understand and control their processes, reduce variability, and improve the quality of their work. Successful QC requires the use of trained personnel, appropriate materials, and reliable equipment and must be a focus of personnel involved in each step of the construction process, from managers to field crews. Documentation, communication, and continuous improvement are essential activities supporting contractor QC efforts and are described in detail later in this document.

Quality control extends far beyond additional acceptance testing, and it is important to distinguish between *specified requirements* and *QC responsibilities*. In recent years, increasingly limited agency resources and other factors have driven an increased reliance on QC data for use as a part of the agency's acceptance decision. If QC data are used in this way, agencies must have provisions to ensure the QC plan is adequate and that its execution will ensure reliable test results. A satisfactory QC plan does not, however, relieve the agency of its responsibility to ensure that verification sampling is performed by qualified and/or certified personnel in qualified and/or accredited laboratories. Trust and partnership fostered between the agency and the construction industry on quality-related initiatives provides benefits to all stakeholders.

The reader is referred to the following resources for a more comprehensive overview of agency QA programs:

- Regulation 23 C.F.R. § 637
- *TechBrief: Independent Assurance Programs*, FHWA-HIF-12-001 (FHWA 2012)

Message to Agencies

Contractor QC is a critical component of an agency's QA program and will play an increasingly important role as agency resources become stretched and steps are taken toward performance specifications. As agencies consider transferring performance risks and responsibilities onto the contractor, along with eliminating some of the prescriptive language on methods contained in many specifications, it will be important for agencies to require contractors to demonstrate how they intend to assume responsibility for quality within their QC programs and plans. Additionally, the roles and responsibilities of the agency, the contractor, and other parties will need to be clearly defined. QC plans document the procedures and activities that support the delivery of a quality project.

AASHTO PP 84, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, summarizes the importance of quality control as performance-based specifications become increasingly common:

"When performance-based measures are selected, the importance of quality control increases; compliance with the acceptance criteria are predicated on a well-designed and executed QC program that includes process, production, and construction control."

A comprehensive contractor QC plan provides a wide range of benefits to agencies, including the following:

- Improved quality of construction as contractors enhance their QC plans
- Increased confidence in the use of contractor QC data as part of the agency's acceptance decision
- Confidence to consider loosening or removing restrictive prescriptive specifications
- Confidence to consider implementing performance-type specifications

The guidance presented in this document will help agencies develop, improve, or enhance those aspects of their specifications and QA provisions that relate to the required contractor QC. Because contractors are well accustomed to providing a product that meets a given specification, they are quite prepared to accept more detailed requirements from agencies as to what constitutes an acceptable QC plan.

The recommendations in this document regarding the components and approaches comprising an appropriate QC plan for concrete paving can help agencies establish how plans should be approved, monitored, and enforced. As part of preparation of this document, 15 agency specifications were reviewed to identify both frequently specified and less frequently specified QC requirements and practices. The findings of this review are presented in Appendix A.

To ensure that the benefits associated with contractor QC are achieved, agencies should ensure that QC plans are followed during construction. QC data should be recognized in some form in an agency's acceptance program, and agencies should require timely submittal of QC data in order to build confidence in the contractor's ability to fulfill QC obligations. In this regard, a common adage used in quality management is "what gets measured gets managed." However, it has also been said that "what gets paid for gets managed." To gain the most value from contractor QC plans, agencies should ensure that there is a close association between payment and execution of the QC plan. This could include periodic payments tied to certain milestones, such as approval of the QC plan, fulfillment of each of the QC plan's actions, or other key achievements associated with the QC plan's provisions. These incentives may only need to be offered in the short term because contractors that develop effective QC programs will tend to be rewarded in the long term through pay factors, increased competitiveness, and improved profitability.

In addition to ensuring that QC plans are followed, clear guidelines need to be established regarding what is expected of contractors' QC test results. For example, agencies should provide guidance on actions that should be taken when an individual test yields failing results, as well as trigger points and suspension points for QC data. Alternatively, QC data could be merged into a PWL analysis with assigned trigger points. Agencies should also establish minimum expectations for the analysis of QC test data and associated actions and suspension limits. The contractor will then be able to develop a sampling and testing plan that supports agency requirements.

Agency acceptance testing and contractor QC testing should be separate and independent. If failing test results are found during construction, agencies should require both additional contractor QC and additional agency acceptance testing to support the identification and implementation of corrective actions in a timely manner. A well-defined dispute resolution process should also be established to support fair decisions when conflicting results arise.

A contractor's adherence to maintaining an internal QC program could be part of the agency's post-project evaluations and, ultimately, help the contractor maintain prequalified status to bid on future agency work. If appropriate QC plans are developed and implemented industrywide, agencies will become more comfortable using QC data, may be willing to relax or eliminate restrictive prescriptive specifications, and may be more inclined to implement performance-type specifications.

The guidance presented in this document was developed for the conventional design-bid-build project delivery method, but many recommendations and approaches could be readily applied (or modified) to meet the organizational requirements, contractual arrangements, and risk associated with alternative project delivery methods.

The following key resources supplement the information provided in this document:

- National Highway Institute (NHI) Course Number 131141, *Quality Assurance for Highway Construction Projects* (NHI 2020)
- *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019)
- *Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012)

Message to Contractors

QC is an integral part of an agency's QA plan and is essential for contractors to successfully deliver projects. QC is also important to the success of a company: good QC increases profitability, lowers risk, and improves reputation, and the money invested in QC activities regularly provides benefits far exceeding the amount invested. Additionally, as agencies become increasingly comfortable using QC data, restrictive prescriptive specifications may be replaced with performance-type specifications that allow contractors more freedom to innovate. Improved QC will also provide an opportunity for contractors to focus materials suppliers on the quality and consistency of the materials supplied for a project and to improve the accountability of each entity involved in the delivery of a project.

Quality must be a mindset embraced by all personnel within a company because all individuals engaged in a project play a role in the quality of the work performed. Fostering a culture of quality from the top down is critical to ensuring the buy-in of personnel working directly for the contractor as well as for subcontractors and materials suppliers. As part of this culture, transparency and communication between all individuals, from managers to laboratory technicians to field crews, are critical to ensuring that opportunities to improve quality are identified and improvement measures are implemented and monitored. Quality management requires continuous improvements such as these, and the lessons learned on each project should be incorporated into future QC activities, processes, and plans. In addition to open communication within a company, open communication with agency personnel and their representatives helps improve the quality of a given project and reduces the potential for conflict.

A successful QC program begins with activities that occur in the "background" of a company's day-to-day operations, regardless of the company's ongoing or upcoming projects. They include personnel training and certification, equipment maintenance, and other routine activities that support the improvement of talent as well as the fitness of equipment for use. A QC program should also include provisions for appropriate communication and recordkeeping, ensuring that a process is in place to support the flow of instructions and information. This document provides insight into the components of a successful QC program and its integration with project-specific QC plans.

Whether required by an agency or not, a QC plan is a beneficial tool that provides written guidance on the procedures and activities required to support the delivery of a quality project. QC plans should be tailored specifically to each project and should not be "one size fits all" or reused from previous projects. The guidance presented in this document supports the development of detailed, usable QC plans for concrete paving projects that are tailored to project needs, contractor preferences, and risk tolerance. The QC activities required for each project differ, and approaches are unique to each contractor. The QC plan outline in Appendix C and model QC plan in Appendix D provide flexible frameworks that contractors can use to develop new QC plans or enhance their existing QC approaches.

The guidance presented in this document was developed for the conventional design-bid-build project delivery method, but many recommendations and approaches could be readily applied (or modified) to meet the organizational requirements, contractual arrangements, and risk associated with alternative project delivery methods.

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- *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019)
- *Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012)

Chapter 2

Quality Control Fundamentals

Introduction to Quality Control

QC is defined by the Transportation Research Board 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.

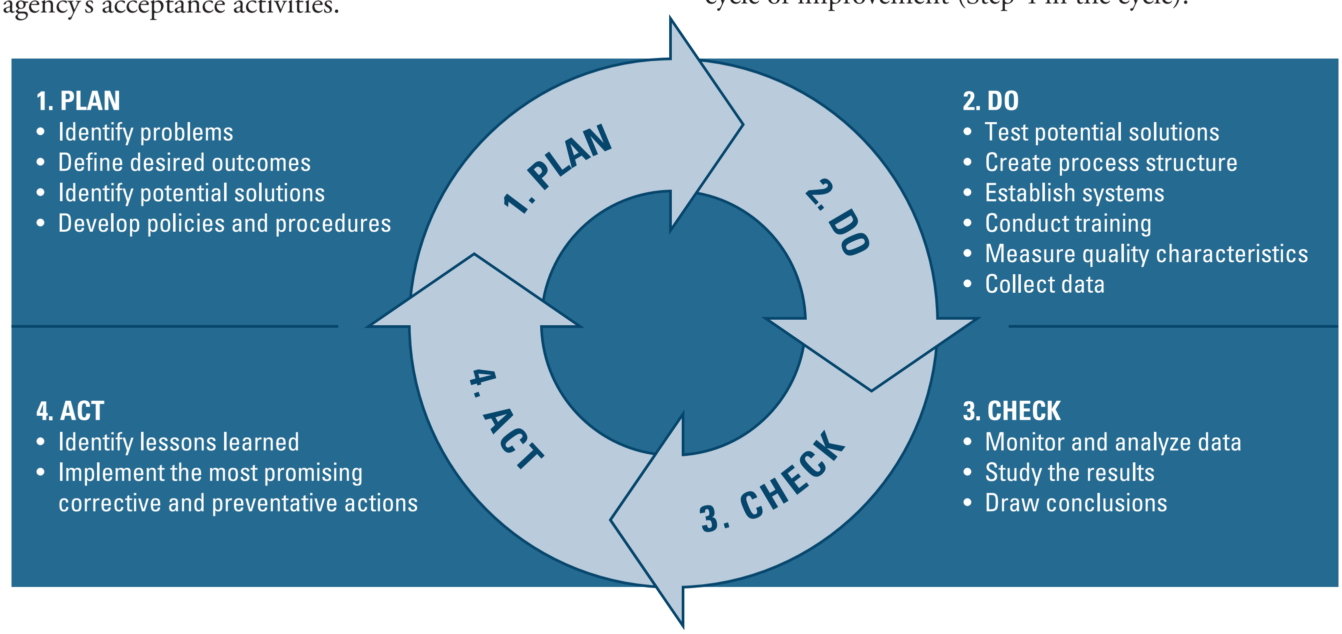
As described in the previous chapter, QC is the first step in a larger process that supports quality construction and is therefore a key component of an agency's QA program. However, QC offers far more to a contractor than simply a checklist for complying with agency requirements. Implementing an effective 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 2.1), 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).



CP Tech Center

Figure 2.1. Plan-do-check-act 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).

Organizational-Level Quality Management

Agency requirements for QC are typically established on a project basis and generally only necessitate minimum levels of personnel qualification/certification, sampling and testing, documentation, and reporting. For contractors to both meet project-level QC requirements and support continuous improvement throughout their operations, an organizational-level QC program that supports the long-term goal of providing high-quality materials and construction on all projects is essential. Additionally, many quality management activities are not tied to specific projects but instead occur continuously "in the background" to support QC efforts across projects and within the company. In this way, a company's broader quality management program, which includes QC efforts as well as more general matters such as human resources and staffing, integrates the various activities and processes within a company to support continuous improvement of the quality of work and to promote a culture of quality within the company. Ultimately, the contractor's QC program should serve as the foundation for the QC efforts for every project the contractor is engaged in, and the practices included in the program should transfer to and support the QC plan prepared for each project.

Contractors' QC programs include procedures and practices that occur continuously within the organization and that support the QC plans and process control required for each project.

For contractors, agencies, and other organizations involved in concrete paving, an effective quality management program should "enable mechanisms of change" (Swift et al. 1997) with provisions that include training and education, communication, assignment of responsibilities, standardization of best practices, and other means to support excellence and improvement. The program should be customer-focused and established and supported by management and should engage stakeholders from across the organization: executives, project managers, technicians, field personnel, purchasing personnel, human resources personnel, and safety personnel, among others. Personnel in all roles within the organization should be empowered and encouraged to identify areas for improvement and have ownership in the improvement process. Employee buy-in to the organization-wide charge of continuous quality improvement will support the success of initiatives and can improve morale and retention.

The framework, mechanisms, and processes used in quality management programs differ among organizations depending on the scope of work, operational structure, needs, and preferences of each. The establishment of a quality management system often includes the following (Thorpe and Sumner 2004):

- Defining the organization's structure and operations
- Identifying key processes, interfaces, and outputs
- Identifying personnel responsibilities
- Developing formal guidance for procedures and practices so they can be implemented in a way that reflects the organization's best practices at that moment in time

The most important part of an organization's quality management program is the establishment of procedures and practices at the core of operations. Regardless of the organization's structure or, for contractors, specialization, these formal procedures and practices should support the following (Taylor et al. 2019):

- Personnel training
- Laboratory certification
- Standardization of processes and best practices
- Procurement of products and services
- Preliminary material testing
- Equipment and process monitoring
- Communication and information flow
- Documentation and recordkeeping
- Control of documents

Each procedure and practice should include means to take corrective action and support the continuous quality improvement cycle. If continuous quality improvement is fostered, best practices will become more readily adopted throughout the organization and will change and improve over time. For contractors especially, growth, market adaptation, and technology advancements will also require changes to an organization's procedures and practices. Formal guidance should be updated accordingly, and quality management documents should essentially be "living" documents.

Establishment of a quality management system can provide many benefits but will require resources. Most organizations find that the benefits of investing in their quality management program far outweigh the costs. In many studies, the costs incurred to prevent failures have been shown to be significantly lower than the costs associated with correcting failures after the fact. Even a small investment in preventing quality issues will pay large returns due to reductions in the cost of failures (Juran and Godfrey 1999).

An example of such benefits was relayed to the FHWA by the QC manager for a concrete supply company. The company partnered with other concrete supply businesses to seek a group insurance policy. During the audit required to apply for the insurance policy, the company identified that 80% of its workplace injuries occurred during rework (work performed to correct quality issues). The company decided to invest in improving its QC, which significantly reduced the number of workplace injuries. Consequently, money was saved on the company's insurance premium, in addition to the likely benefits of improved worker safety (in terms of a reduction in injury claims and lost-time incidents), reduced costs associated with rework, and increased productivity.

The benefits of good QC are not only enjoyed by contractors and agencies; materials suppliers benefit from QC as well. One cement supplier indicated that it could provide many examples in which data from its QC program prevented it from becoming involved in construction lawsuits. The supplier representative stated, "Facts are stubborn things, as they do not change. As such, facts (data) from your quality program can save a lot of potential issues and grief."

Communication

All quality-related initiatives are driven by people, and all individuals working on a project are responsible for some aspect of the project's quality. The importance of timely, accurate, open, and respectful communication between people while planning and executing processes cannot be understated. Personnel from each entity involved in a process, regardless of position, should feel empowered to communicate the information needed to support the quality process without fear of repercussion.

Along with communication must come understanding. The information communicated must be clearly relayed, and the person receiving the information must be able to successfully act on it. Quality-related communication specifically must contain enough information and detail to support decision-making and action, since limited or poor communication results in errors, omissions, and a reduction in productivity and quality.

"The single biggest problem in communication is the illusion that it has taken place."

— George Bernard Shaw

As part of quality processes, communication can be written or spoken. Messages can be relayed through a variety of means, including verbal conversations, email and text messages, paper documents, electronic files, and information and modeling software. Communication is also becoming more rapid as cloud-based construction management software and intelligent construction technologies become more robust and more commonly utilized. The power of these tools should be capitalized upon, and they should be integrated into quality processes to enhance the speed and accuracy of communication.

The language used in quality management documents, including QC plans, is critical. QC provisions should be written in an appropriate tone, have an easy-to-follow structure, and contain the necessary content at the appropriate level of detail. To illustrate the importance of the type of language and level of detail used in QC plans, examples of "poor," "fair," and "good" QC plan provisions are provided in Appendix B. The QC plan outline presented in Appendix C provides a recommended structure for this type of document, along with suggestions regarding content and level of detail. An alternative to the use of this outline is the model QC plan presented in Appendix D, which is modeled after the NETTCP Typical Model Quality Control Plan.

Quality Control Plans

All parties that contribute in some way to a given project, including the prime contractor, subcontractor, materials suppliers, and fabricators, contribute to QC. However, it is the responsibility of the prime contractor to lead and oversee the QC activities and to ensure that personnel from all entities are engaged and focused on contributing to quality work. Central to this effort at the project level is a QC plan. The FHWA defines a QC plan as "a project-specific document prepared by the contractor which identifies all QC personnel and procedures that will be used to maintain all production and placement process 'in control' and meet the agency specification requirements" (FHWA 2008).

A QC plan is often submitted to an owner, such as an agency or other entity, or an owner's representative prior to the start of the work. The QC plan can be a standard plan used internally by the contractor (modified as necessary to meet project requirements) or can be developed specifically to meet an agency/owner's requirements for a project. Either way, the QC plan should fit the scope of work for that project. As stated above, many agencies specify minimum QC requirements, but to successfully complete most projects contractors must include more in their QC programs and plans. "Boilerplate" QC plans that have not been modified to meet project-specific needs and requirements and/or do not contain the information necessary to effectively support process control provide no assurance that a quality project will be delivered.

Different agencies have different requirements regarding the components of a project for which a QC plan must be prepared and the items that must be included in a QC plan. Often, agencies require a QC plan for some components of a project but not others. Therefore, the entity (or entities) preparing and submitting the QC plan(s) may differ depending on the following:

- The components of the project for which the agency requires a QC plan
- The components of the project for which the prime contractor or subcontractors deem a QC plan to be necessary or desirable
- Relationships between the prime contractor, subcontractor, and materials suppliers
- The project delivery method

A comprehensive QC plan for a concrete paving project is often prepared by the prime contractor, although parts of the plan can be prepared by others based on agency requirements and project responsibilities. For example, agencies often require QC plans from materials suppliers as part of certified producer programs, and these QC plans may or may not need to be included in a project-level QC plan. Subcontractors performing work in areas such as grading, utilities, or other specialties may provide their own QC plans to the agency or may instead contribute to the QC plan submitted by the prime contractor. For projects that include bridge components, a QC plan from a bridge contractor may be required as part of the paving contractor's plan if the latter is the prime contractor. Conversely, if the bridge is the key component of the project, the paving contractor's QC plan may be included as a component of the QC plan prepared by the bridge contractor.

For the purposes of this document, "contractor" generally refers to a party preparing any QC plan or component of a project-level QC plan. In instances where specific parties are intended, more specific terms (such as prime contractor, subcontractor, materials supplier) are used.

Regardless of whether a QC plan is tried and true or developed specifically for a unique project, the objective of a QC plan remains the same: To establish a framework of activities and actions that, when implemented over the course of a project, enable a contractor to reduce the risk of out-of-specification work and associated delays, costs, and impacts to reputation.

The provisions included in the QC plan should provide a proactive approach to ensuring that quality standards are met during construction. The plan should describe specific measures, including process control activities such as self-inspection, sampling, and testing, to ensure that issues are identified while adjustments can still be made (in real-time, when possible) instead of after work is completed and corrective actions are required. The QC plan should ultimately give the owner confidence that the project will reliably meet specifications.

A QC plan is not a one-size-fits-all document. While an agency may establish the minimum required components of a plan and the level of detail required, the prime contractor has the freedom to develop and implement a QC plan that best suits both the project's requirements and the contractor's processes, personnel, and risk tolerance. Over time, experience will allow the contractor to improve and refine the QC processes used and the QC plans prepared for subsequent projects. As such, the contractor should view a QC plan as a highly beneficial tool that supports the company's goals of profitability and risk mitigation, not as an undesirable addition to the list of agency requirements.

A QC plan typically includes the following elements:

- A description of the relationships between the parties involved in the project or in the portion of work covered in the QC plan. Communication between the contractor's QC personnel and the contractor's production personnel and between the agency's personnel and the contractor's QC personnel is critical to maintaining a workflow and resolving potential problems. For this reason, contact information for key personnel in the project's communication chain should be provided.
- A list of personnel involved in the project or in the portion of work covered in the QC plan, including their certifications and relevant experience. The personnel listed should include managers, superintendents, foremen, technicians, and others.
- The role and responsibilities of each person involved in the QC process and a hierarchy or line of responsibility that includes information on decision-making authority.
- Documentation required for the materials and manufactured products used in the project.
- Reference to the appropriate specification provision(s) for each material or component included in the project. The tests to be performed and test methods used, a sampling plan, testing frequency, and other relevant information supporting the testing program should be adequately described.
- A description of monitoring activities, including frequency and other relevant information.
- A procedure for evaluating data, including analysis methods and tools. This procedure should include both limits for action, indicating when corrective action should be taken or processes should be adjusted, and limits for suspension, indicating when processes should be stopped and adjusted prior to continuing production.
- A description of the means for maintaining control of the portion of work covered in the QC plan, including methods (with corresponding channels of authority) to adapt processes or stop work until it complies with expectations.
- Corrective actions that should be taken to both address out-of-control processes and remedy deficient work. Levels of corrective action could be established for various items to address issues that (1) may simply need correction or adjustment, (2) may require suspension of the work, or (3) may require corrective work. For example, the contractor could propose that concrete production be suspended when the results of air content tests fall below a certain threshold for three lots. Along with corrective actions, provisions could be included that detail the means to proceed with limited operations when operations are suspended (including information on such items as production rate/speed, testing frequency, and desired results) until satisfactory test results are achieved.
- Information regarding documentation of the work supporting the QC plan and the dissemination and archiving of this documentation.

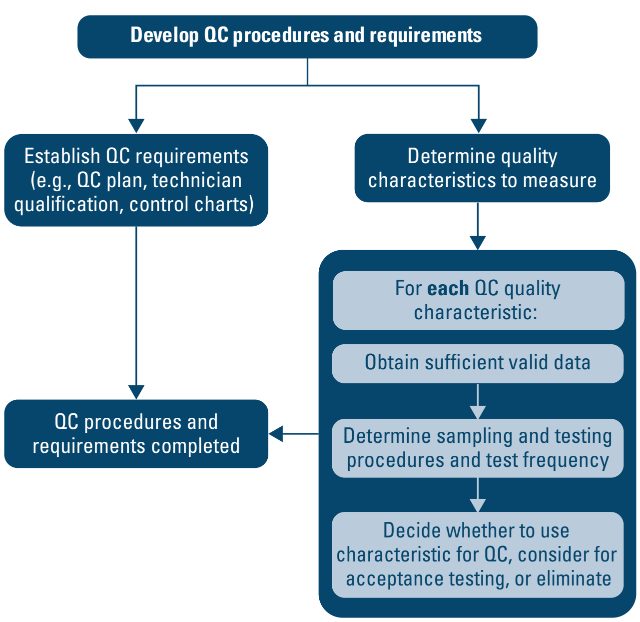
Given the purpose of a QC plan, as well as the typical provisions required by many agencies (see Appendix A), it is clear that an effective QC plan is not an empty, feel-good promise that a quality project will be delivered by the contractor. The plan should not simply restate the agency's specifications without providing details regarding how these specifications will be met and requirements achieved. Instead, it should provide an adequate level of detail and sufficient information as to "who, what, when, where, and how" to support efficient and successful implementation by contractor personnel.

Conversely, a QC plan is not useful if it is overly complicated, unorganized, or presented in a manner that cannot readily be followed by the personnel responsible for its implementation. For example, the QC plan should not require the collection of a certain type of data if the plan does not include provisions to use those data for improvement or other purposes. The QC plan should be written in clear language and should be structured in a manner that makes it straightforward for personnel to interpret and execute.

The QC plan is a binding contract document. It should be well structured, provide sufficient detail, and be straightforward for personnel to interpret and execute.

Selecting the appropriate quality characteristics to measure and control is critical to the success of a QC effort. As general guidance, the FHWA (2003) provides a flowchart illustrating the QC process, shown in Figure 2.2. Many quality characteristics used for acceptance cannot readily be measured while work is ongoing but can only be measured days or weeks after a particular segment of pavement is constructed. In such cases, quality is monitored using characteristics of the materials and the construction process that can be measured prior to or during construction (often as part of process control). Collectively, measurement, monitoring, and control of the appropriate characteristics helps ensure that the constructed work will meet the agency's acceptance criteria after the pavement is in place.

Once selected, the appropriate quality characteristics should be measured accurately. Measurements should also be made at intervals that allow the contractor to remain confidently aware of the status of the process in question and to be alerted to trends indicating that the process should be adjusted so that it remains in control. If sampling intervals are too long, the contractor will be unable to adjust the process in time to prevent out-of-specification work.



Recreated from FHWA 2003

Figure 2.2. FHWA quality control flowchart

The simple act of paying attention to one aspect of the work often drives improvement in a wide range of other areas. In other words, monitoring and controlling one quality measure can help to identify other areas of potential improvement that, in turn, have corresponding measures that could be monitored and managed. As an added benefit, actions to improve the performance of one measure often translate into improvements in other measures.

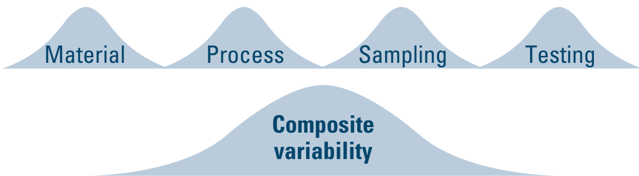
Within an agency's QA program, acceptance sampling and testing, also referred to as verification sampling and testing, verify the quality of the contractor's work and the reliability of the contractor's QC. The acceptance sampling and testing performed by an agency (or agency's representative) is separate from the contractor's QC testing and typically aims to confirm the contractor's QC test results using fewer or less frequent tests. Due to resource limitations and other reasons, however, some agencies incorporate validated QC data from the contractor into the acceptance process, relying upon the contractor's QC data to help provide confidence that the work is in conformance with project plans and specifications and will ultimately meet acceptance criteria.

Nonconforming work is detrimental to contractors due to the costs of correction, the impacts of rework on scheduling, the impacts on other work due to the need to allocate resources to the nonconforming project, and reputational damage. Ultimately, substandard performance due to poor quality control can lead to an agency's reluctance to use a particular product or material, retain a certain contractor, or select a particular material type for its roadway network.

Understanding Variability

Types and Sources of Variability

All products and processes, including those used in construction, are subject to variability. High variability can cause quality issues, while low variability is key to ensuring that a process is "in control" and capable of consistently producing a quality end product. To reduce variability, it must be measured and assessed. Minor variation may not even be noticeable, but when the variation is outside the contractor's defined limits for corrective action, it should be addressed. Excessive variability for a given characteristic may result in the work being out of specification, may be reflected in the acceptance testing, and may make rework or rejection of the work likely.



Recreated from Fick et al. 2012

Figure 2.3. Sources of construction variability

Every construction process or component is subject to variability due to materials, processes, sampling, and testing. The variability within each of these four separate sources can be combined into the composite variability for a construction process (Figure 2.3).

The four sources of variability can be described as follows:

- Material variability is a function of variations in the raw materials, including their composition and properties such as strength, ductility, porosity, moisture content, and many other natural characteristics or characteristics imparted by the production process.
- Process variability is the result of variation induced by equipment, operators, or the environment.
- Sampling variability and testing variability are the result of many types of environmental-, human-, and equipment-related factors.

Equipment-related variability can affect each of the four of the sources of variability listed above. Variability can result from changes in the equipment or equipment operator used or from the use of equipment that is not operating properly, is damaged, is not utilized correctly, or is not calibrated. In terms of the equipment itself, variability can result from tool wear, vibration, device positioning, hydraulic or electrical fluctuations, or other changes. Operator-related issues can also impart variability into processes, sampling, or testing. For a given operator, changes in skill level, experience, and emotional or physical well-being can result in variability in the way the operator performs tasks. Training and the use of automated equipment can help reduce variability due to operators and equipment.

Construction materials typically fall into one of three categories, each of which introduces a different level of variability: project-produced materials, fabricated structural materials, and standard manufactured materials. The categories can be summarized as follows:

- For project-produced materials, the production process occurs on-site or nearby. Materials arrive in a nonsolid or a loose mixture state, and steps to place, compact, cure, or otherwise prepare the material for final form are required. Examples of project-produced materials include portland cement concrete, asphalt concrete, and base materials such as granular bases and lean concrete.
- Fabricated structural materials are manufactured off-site, often in a controlled manufacturing environment. These types of materials include steel or precast concrete structural members, precast concrete pavement slabs, and other load-bearing assemblies.
- Standard manufactured materials are also produced routinely in a controlled manufacturing environment but are not produced for a specific project. Standard manufactured materials do not change during transport and arrive at the jobsite ready for installation. Examples include dowel bars, backer rods, and precast concrete drainage components.

The three categories of construction materials, as well as work produced using these materials, are subjected to environmental-related variability to different extents. Environmental conditions that affect variability include temperature, humidity, precipitation, exposure to light, and other ambient conditions. In some cases, such as in a fabrication shop, environmental factors can be controlled. However, in most construction processes they cannot. Illustrating this point, the variability of standard manufactured materials and fabricated structural materials is often observed to be less than that of site-produced materials because the former are often produced in a more highly controlled environment.

Variation in a material or in a produced component can be of several types:

- Within-piece variation occurs within a single unit and results when a characteristic or attribute differs at different locations on a piece or within a material. Examples include dimensions, color, or hardness.
- Piece-to-piece variation involves differences that occur among pieces manufactured, installed, or produced at the same time. Examples include products produced from the same machine, same source materials, or same casting or curing procedure.
- Time-to-time variation involves differences in materials or components produced at different times during a project or a production run. Time-to-time variation can result from changes in tools, equipment operators, ambient conditions, and other factors.

Operational and site characteristics, such as the size, layout, and organization of a contractor's yard, and techniques for handling or managing stockpiles and materials play a role in reducing material variability and preventing cross contamination.

Some variability may even be introduced during inspection, sampling, and testing activities, often called "reported variation." This type of variation may be attributable to the inspector, the testing or inspection equipment, or the environment and can result from faulty inspection equipment, incorrect application of a quality standard, deviation from a test method, or something as simple as too much pressure on a measuring device.

Reported variation results in an incorrect assessment of the variability in construction. It can be minimized by using trained or certified testing personnel and maintaining consistency in the personnel performing the tests, by using the appropriate equipment (calibrated as required), and by following testing standards. Overall, four of the six elements of QA (independent assurance, dispute resolution, laboratory qualification, and personnel qualification and certification) each play a role in reducing sampling, testing, and inspection variability. A good rule of thumb is that reported variability should be less than 1/10 of the variability of the other sources combined (Besterfield 2009).

Process control includes measurements made and actions taken to help minimize the variation in a process. Process control activities can include the sampling, testing, and inspection performed by a contractor in addition to the required QC activities. These additional activities help improve the likelihood that the product will meet the quality requirements (specifications). Process control activities are not used in the acceptance decision process but instead are used to help guide the contractor's corrective actions. Process control activities are often performed on the "front end" of a process and may include inspecting materials and measuring material characteristics prior to use in hopes of reducing the variability of the end product.

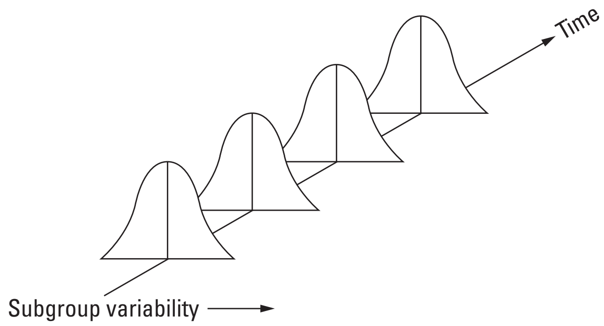
Process control activities include measurements made and actions taken by a contractor in addition to the required QC activities in an effort to reduce variability in the final product.

Process control often includes sampling, testing, and inspection of materials and processes early in the respective processes to reduce variability in the end product.

Variability and Process Control

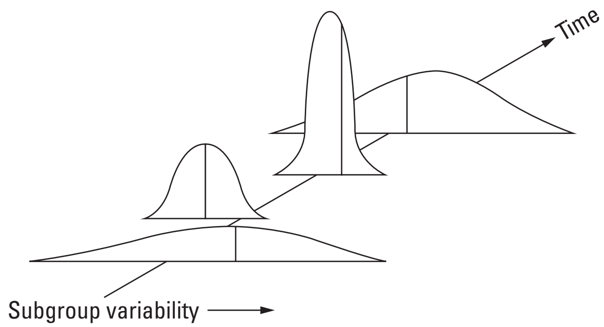
If variability that can be attributed to materials, processes, sampling, and testing fluctuates in a natural or expected manner, a stable pattern of chance cause variation develops. Chance cause variation is defined as "a source of variation that is inherent in any production process and cannot be eliminated as it is due to random, expected causes" (TRB 2018). Chance cause variation is also called random cause or natural cause variation. Each instance of chance cause variation is typically small and tends to be difficult to identify or detect without effort. If only chance cause variation is present in a process, the process is considered stable, predictable, and in a state of statistical control.

Variability within a process can be assessed using statistical methods. By computing values such as sample means, standard deviations, and confidence intervals (such as 95% upper and lower limits), an understanding of the variation observed in a process can be gained. Measurements of a quality characteristic from a series of subgroups will exhibit predictable averages and distributions, as shown in Figure 2.4.



After Besterfield 2009, Montgomery and Runger 2014, Wheeler and Chambers 2010

Figure 2.4. Variation observed in subgroups sampled from an in-control process experiencing only chance cause (natural) variability



After Besterfield 2009, Montgomery and Runger 2014, Wheeler and Chambers 2010

Figure 2.5. Variation in subgroups sampled from an out-of-control process experiencing assignable cause (not natural) variability

Changes to a process that are unexpected or the development of unwanted issues or problems can cause large changes in variability that are disruptive or troublesome to a process. These types of issues are not considered chance cause variability but are instead called assignable cause variability. Assignable cause variability triggers excess variability beyond that expected due to natural variability. If assignable cause variability is present in the materials, processes, sampling, or testing associated with a process, excessive variability in one or more quality measurements will often result. Measurements of a quality characteristic from a series of subgroups will exhibit unacceptably different means and standard deviations, as shown in Figure 2.5, and the process can be considered out of control.

Measures can be taken to reduce both chance cause and assignable cause variability in a construction process, reducing the standard deviation of subgroups and reducing the distance of subgroup means from the line of central tendency. Actions that can reduce variability include training and using qualified/certified personnel, limiting changes in the equipment operators and technicians performing tests, inspecting equipment to ensure that it can be operated appropriately, and calibrating and maintaining measuring and testing devices. The goal of a QC plan is to prescribe practices that, when implemented, help a contractor monitor, manage, and reduce variability from both chance and assignable causes. Chapter 5 of this document describes approaches and best practices that can be included in a contractor's QC plan to help reduce variability from materials and processes.

Statistically based acceptance methods, such as PWL, are often at least partially based on standard deviation. When properly developed, the PWL approach accounts for typical levels of variability in each material and/or process and rewards contractors for reducing the variability that is within their control. Although some variability may not be directly in the contractor's control, producing concrete with consistent properties and performance should reduce much of the variability.

QC and acceptance testing should be performed independently from one another to avoid introducing bias and influencing the respective outcomes. Disagreements and disputes often occur due to differences in test results between acceptance and QC personnel and laboratories. In many cases, the precision of the tests is such that both sets of results may be correct. An understanding of the level of precision of each test and open communication between acceptance and QC personnel regarding test results are necessary to ensure that the variability inherent in different test results is understood, conflicts are minimized, and the materials and test results accurately represent the condition of the in-place pavement. The precision and bias associated with each test method should be considered when evaluating the test results, and formal, predetermined dispute resolution processes should be implemented when differences between QC and acceptance tests arise.

Agency and contractor personnel should understand that tests performed on concrete have different levels of precision and variability. Table 2.1 provides a list of test methods commonly used in concrete pavement construction, along with sample results (Taylor et al. 2019). The confidence intervals shown in Table 2.1 were computed using the sample size, mean, and standard deviation of each tested sample and a statistical value based on the desired confidence level. The upper and lower 95% confidence limits represent an acceptable range of differences between two tests from the same sample, with the range of values associated with each set of test results dependent on the precision of that test. One can be 95% confident that the true value of the material is between the lower and upper confidence limits shown in Table 2.1.

Sampling and Statistical Process Control

For each quality characteristic included in a QC plan, a sampling plan should be developed to guide the process used to obtain measurements. The minimum requirements of a sampling plan may be specified by an agency. However, to maintain process control, enough tests must be performed to statistically characterize the material population. In addition to providing an agency with the required data, a sampling plan can also be developed in a manner that helps the contractor reduce risk and increase profitability.

When developing a QC sampling plan, many factors should be considered. These include the construction material or process of interest, the knowledge and experience of the personnel involved, the potential for the system to change, and risk tolerance. The sampling plan may be different for various stages of a project or be subject to modification due to issues or events that may occur during the work. The contractor's QC team will need to consider both project requirements and available resources to develop an appropriate sampling plan, as well as provisions to adapt that plan if needed. Both randomized and biased/selective (also referred to as selective systematic or time-ordered) sampling and testing can be considered in order to achieve specific goals. These two approaches to sampling are discussed in more detail below.

To support a good statistical program, a sampling plan should have six important characteristics (Deming 1950):

- It is useful and comprehensive in content.
- Results are reliable and sufficient for the purpose or goals.
- Classifications and definitions are understood.
- Activities can easily be performed and are not overly burdensome in terms of time or effort.
- It is cost effective.
- Results can be accurately interpreted, presented, and utilized.

A sampling plan must be sufficiently robust to support the production/construction of a quality product at a reasonable cost with an acceptable level of risk to the manufacturer or contractor.

Table 2.1. Examples of testing precision

Test	95% lower limit	Sample result	95% upper limit
Sieve analysis (passing ½ in.)	22%	28%	34%
Slump	½ in.	1¼ in.	2 in.
Air content	4.7%	5.5%	6.3%
Unit weight	142.7 lb/ft^3	145.0 lb/ft^3	147.3 lb/ft^3
Compressive strength	3,100 lb/in^2	3,600 lb/in^2	4,100 lb/in^2
Flexural strength	565 lb/in^2	700 lb/in^2	835 lb/in^2

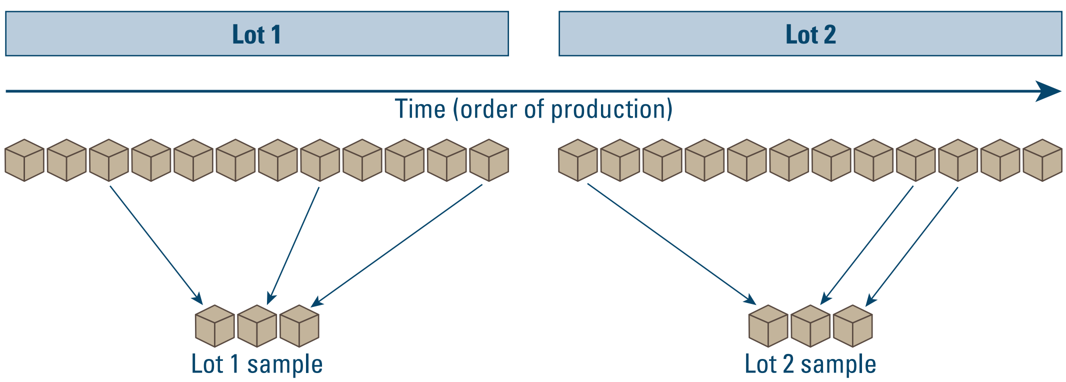
Source: Taylor et al. 2019

One of the founders of quality management, William Edwards Deming, stated that "sampling is not mere substitution of partial coverage for total coverage. Sampling is the science and art of controlling and measuring the reliability of useful statistical information though the theory of probability" (Deming 1950). As this statement suggests, QC activities become more useful when quantitative methods are used to monitor a process, inform decisions, and drive improvement. Statistical process control involves evaluation of QC data and often relies upon the use of control charts to indicate whether a process is in control or whether results are unusual or indicative of issues with a process. Control charts are described in depth in Chapter 6 and Appendix E.

Lots are a rational subgroup used to divide a component of work into portions for the purpose of QA and are often the basis of a sampling plan and associated control charts. TRB defines a population as "a collection of all possible individuals, objects, or items that possess some common specified characteristic(s) which can be measured" and defines a lot as "a specific quantity of material from a single source which is assumed to be produced or placed by the same controlled process" (TRB 2018). A sample is defined in AASHTO R 10, Definition of Terms Related to Quality and Statistics as Used in Highway Construction, as "a small part of a population (or lot) that represents the whole." As the sample size (n) increases, the sample theoretically provides a better estimate of the population or lot. The results of tests on samples with some statistical power are used to estimate the characteristics of a lot for both QC and acceptance purposes.

Two approaches to sampling are usually taken, shown in Figures 2.6 and 2.7:

- Random sampling (also called period-in-time or population sampling)
- Biased or selective sampling (also called time-order, instant-in-time, or process sampling)



CP Tech Center

Figure 2.6. Random sampling

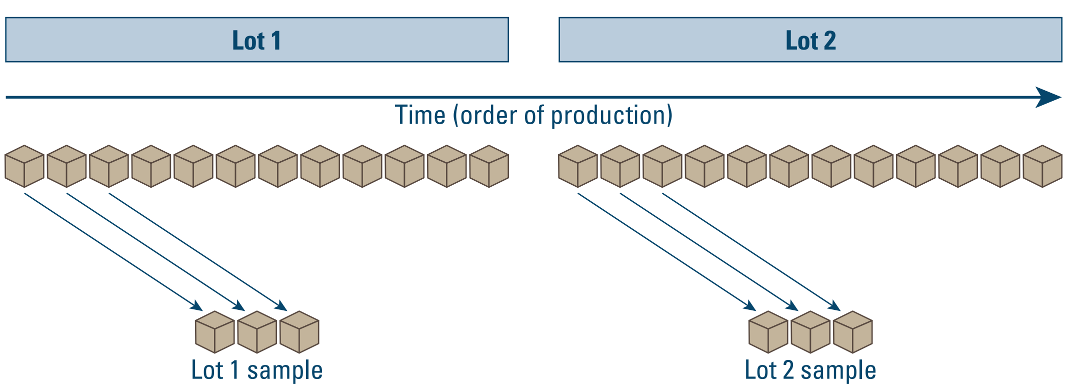


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Figure 2.7. Biased/selective sampling (in this example, by time order)

Random sampling is used when characterizing a larger population and is required (by 23 C.F.R. § 637.205) for use in the agency's acceptance decision and to calculate a price adjustment for a population (a lot of material). Random sampling is also required for the use of statistical tools such as control charts (see Chapter 6 of this document). The subgroup of units comprising the random sample represents the entire output over a defined interval, and each sample has an equal probability of selection. Often, random samples are obtained in accordance with ASTM D3665, Standard Practice for Random Sampling of Construction Materials, or in accordance with other agency-approved procedures. These procedures can include random number tables or random sampling techniques using a spreadsheet or other software. Random sampling provides the advantages of easier identification of rapid shifts of a process in and out of control and the removal of human bias from the process.

Biased/selective sampling is useful for process control and to monitor production at startup, after an adjustment, or at regular intervals. Biased/selective sampling is also used to evaluate any visual defects for acceptance or rejection of a discrete quantity. When biased/selective sampling is used, samples are targeted for selection based on the need of the contractor. Time-order sampling, a method of biased/selective sampling, provides a snapshot of production at a certain time and can be used to provide a reasonable estimate of the standard deviation of a process. Although this approach provides a stronger chance of identifying variability that results from assignable causes between samples, it reduces the chance of identifying variability that results from assignable causes within a sample (because the samples are taken sequentially, not over a longer duration of time).

Biased/selective sampling is often appropriate for collecting data after changing a process, for example, when changes are made to dosages of a water-reducing admixture (WRA) to adjust the workability of a concrete mixture. Testing samples from the first several batches of concrete produced after this change (similar to the first lot in Figure 2.7) would be appropriate to enable the contractor to evaluate the effects of the change in mixture design. These data would not, however, be included in the acceptance decision. Other instances where selective sampling would be appropriate include when the contractor is attempting to identify the extent or limits of materials or work that are out of specification.

An independent sample is one that is selected without consideration of previous samples from the same lot. 23 C.F.R. § 637.207 requires that independent samples be used for verification sampling and testing and that an independent sample be used to verify the acceptance or rejection decision. For samples to be considered independent of each other, each sample must reflect all sources of variability associated with the material, process, sampling, and testing (FHWA 2004).

As part of an agency's processes, both random and biased/selective samples are often split into two or more parts to support multiple tests representing the same material. Split samples can be used in the agency's acceptance decision "if the data is used properly to provide validation of independent data" (FHWA 2004). Validation procedures to confirm that samples are independent often include the F-test (comparison of variances) and the t-test (comparison of means); however, split samples typically require the paired t-test to facilitate the comparison. Additional guidance is presented in AASHTO R 9, Burati et al. (2003), and FHWA (2004).

Chapter 3

Quality Control for Materials Suppliers

The quality of concrete is heavily influenced by the quality and consistency of the component materials. To produce a concrete pavement that meets specifications and provides the desired performance, the contractor should be confident in the characteristics of the materials bought and used for the project and how the materials will perform. A comprehensive QC plan requires that, for all materials supplied to the project, the quality and production personnel should know and understand the following:

- The specifications for all products being supplied
- How to measure the required uniformity of the products being supplied
- Adjustments to make to the process if the uniformity changes

The following sections describe the component materials of concrete and provide information on the best practices that should be in place at the materials suppliers' facilities to support contractor QC.

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Figure 3.1. Cement plant in Missouri that produces 4 million tons annually and supplies 23 states

Portland Cement and Blended Cement

Portland cements are produced in accordance with either AASHTO M 85 or ASTM C150, Standard Specification for Portland Cement. Both specifications have been harmonized by the industry and are essentially identical.

In general, portland cements from the same source tend to be quite uniform. The QC testing performed at a cement plant by the producer is extensive, and in a modern cement plant (Figure 3.1) testing is largely automated. Cement manufacturers are required to sample and test their product in accordance with ASTM C183, Standard Specification for Sampling and the Amount of Testing of Hydraulic Cement, which specifies the kinds and sizes of samples, by whom the samples should be taken, the testing time requirements, the sampling procedure, the preparation of samples, the amount of testing, and the procedures for noncompliance and retests.

Testing at a cement plant begins in the limestone quarry, where it is typical for all raw materials to be tested separately and then tested again after blending before the initiation of pyroprocessing (Kosmatka and Wilson 2016). The production of the clinker is closely monitored, and adjustments are made to ensure that the correct chemical composition is achieved.

During the process of grinding the clinker to produce portland cement, conformity to both chemical and physical requirements is checked frequently. QC tests at the cement plant primarily include the chemical composition and physical requirement tests prescribed in AASHTO M 85 and ASTM C150.

The cement specifications also require that, at the request of the purchaser, a report (often called a mill certificate) must be furnished at the time of shipment (Figure 3.2). The mill certificate provides information about the cement, including the chemical composition (oxide analysis), alkalis, loss on ignition (LOI) test results, cement phases, and other data, and the results of physical tests such as strength, set time, autoclave and mortar bar expansion, and other required tests. A mill certificate certifies that the product supplied meets the required specification, and the cement manufacturer can (and should) explain the information on the certificate to users so they can interpret the information.

It is standard practice in the industry for producers to issue mill certificates on a monthly basis, providing the average of all tests for any given time period. Given that mill certificates provide a monthly average (usually a composite of daily production) of all tests for a given material produced, contractors should be aware that some cement purchased may have a chemical composition and physical properties that differ to some extent from those listed on the mill certificate.

Holcim

NSF Certified to NSF/ANSI 61 & 372

Material Certification Report

Material: Portland Cement
Type: I-II Low Alkali

Test Period: 01-July-2020 to 31-July-2020
Date Issued: 14-Aug-20

Certification

This cement meets the specifications of ASTM C150 and AASHTO M85 for Type I-II cement.

General Information

Supplier:

Address:

Contact:

Source Location:

Contact:

The following is based on average test data during the test period. The data is typical of product shipped from this source; individual shipments may vary.

Test Data on ASTM Standard Requirements

Chemical			Physical		
Item	**Limit [1]**	**Result**	**Item**	**Limit [1]**	**Result**
SiO_2 (%)	-	19.8	Air Content (%)	12 max	7
Al_2O_3 (%)	6.0 max	4.5	Blaine Fineness (m^2/kg)	260 min	396
Fe_2O_3 (%)	6.0 max	3.1			
CaO (%)	-	64.3	Autoclave Expansion (%) (C151)	0.80 max	0.04
MgO (%)	6.0 max	2.1	Compressive Strength MPa (psi)		
SO_3 (%) [2]	3.0 max	3.3	1 day	-	16.6 (2410)
Loss on Ignition (%) [5]	3.5 max	3.0	3 day	10.0 (1450) min	28.8 (4180)
Insoluble Residue (%)	1.50 max	0.27	7 day	17.0 (2470) min	35.0 (5070)
CO_2 (%)	-	1.8	28 day (previous month's data)	-	45.5 (6600)
$CaCO_3$ in Limestone (%)	70 min	89			
Potential Phase Compositions [3]:			Initial Vicat (minutes)	45-375	92
C_3S (%)	-	65			
C_2S (%)	-	6	Mortar Bar Expansion (%) (C1038)	0.020	0.002
C_3A (%)	8 max	6			
C_4AF (%)	-	9			
$C_3S + 4.75C_3A$ (%)	-	93.5			

Test Data on ASTM Optional Requirements

Chemical			Physical		
Item	**Limit [1]**	**Result**	**Item**	**Limit [1]**	**Result**
Equivalent Alkalies (%)	-	0.52	False Set (%)	50 min	81

Notes (*1-9)

1 - Dashes in the Limit / Result columns mean Not Applicable.
2 - It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020% at 14 days.
3 - Adjusted per Annex A1.6 of ASTM C150 and AASHTO M85.
5 - Limit = 3.0 when limestone is not an ingredient in the final cement product
Equivalent Alkalies (%) Minimum = 0.47, Maximum = 0.56
This data may have been reported on previous mill certificates.

Additional Data

Item	Limestone	Inorganic Processing Addition	Base Cement Phase Composition	Result
Type	-	IPA		
Amount (%)	4.5	0.4	C_3S (%)	69
SiO_2 (%)	8.7	37.1	C_2S (%)	6
Al_2O_3 (%)	0.84	10.7	C_3A (%)	7
Fe_2O_3 (%)	0.46	2.2	C_4AF (%)	10
CaO (%)	48.4	36.7		
SO_3 (%)	0.12	0.6		

John Q. Quality

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Figure 3.2. Typical mill certificate for portland cement

It is also common in the industry for purchasers to request a report of testing in accordance with ASTM C917, Standard Test Method for Evaluation of Variability of Cement from a Single Source Based on Strength. Pairing this report (shown in Figure 3.3) with the mill certificate, the user obtain monthly summaries of compliance and a summary of strength consistency.

Unless the cement source changes, existing practices should provide the user the data necessary to evaluate the cement obtained for use on a project. If the source of cement changes, the contractor will need to obtain additional information from the supplier to properly assess the effect of such a change on the concrete's properties and performance.

ASTM C917 Report

	From	To
Date Range:	**1-Apr-20**	**8-Aug-20**
Product Type:	C12LALSA	
Query Time:	13:53 17-Aug-2020	

Measurement Analysis Data	7 Day	28 Day
Average Strengths	36.9 (5347)	46.7 (6776)
Total Standard Deviation	0.9 (135.6)	1.1 (156.4)
Number of Tests	42	35
Testing Standard Deviation	0.63 (91.1)	0.72 (104.5)
Number of Tests	10	10
Corrected Standard Deviation	0.69 (100.5)	0.8 (116.4)

Sample Number	**Date Shipped**	**7 Day Strength, MPa (psi)**		**28 Day Strength, MPa (psi)**		**Load Number**	**Bins / Silos**	**Transport Type**
		Result	Avg-5	Result	Avg-5			
GV20010205	1-Apr-20	37.3 (5412)	-	46.2 (6699)	-	-	B	Barge
GV20010208B	1-Apr-20	35.6 (5166)	-	45.3 (6575)	-	-	B	Barge
GV20011415	6-Apr-20	36 (5214)	-	47.5 (6885)	-	-	B	Barge
GV20011538	9-Apr-20	37.4 (5420)	-	48.3 (7001)	-	-	B	Barge
GV20012527	17-Apr-20	36.6 (5308)	36.1 (5241)	47.3 (6857)	46.6 (6762)	-	B	Barge
GV20013361	21-Apr-20	36.3 (5262)	36.7 (5323)	45.4 (6586)	46.9 (6806)	-	B	Barge
GV20013903	23-Apr-20	36.2 (5251)	36.5 (5291)	45.7 (6635)	46.8 (6793)	-	B	Barge
GV20014802	27-Apr-20	37.5 (5432)	36.8 (5335)	47.7 (6917)	46.9 (6799)	-	B	Barge
GV20014266	28-Apr-20	36.6 (5305)	36.6 (5312)	45.8 (6645)	46.4 (6728)	-	B	Barge
GV20014978	29-Apr-20	35.6 (5161)	36.4 (5282)	46.4 (6724)	46.2 (6701)	-	B	Barge
GV20015163	30-Apr-20	36.8 (5336)	36.5 (5297)	46.3 (6721)	46.4 (6728)	-	B	Barge
GV20015213	4-May-20	37.7 (5461)	36.8 (5339)	47 (6817)	46.6 (6765)	-	B	Barge
GV20015215B	4-May-20	37.3 (5412)		47.3 (6859)		-	B	Barge
GV20016037	6-May-20	37 (5370)	36.7 (5327)	46.5 (6743)	46.4 (6730)	-	B	Barge
GV20016772	8-May-20	38.2 (5539)	37 (5374)	47.2 (6841)	46.7 (6769)	-	B	Barge
GV20017129	11-May-20	38 (5507)	37.5 (5443)	47.9 (6942)	47 (6813)	-	B	Barge
GV20017667	15-May-20	36.5 (5287)	37.5 (5433)	46.5 (6749)	47 (6818)	-	B	Barge
GV20018017	19-May-20	37.2 (5391)	37.4 (5419)	46.8 (6789)	47 (6813)	-	B	Barge
GV20018357	21-May-20	35.6 (5163)	37.1 (5378)	44.2 (6404)	46.5 (6745)	-	B	Barge
GV20018937	25-May-20	37.9 (5501)	37 (5370)	47.6 (6905)	46.6 (6758)	-	B	Barge
GV20019585	27-May-20	38.3 (5553)	37.1 (5379)	49.6 (7196)	46.9 (6808)	-	B	Barge
GV20019779	1-Jun-20	38.6 (5603)	37.5 (5442)	47.7 (6919)	47.2 (6842)	-	B	Barge
GV20019781B	1-Jun-20	37.9 (5492)		46.5 (6744)		-	B	Barge
GV20020355	3-Jun-20	38 (5507)	37.7 (5466)	48.1 (6976)	47.4 (6880)	-	B	Barge
GV20020476	5-Jun-20	38.1 (5530)	38.2 (5539)	47.1 (6824)	48 (6964)	-	B	Barge
GV20021050	9-Jun-20	37.5 (5445)	38.1 (5528)	47.2 (6851)	47.9 (6953)	-	B	Barge
GV20021174	11-Jun-20	37 (5360)	37.8 (5489)	46.4 (6724)	47.3 (6859)	-	B	Barge
GV20021535	16-Jun-20	35.7 (5179)	37.3 (5404)	45.7 (6624)	46.9 (6800)	-	B	Barge
GV20021754	18-Jun-20	38.1 (5522)	37.3 (5407)	47.5 (6892)	46.8 (6783)	-	B	Barge
GV20022166	22-Jun-20	36.8 (5333)	37 (5368)	47.2 (6843)	46.8 (6787)	-	B	Barge
GV20022749	24-Jun-20	36.7 (5326)	36.8 (5344)	46.8 (6786)	46.7 (6774)	-	B	Barge
GV20022877	26-Jun-20	37.4 (5417)	36.9 (5355)	47 (6822)	46.8 (6793)	-	B	Barge
GV20023085	2-Jul-20	36.2 (5253)	37 (5370)	46.9 (6807)	47.1 (6830)	-	B	Barge
GV20023087B	2-Jul-20	35.9 (5213)		46 (6670)		-	B	Barge
GV20023390	6-Jul-20	35.3 (5113)	36.5 (5288)	45.2 (6559)	46.6 (6763)	-	B	Barge
GV20023905	8-Jul-20	35.4 (5134)	36.2 (5248)	46.1 (6688)	46.4 (6732)	-	B	Barge
GV20024033	10-Jul-20	35.4 (5136)	35.9 (5210)	44.7 (6479)	46 (6671)	-	B	Barge
GV20024755	14-Jul-20	35.6 (5158)	35.6 (5159)	45.7 (6629)	45.7 (6632)	-	B	Barge
GV20024926	16-Jul-20	36.8 (5344)	35.7 (5177)	46 (6672)	45.5 (6605)	-	B	Barge
GV20025410	20-Jul-20	36 (5223)	35.8 (5199)			-	B	Barge
GV20026035	22-Jul-20	37.4 (5421)	36.2 (5256)			-	B	Barge
GV20026198	24-Jul-20	36.9 (5347)	36.5 (5299)			-	B	Barge
GV20026997	28-Jul-20	37.1 (5384)	36.8 (5344)			-	B	Barge
GV20027680	3-Aug-20	35.7 (5184)	36.6 (5312)			-	B	Barge
GV20027682B	3-Aug-20	37.6 (5449)				-	B	Barge
GV20028274	5-Aug-20	38.1 (5530)	37 (5373)			-	B	Barge
GV20028350	7-Aug-20	36.1 (5233)	36.8 (5336)			-	B	Barge

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Figure 3.3. ASTM C917 report showing cement variability during a certain production period

If blended cements are to be used, they should be produced in accordance with ASTM C595, Standard Specification for Blended Hydraulic Cement, or its AASHTO equivalent, AASHTO M 240. Blended cement specifications place strict limits on the allowable quantities and variations in the components of any given blend. Mill certificates for blended cements are commonly provided for each production run of a given blend.

The mill certificate for a blended cement will likely be as reliable as the mill certificate for portland cement. However, blended cements may vary more from one production run to the next simply because changes are introduced in the process each time the plant starts up and shuts down. No common industry practice exists for evaluating the uniformity of strength performance for blended cements. However, a user could request such uniformity data from a given cement supplier.

A performance-based standard, ASTM C1157, Standard for Performance Specification of Hydraulic Cement, can be used for portland limestone cements or other cements that do not meet the requirements of ASTM C595/AASHTO M 240. ASTM C1157 does not have an equivalent AASHTO standard. This specification has no restrictions on the composition of the cement or its constituents. This specification does, however, have standard physical requirements for all six types of cement designated in this standard.

Supplementary Cementitious Materials

Slag Cement

Ground granulated blast furnace slag (GGBFS), commonly referred to as slag cement, is a coproduct of the production of iron in a blast furnace and can be used for improving the strength, improving the durability, or reducing the heat of hydration of concrete. The mixture proportions of the materials placed into a blast furnace as part of the production of iron are well controlled. Therefore, the resulting chemistry of slag is typically consistent. The specification for GGBFS or slag cement is AASHTO M 302 or ASTM C989, Standard Specification for Slag Cement for Use in Concrete and Mortars.

The slag cement specifications define three grades for slag cement: Grade 120, Grade 100, and Grade 80. Each grade number indicates the slag activity index (SAI) value of the slag cement for 28-day strength. The SAI is the ratio of the strengths of two mixtures: one comprised of equal parts slag and a reference portland cement plus a specified amount of sand and the other containing only the same reference portland cement and the same amount of sand. A mortar containing Grade 100 slag should exhibit the same strength as a reference cement mortar at 28 days.

The chemical composition and physical characteristics of slag cement are generally uniform when supplied from a single source, and, in general, slag can be expected to increase concrete set time and reduce early strength. The industry norm is to issue monthly mill certificates showing limited chemical results, the SAI values for 7- and 28-day strength, and fineness. The customer can also request uniformity data from the supplier.

Fly Ash

Fly ash is a byproduct of the coal burning process, and its use as a replacement for portland cement in concrete mixtures has long been demonstrated to improve durability (Taylor et al. 2013). The chemical composition and physical properties of fly ash can change from source to source or within a single production source, depending on the type and origin of the coal, the power generation process, the treatment of the fly ash, and other factors. Therefore, to understand the performance of fly ash in a given concrete mixture, its composition and uniformity should be monitored.

The specifications for fly ash are AASHTO M 295 or ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolans for Use in Concrete. Both specifications cover the chemical and physical requirement of Class C and Class F fly ashes and include limits on the uniformity of fly ash for density and fineness.

Because the variability of the chemical composition and physical properties of fly ash can be an issue, it is important that the supplier and user establish testing requirements beyond those specified by ASTM/AASHTO and communicate frequently about any changes in the product. Changes in fly ash composition are particularly important due to the potential impacts on air entrainment. Some agencies have lowered the LOI limit specified in ASTM C311 for fly ash to address air entrainment issues, and in some cases fly ash suppliers provide foam index test results (ASTM C1827) as a way to inform users about potential air entrainment issues (Harris et al. 2008, Ahmed 2012). Other methods to evaluate the compatibility of materials include ASTM C1753, Standard Practice for Evaluating Early Hydration of Hydraulic Cementitious Mixtures Using Thermal Measurements, and ASTM C1810, Standard Guide for Comparing Performance of Concrete-Making Materials Using Mortar Mixtures.

Natural Pozzolans

In some areas of the country, natural pozzolans (either raw or calcined) are available. Natural pozzolans can be useful for improving the durability of concrete in terms of sulfate resistance or alkali-silica reactivity (ASR) mitigation (Taylor et al. 2013). ASTM C618 and AASHTO M 295 include a designation for Class N natural pozzolans that defines the chemical and physical requirements for compliance. Although they have different chemical requirements than fly ashes, pozzolans have the same physical requirements with the exception that they are allowed a higher water demand.

Natural pozzolans have not been used in the United States in a manner that provides a robust performance history, and therefore trial batches are strongly recommended before the material is used in concrete mixtures. As with other supplementary cementitious materials (SCMs), understanding the uniformity of a pozzolan from lot to lot is also important. Information that indicates the uniformity of a product should be requested from the supplier.

Chemical Admixtures

Chemical admixtures such as water-reducing and air-entraining agents are defined by ASTM C494, Standard Specification for Chemical Admixtures for Concrete. This specification includes provisions for eight different types of admixtures. Admixtures are produced in tightly controlled manufacturing processes and therefore exhibit strong uniformity from lot to lot. ASTM C494 provides details on how users can use infrared analysis to test for (1) the uniformity of a lot and (2) the equivalence from lot to lot. Due to their liquid state, as well as their chemical compositions, admixtures are sometimes subject to environment-induced changes. Therefore, admixtures should be stored in the manner specified by the manufacturer, protected from the environment (e.g., from freezing), and used within the timeframe deemed appropriate by the manufacturer.

Aggregates

AASHTO M 80, Standard Specification for Coarse Aggregate for Hydraulic Cement Concrete; AASHTO M 6, Standard Specification for Fine Aggregate for Hydraulic Cement Concrete; and ASTM C33, Standard Specification for Concrete Aggregates, define the requirements for the uniformity, gradation, and quality of fine and coarse aggregate used in concrete. These standards also prescribe methods of sampling and testing aggregates and provide guidance regarding deleterious substances contained within aggregates, soundness, and susceptibility to alkali-aggregate reactivity (AAR). Common tests for the physical properties of aggregates include ASTM C29, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate; ASTM C127, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate; and ASTM C128, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate. Gradations are determined by ASTM C136, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

Those responsible for selecting the proportions of the concrete mixture have the responsibility for determining the nominal maximum aggregate size, the proportions of fine and coarse aggregate, and the extent of aggregate blending (if required or approved). The availability and quality of aggregates vary greatly in different parts of the country. Regardless of the differences in concrete mixtures from one part of the country to the next, the aggregates supplied should contribute to the mixture in the following ways:

1. Provide a workable plastic concrete mixture
2. Meet the design strength requirements
3. Provide a durable concrete mixture

In addition to referencing the standards listed above, most agency specifications include other provisions and requirements to help ensure that the aggregates used on agency projects are of acceptable quality and provide suitable durability performance. Aggregates should meet agency specifications related to soundness, AAR, and other characteristics. Additional guidance on evaluating the reactivity of aggregates is provided in AASHTO R 80, Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction.

The suppliers of aggregates used in concrete should participate in an appropriate agency-approved producer program, if applicable. Many approved producer programs provide the minimum QC sampling, testing, and recordkeeping provisions required for approval to supply aggregates for agency projects.

As part of their approved producer programs, many agencies require aggregate suppliers to submit one or more QC plans for their operations. The agency requirements for these plans are often site-specific, with a plan required for each quarry, pit, or other source.

Each plan is often required to provide the location of the source, the personnel responsible for production and QC at the site, stockpile locations and signage, and a loading and shipping control plan. The plan must also detail how the aggregate producer plans to control its production process, including the testing program used to monitor the product and the equipment and methods used to control the production processes. The plan should also include provisions for addressing nonconformance.

Aggregate producers are often required to maintain a qualified or approved laboratory on site or to retain the services of an approved third-party laboratory for QC purposes. The aggregate supplier's QC plan should detail the processes for the calibration of laboratory equipment and recordkeeping. The agency may need to certify the technicians who perform tests on aggregates as part of its requirements.

As with the information provided by other materials suppliers, the contractor should understand the information provided in the aggregate supplier's QC plan. Contractors should communicate with aggregate suppliers regarding events or issues that may impact quality, such as the supplier moving its operations to a different face or bench of rock, the balance between demand and delivery among multiple customers, and stockpiling procedures.

Summary and Additional Resources

Concrete is a product produced on site, and controlling the quality and consistency of the component materials is critical to the success of a concrete paving project. ASTM and AASHTO standards state the requirements for each product, and agency specifications often include additional provisions to support the use of quality materials on their projects. Materials suppliers are also responsible for using their own QC programs to ensure that the material sold for use on a project complies with the appropriate standards.

Information regarding each product should be accurately conveyed to the user. For all materials used to produce a concrete pavement, there is no substitute for timely and useful communication between the materials suppliers and the contractor. Particular attention needs to be paid to variability if the source of any material changes.

Additionally, combinations of the component materials of any concrete mixture should be tested using trial batching prior to submission of the mixture design. The mixture design and verification processes are discussed in Chapter 5 of this document. Trial batches and tests should be conducted in conditions that simulate the actual project conditions when possible.

In addition to the standards referenced above, the American Concrete Institute (ACI) has published guidance on the use of each of the materials discussed in this chapter. The guidance documents listed below provide stakeholders with additional details on each material and its use:

- *ACI 225R-19: Guide to the Selection and Use of Hydraulic Cements* (ACI Committee 225 2019)
- *ACI 232.2R-18: Report on the Use of Fly Ash in Concrete* (ACI Committee 232 2018)
- *ACI 232.1R-12: Report on the Use of Raw or Processed Natural Pozzolans in Concrete* (ACI Committee 232 2012)
- *ACI 233R-17: Guide to the Use of Slag Cement in Concrete and Mortar* (ACI Committee 233 2017)
- *ACI 212.3R-16: Report on Chemical Admixtures for Concrete* (ACI Committee 212 2016)
- *ACI 221R-96 (Reapproved 2001): Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete* (ACI Committee 221 2001)
- *ACI 221.1R-98 (Reapproved 2008): Report on Alkali-Aggregate Reactivity* (ACI Committee 221 2008)
- *ACI E4-12: Chemical Admixtures for Concrete* (ACI Committee E-701 2012)
- *ACI E1-16: Aggregates for Concrete* (ACI Committee E-701 2016)

Chapter 4
Performance-Engineered Concrete Mixtures

Concrete pavements have been constructed for over a century. To the casual observer, it might seem as though little has changed in constructing these pavements over the years. It may appear that other than some changes in equipment, concrete is still concrete and quality control should be straightforward. There is a sliver of truth in that viewpoint, in that many of the same test procedures that were developed in the early 20th century are still used today. But in reality, many things have changed over the years. The two primary differences are that (1) materials have evolved significantly and (2) the use of deicing chemicals on pavements is now much more prevalent than in the past.

Because of these developments, a movement towards PEMs has arisen. The PEM approach allows the designer to optimize specific concrete properties with respect to the environment, function, and design life of the structure. AASHTO PP 84, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, expands upon the need for and objective of PEMs:

> Specifications for concrete pavement mixtures have traditionally been prescriptive, with agencies specifying means and methods for both constituent materials and specific requirements for proportioning. This places the majority of the performance risk on the agency and limits innovation. Recent trends of blending cementitious materials, reducing paste content, using modern additives and admixtures, and other innovations in the industry provide the opportunity to move towards specifying the performance characteristics of concrete mixtures and allowing industry to design mixtures that meet specific performance requirements. New methods to evaluate concrete performance have been developed, and others are being formulated, that can result in improved performance and economics. Further, shifting the responsibility for performance to the contractor provides an opportunity for innovation.…
>
> This practice is intended to provide agencies flexibility in their approach to the use of alternative performance measures and includes a range of choices that can be selected to best fit the needs of the agency.…
>
> Life-cycle cost of concrete pavements will be considerably reduced, as a result of extended service life, by reducing material and construction variability. **This is achieved by a robust quality control (QC) program.** [emphasis added]

The context and background provided by these quotations from AASHTO PP 84 justify the increased emphasis being placed on contractor QC and agency acceptance. The need for PEMs has arisen from multiple factors, which include but are not limited to the following:

- Changes to constituent materials such as portland cement and fly ash
- Changes to and increased use of deicing materials on pavements in wet freeze-thaw environments
- New and improved test methods for concrete and the materials used in concrete
- In some cases, premature distress and failure of concrete pavements designed and constructed using traditional specifications

Given that PEMs are designed to meet performance objectives, it should be noted that agency specification and acceptance thresholds are provided to ensure the desired performance of the final product. The minimum level of quality is therefore full conformance with the contract specifications. Contractor QC and other agency QA activities are necessary to assess the level of conformance to the specifications and thus indicate the expected level of performance. An intentional focus on quality, through observing each of the elements in a QA program (Figure 1.2), is necessary to ensure that the durability properties promised by PEMs are indeed achieved; simply naming something “performance engineered” does not improve the durability of a concrete pavement.

Some agencies have begun to implement PEMs into their specifications, while for others implementation may take some time. With respect to a materials supplier’s and/or contractor’s approach to QC, it should not matter whether a pavement is constructed under PEM specifications or traditional concrete pavement specifications. The intent of this document is to provide guidance on QC best practices for the construction of portland cement concrete pavements. These best practices are tailored to PEMs to follow the trend of agency adoption but still apply to any concrete paving project regardless of the specification details.

Summary of Performance-Engineered Mixture Requirements

Six concrete properties are used to characterize PEMs. These properties and their requirements are briefly described below, and Table 4.1 summarizes the current test methods for each property.

It should be noted that the PEM approach is scalable and customizable, meaning the engineer can pick and choose which concrete properties and test methods are appropriate for the project scope, size, and environment. For more information on PEMs and their performance characteristics, refer to the resources available from the National Concrete Pavement Technology Center at https://cptechcenter.org/performance-engineered-mixtures-pem/ and the most recent version of AASHTO PP 84.

Concrete Strength

Adequate concrete strength is necessary to meet the designed axle loading. Although sufficient strength is required to meet the design requirements, along with some overage to ensure the specification is reliably met, strength in excess of the specification does not necessarily correlate to improved performance. The contractor should carefully consider how much strength is needed for a given application. Strategies to achieve adequate concrete strength while reducing the potential for undesirable cracking and other durability issues include the following:

- Use of water-reducing admixtures and an appropriate water-to-cementitious material (w/cm) ratio
- Placement of limits on cement content and inclusion of SCMs

Susceptibility to Slab Warping and Cracking Due to Shrinkage

It is imperative to produce a mixture and construct a pavement that provides volume stability and is resistant to changes in slab shape. This reduces the potential for cracking due to shrinkage and unwanted slab warping due to moisture and temperature gradients within the pavement. Design elements to reduce curling and warping include the use of shorter slabs and doweled joints and bonding a slab to an underlying stabilized base. Strategies to reduce a mixture's susceptibility to curling and warping include the following (Van Dam 2015):

- Adjustments to the materials and proportions used in the concrete to reduce drying shrinkage. Strategies include reducing the amount of water used and adjusting the amount and/or type of SCMs used. Cement fineness and the nature of the aggregates and admixtures used can also affect shrinkage (Kosmatka and Wilson 2016); the use of saturated lightweight aggregates provides internal curing benefits that can reduce shrinkage.
- Use of curing practices that minimize moisture loss at early ages

Freeze-Thaw Durability

For wet freeze-thaw environments, the cement paste portion of the mixture should be able to withstand the internal stresses caused by the expansion of freezing moisture within the concrete matrix. In addition, where chloride-based deicers are used, the formation of expansive calcium oxychlorides should be mitigated (Suraneni et al. 2016). Multiple approaches are used to provide freeze-thaw durability:

- Use of an appropriate w/cm ratio and inclusion of SCMs whenever possible
- Use of proper entrained air properties, including bubble size and spacing
- Use of appropriate quantities of SCMs to reduce the amount of calcium hydroxide in the concrete, thereby preventing deleterious reactions with chloride-based deicers (Suraneni et al. 2016)

Transport Properties

Moisture and deicing chemicals penetrate and move within a concrete structure through connected pores. The electrical resistivity of a concrete specimen is an indicator of the quantity of connected pores in the specimen (Suraneni et al. 2016). The provisional AASHTO standard (AASHTO TP 119) for quantifying the formation factor states, "Formation factor is a physical property of the system and is assessed as the ratio of the resistivity of the sample over the resistivity of the pore solution." The following actions reduce the quantity of connected pores in the concrete:

- Use of an appropriate w/cm ratio and inclusion of SCMs whenever possible
- Use of appropriate quantities of SCMs to reduce the amount of calcium hydroxide in the concrete, thereby preventing deleterious reactions with chloride-based deicers (Suraneni et al. 2016)

Aggregate Stability

Aggregates associated with D-cracking in concrete should not be used. Depending upon the severity of the aggregates' susceptibility to AAR, mitigation is possible using SCMs and/or admixtures. The effectiveness of mitigation should be demonstrated in a laboratory before using alkali-reactive aggregates.

Workability

In addition to meeting all performance and material requirements, PEMs should be workable enough to allow efficient construction at or below the maximum w/cm as determined during the mixture qualification stage. The following mixture design approaches improve workability:

- Use of an appropriate w/cm ratio and use of water-reducing admixtures to help achieve the desired workability while controlling water content
- Use of fly ash, which typically improves workability due to the spherical shape of the particles
- Modification of the aggregate gradation and selection of aggregates with the appropriate size, texture, and shape
- Increase in the entrained air content (within specification)

Table 4.1. PEM properties and test methods

Concrete property	Test methods
Concrete strength	• AASHTO T 97, Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) • AASHTO T 22, Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens
Susceptibility to warping and cracking due to shrinkage	• AASHTO T 160, Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete • AASHTO T 334, Standard Method of Test Estimating the Cracking Tendency of Concrete (Figure 4.1) • AASHTO T 363, Standard Method of Test for Evaluating Stress Development and Cracking Potential due to Restrained Volume Change Using a Dual Ring Test
Freeze-thaw durability	• AASHTO T 152, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method • AASHTO T 196M/T 196, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method • AASHTO TP 118, Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method (Figure 4.2) • AASHTO M 224, Standard Specification for Use of Protective Sealers for Portland Cement Concrete • AASHTO T 365, Standard Method of Test for Quantifying Calcium Oxychloride Formation Potential of Cementitious Pastes Exposed to Deicing Salts • ASTM C1585, Standard Test Method for Rate of Absorption of Water by Hydraulic-Cement Concretes
Transport properties	• AASHTO TP 119, Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test (Figure 4.3) • AASHTO T 358, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (Figure 4.4)
Aggregate stability	• ASTM C 1646, Standard Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete • AASHTO T 161, Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing • AASHTO R 80, Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction
Workability	• AASHTO TP 129, Standard Method of Test for Vibrating Kelly Ball (VKelly) Penetration in Fresh Portland Cement Concrete (Figure 4.5) • Box Test (Ley et al. 2012, Cook et al. 2014) (Figure 4.6)

University of North Carolina at Charlotte, used with permission

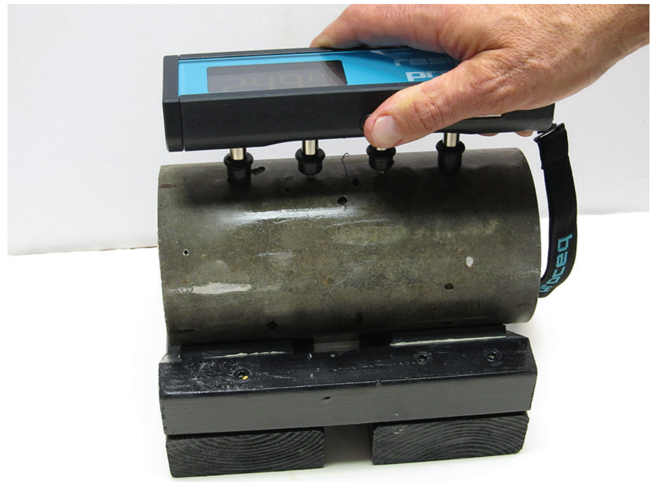
Figure 4.1. AASHTO T 334 cracking tendency test

CP Tech Center

Figure 4.2. AASHTO TP 118 Super Air Meter (SAM)

CP Tech Center

Figure 4.3. AASHTO TP 119 bulk resistivity test



CP Tech Center

Figure 4.4. AASHTO T 358 surface resistivity test

CP Tech Center

Figure 4.5. AASHTO TP 129 VKelly test

CP Tech Center

Figure 4.6. Box Test

Recommended Approach for Contractor Quality Control

From the summary of the six PEM requirements above, it is obvious that this new approach to designing, specifying, producing, and constructing with concrete mixtures is different than the traditional method of specifying mixtures by cement content, air content, slump, and strength. As stated previously, changes in materials, deicing chemicals, and deicing policies have made this new approach necessary.

Because traditional quality control and acceptance methods do not provide adequate assurance that PEMs will achieve the desired performance, these methods should also evolve. Contractors and agencies should adopt new testing methods and develop QC and acceptance systems that fill the gaps between specified properties, mixture qualification, acceptance criteria, and performance. One approach is shown in Figure 4.7.

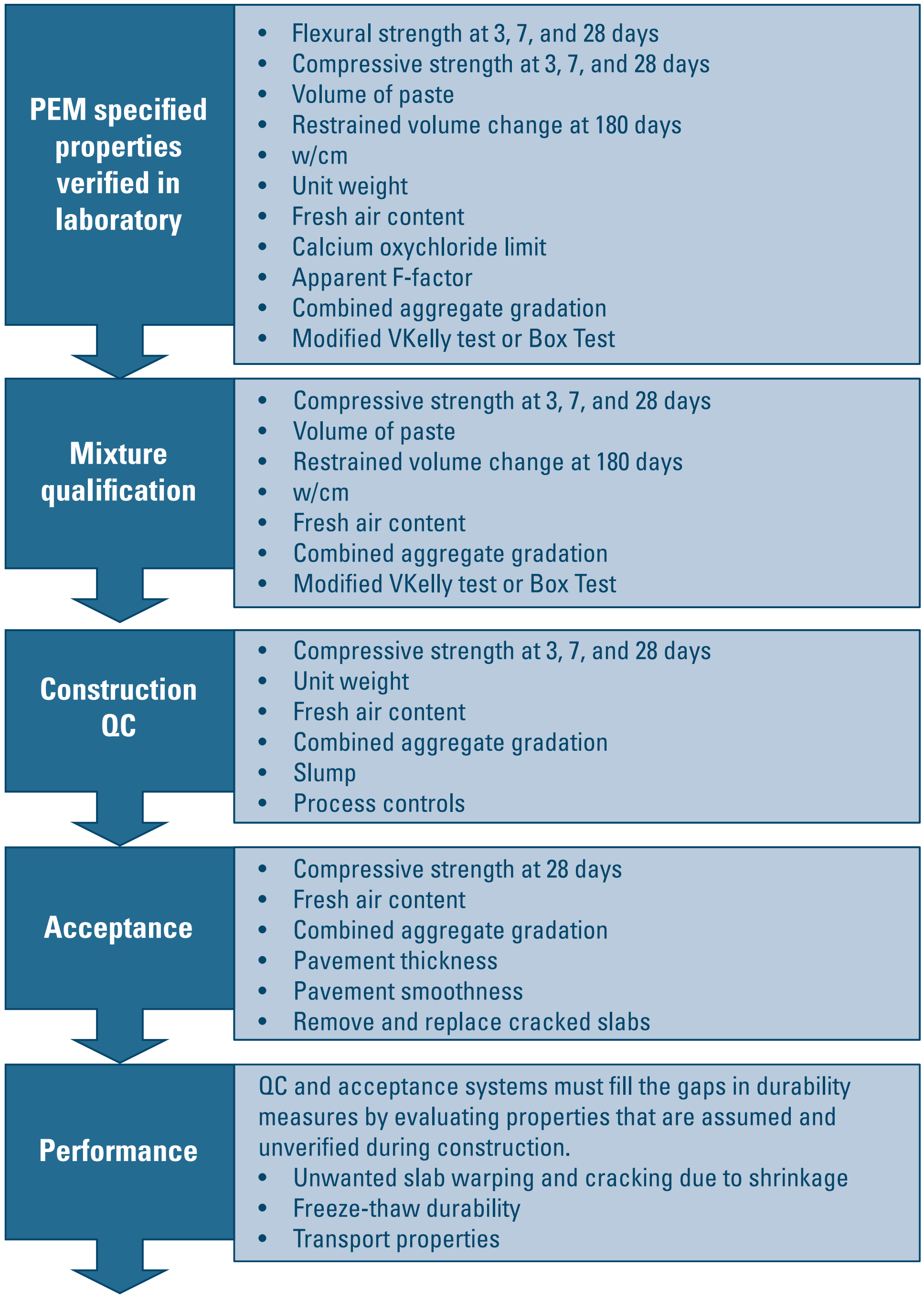
As shown in Figure 4.7, many of the durability tests used in the design and qualification stages are not practical for QC or acceptance. Therefore, to improve the performance of concrete pavements, contractor QC activities need to incorporate process control methods, crew training, and documentation of best practices during the construction stage. From an agency perspective, it is necessary to implement a comprehensive QC specification that clearly communicates the need for contractor QC to encompass more than additional acceptance testing (see Appendix C for a QC plan outline and Appendix D for a model QC plan).

Although some contractors have effective QC programs or systems in place regardless of customer requirements, a contractor cannot be expected to provide more than what is clearly defined in the contract documents. While even the best materials and process controls cannot guarantee performance, the development of pure performance specifications and reliable measurement systems to validate conformance to the performance criteria can help bridge the gap between specified properties and expected performance.

From a concrete production and paving perspective, numerous factors influence durability and performance. For example, multiple construction factors affect w/cm ratio, which in turn affects multiple PEM properties. This interaction is shown in Figure 4.8.

Many relationships similar to those shown in Figure 4.8 could be illustrated for the paving process. These include, but are not limited to, the following:

- Improper vibrator frequencies causing mixture segregation and cracking
- Misaligned dowels resulting in slab cracking
- Inadequate curing accompanied by surface evaporation resulting in connected capillary voids and drying-shrinkage cracking
- Changes to cement and/or SCM chemistry causing early stiffening and driving a demand for increased water over the designed w/cm ratio
- A multitude of other potential occurrences during the construction process



CP Tech Center

Figure 4.7. Example of PEM implementation and project flow

A comprehensive approach to QC goes beyond material sampling and testing at the specified frequencies. It involves establishing methods, practices, and measurements for all embedded processes that enable adjustments to the materials and processes in a timely manner. Again, this approach does not guarantee performance, but it is the best approach for improving the performance of concrete pavements. The recommendations in this guide are intended to help contractors establish effective QC programs and agencies enhance QA provisions regarding QC.

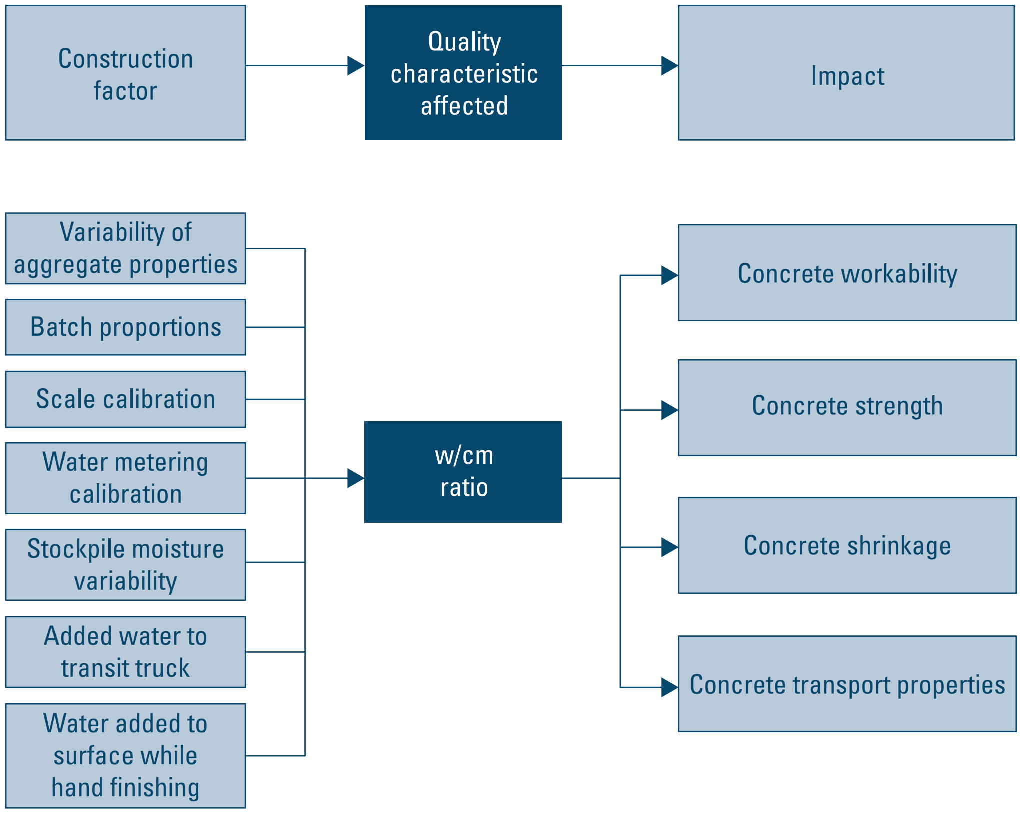


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Figure 4.8. Example of construction factors affecting w/cm ratio and PEM properties

Best practices for material selection, mixture production, and construction are documented in the second edition of *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019). This manual and the PEM resources available on the CP Tech Center's website, https://cptechcenter.org/performance-engineered-mixtures-pem/, should be consulted during the development of a QC program for PEMs.

Implementing Quality Control

The first step towards implementing QC for any concrete paving project, regardless of whether PEMs and PEM testing technologies are used, is to develop a QC plan. The QC plan should document all items that are to be measured and/or monitored. Clear action limits should be provided in the QC plan because they are necessary to ensure that proper process, mixture, and equipment adjustments can be made. Adjustments should be data driven whenever possible.

For both PEMs and conventional mixtures, accurate and reliable data are critical for making appropriate process adjustments; these data are a valuable tool for decision-making. The sharing of data between contractor QC and agency acceptance personnel should also be transparent to encourage timely and appropriate adjustments. To achieve transparent, data-driven decision-making in the QC process, QC data should be used as a "flashlight," which enlightens the areas that need attention. If agencies choose to only use QC data as "hammer," or a means to penalize the contractor, the likely response will be for the contractor to only share data that do not result in a penalty. In the long run, this approach will result in breakdowns in the QC process. As described in Chapter 2, organizational commitment emphasizing the need for (and importance of) QC is critical to the long-term effectiveness of a contractor's QC program or system.

A QC plan outline is provided in Appendix C, and a model QC plan is provided in Appendix D.

Chapter 5

Quality Control for Concrete Pavement Construction

This chapter provides an overview of QC program activities, QC plans, and processes used for concrete pavement construction. QC for concrete pavement construction differs based on agency requirements, the characteristics of a given project, and the contractor's resources, methods, preferences, and risk tolerance. The information presented in this chapter is not intended to be all-inclusive. Rather, this chapter provides a comprehensive description of current best practices. Paired with the QC plan outline provided in Appendix C and the model QC plan provided in Appendix D, the information in this chapter should serve as a starting point for contractors to develop QC programs and plans that meet their operational and project-based needs. In the spirit of performance specifications, this chapter provides guidance on what to do, not specifically how to do it.

Implementation of Quality Control for Concrete Pavement Construction

A project-specific QC plan should be developed that, as described in Chapter 2, clearly defines all QC responsibilities and activities. (An outline of a QC plan is provided in Appendix C.) In many cases, once approved by the agency, the QC plan becomes part of the contract documents. Important elements of a QC plan include the following:

- Organization of the QC process (including personnel and operational units such as laboratories and crews) and personnel qualifications
- The elements of the company's QC program that support the QC plan, such as personnel training, qualification, and certification; laboratory certification; and equipment calibration and/or maintenance
- A listing of and full references to all applicable specifications and standards
- A listing of all materials required
- A description of mixture production, including stockpiling, aggregate testing, fresh concrete testing, hardened concrete testing, etc.
- A concrete paving plan, including prepaving activities, paving activities, joint sawing, joint sealing, etc.
- Adjustments to be made for various weather conditions and appropriate actions to take in response to changes in weather

All items should be described in sufficient detail to guide the work and should include appropriate action limits, suspension limits, and corrective actions for nonconforming materials and/or construction.

In a QC plan, the contractor should describe the actions that will be performed to control the process. During construction, these actions should then be performed.

In other words, "Say what you do and then do what you say."

The QC plan for portland cement concrete pavement construction addresses four stages, as shown in Figure 5.1: mixture design (prequalification), mixture verification (field setup), mixture and construction QC, and mixture and construction acceptance. Each of these stages is further described below.

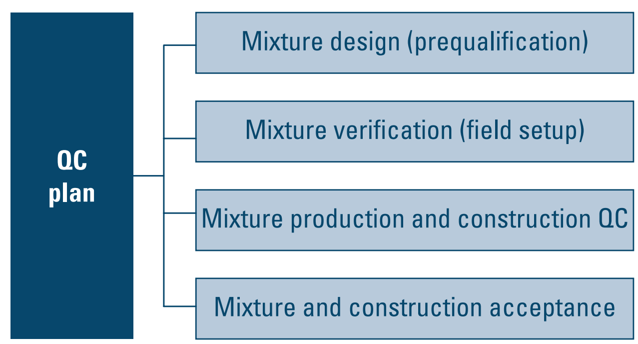

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Figure 5.1. Four stages of QC for portland cement concrete paving that should be included in a QC plan

1. **Mixture Design (Prequalification).** This stage involves preparing and testing laboratory mixtures to evaluate whether they conform with the specified acceptance criteria and to determine whether the mixtures will be workable at the anticipated placement temperatures. Mixture designs should be prepared using materials that have been obtained from the sources that will supply the project, and the materials should be properly sampled so as to be representative of those used during mixture production. Laboratory testing of mixtures that have been previously approved and/or preapproved through a certified producer's protocol may be limited in scope or waived completely.

2. **Mixture Verification (Field Setup).** Prior to construction, a trial batch should be produced from the plant that will be used for construction. The full scope of QC tests should be performed on the trial batch and all of the constituent materials, and the results should be compared to the laboratory mixture test results to verify that the mixture has similar properties.
3. **Mixture Production and Construction Quality Control.** From the first day of production and continually throughout construction until all paving is completed, the mixture and construction processes should be evaluated in accordance with the approved QC plan. This includes material testing, checklists, visual inspections, and, if necessary, corrective action.
4. **Mixture and Construction Acceptance.** Official acceptance testing should be performed as specified. This may include agency testing only or a combination of agency and contractor testing.

As stated in previous chapters, QC is more than additional acceptance testing. It should include checklists, visual inspections, and objective testing of materials and pavement properties. Best practices for mixture production, construction, and quality testing are documented in *Integrated Materials and Construction Practices (IMCP) for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019). The QC plan and construction processes should rely heavily on the guidance provided in the following chapters of the IMCP manual:

- Chapter 7. Mixture Design and Proportioning
- Chapter 8. Construction
- Chapter 9. Quality and Testing

Additionally, the *Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012) includes extensive checklists and recommendations for QC measurements. Some of these checklists and recommendations have been adapted for inclusion in this guide.

Drawing from project contract documents, the IMCP manual (Taylor et al. 2019), the *Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012), and PEM objectives, an example framework for QC measurements and observations is shown in Table 5.1. As mentioned above, the specific items required will differ for each agency and project. Only the PEM parameters that are deemed necessary for a specific project should be required, and some parameters may be impractical to include for a given project. Additional QC activities beyond those required should be included to ensure that the contractor has addressed risks in order to provide confidence that the project will meet contract requirements.

Once an approved QC plan is in place for a project, daily construction activities should be monitored and adjusted accordingly. Monitoring and adjustment should be performed on the items required to control each construction activity or process outlined in the QC plan. These items include but are not limited to checklists, materials testing, measurements, and process adjustments. In addition to these items, elements of the contractor's QC program, such as personnel training and certification and equipment calibration and maintenance, should be monitored to ensure compliance with the plan.

The following sections describe QC activities and best practices for concrete paving. Actions, checklists, measurements, and inspection items included in the subsequent sections do not represent all items that could or should be included in a QC plan. However, they provide a starting point for contractors to begin developing QC plans that meet their specific needs.

The guidance presented in the following sections is heavily based on material presented in the following resources:

- ***Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012)**
- ***Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019)**

The reader is encouraged to refer to these resources for additional details and supporting information, along with the following document:

- **ACPA publication EB238P, *Concrete Pavement Field Reference: Paving* (ACPA 2010)**

Table 5.1. Example framework for project-level QC activities

<table>
<tr><th>Item</th><th>Mixture design (prequalification)</th><th>Mixture verification (field setup)</th><th>Mixture and construction QC</th><th>Mixture and construction acceptance</th></tr>
<tr><td>QC plan</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Determination of mixture materials</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Aggregate grading</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Mixture proportioning</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Temperature sensitivity of mixture</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Mixture properties (example for PEM shown)[1]</td><td>• As specified
• Flexural strength at 3, 7, and 28 days
• Compressive strength at 3, 7, and 28 days
• Volume of paste
• Restrained volume change at 180 days
• w/cm ratio
• Unit weight
• Fresh air content
• Calcium oxychloride limit
• Apparent F-factor
• Combined gradation
• Modified VKelly test
• Permeability</td><td>• As specified
• Compressive strength at 3 and 7 days
• Volume of paste
• Restrained volume change at 7 days
• w/cm ratio
• Fresh air content
• Combined gradation
• Modified VKelly test
• Permeability</td><td>• As specified
• Compressive strength at 3 and 7 days
• Unit weight
• Fresh air content
• Combined gradation
• Workability</td><td>• As specified
• Compressive strength at 28 days
• Fresh air content
• Combined gradation
• Permeability</td></tr>
<tr><td>Prepaving activities</td><td colspan="4"></td></tr>
<tr><td>Subgrade</td><td></td><td></td><td rowspan="5">Perform QC measurements and develop checklists</td><td></td></tr>
<tr><td>Subbase(s)</td><td></td><td></td><td></td></tr>
<tr><td>Steel placement</td><td></td><td></td><td></td></tr>
<tr><td>Paver controls</td><td></td><td></td><td></td></tr>
<tr><td>Paving equipment setup</td><td></td><td></td><td></td></tr>
<tr><td>Mixture production</td><td colspan="4"></td></tr>
<tr><td>Stockpile management</td><td></td><td></td><td rowspan="3">Perform QC measurements and develop checklists</td><td></td></tr>
<tr><td>Plant calibration</td><td></td><td>✓</td><td></td></tr>
<tr><td>Transportation of concrete mixture</td><td></td><td></td><td></td></tr>
<tr><td>Mixture adjustments</td><td></td><td>Appropriate adjustments:
• Subtraction/addition of water (not to exceed the w/cm ratio of the approved mixture design)
• Adjustment of admixture dosages
• Minor reproportioning of aggregates
• Heating or cooling of the mixture</td><td>Appropriate adjustments:
• Subtraction/addition of water (not to exceed the w/cm ratio of the approved mixture design)
• Adjustment of admixture dosages
• Minor reproportioning of aggregates
• Heating or cooling of the mixture</td><td></td></tr>
</table>

Table 5.1 continued on following page

Table 5.1 continued from previous page

Item	Mixture design (prequalification)	Mixture verification (field setup)	Mixture and construction QC	Mixture and construction acceptance
Paving				
Spreading of concrete			Perform QC measurements and develop checklists	• Pavement thickness • Pavement smoothness
Fixed-form placement				
Slipform placement				
Hand finishing				
Texturing				
Curing				
Sawing of joints				
Sealing of joints				
Backfilling of pavement edges				
Protection of existing and new pavement				
Opening to construction traffic				
Opening to public traffic				

[1] Note that PEM requirements are intended to be project specific; only the parameters that are deemed necessary for a specific project, location, climate, etc., should be included. It may be impractical to include some PEM parameters for a given project (e.g., restrained volume change at 180 days).

Prepaving

Subgrade/Subbase

Prior to placing any concrete, preplacement QC activities should be performed to ensure that the site, materials, equipment, and personnel are prepared. Activities to ensure proper preparation of the subgrade/subbase should be included in the project-level QC plan, and/or that QC plan should reference any additional QC plans specific to the types of work involved in the project (e.g., for asphalt paving, earthworks, and subgrade, base, or subbase work). The subgrade/subbase condition should be confirmed daily prior to concrete placement.

Key items during subgrade inspection include identifying changes in soil type and monitoring moisture content. Intelligent compaction (Figure 5.2) or proof rolling (Figure 5.3) should be used to identify nonuniform or unstable areas, which should be repaired or undercut and replaced with suitable material. The type of equipment used for proof rolling should meet agency requirements. Additional moisture should be added to either the subgrade or subbase as needed to ensure that it is uniformly moist. Recommended inspection items, QC measurements, and checklists for the inspection of natural and chemically modified subgrades are provided in Table 5.2.

Center for Earthworks Engineering Research, Iowa State University

Figure 5.2. Intelligent compaction used on subgrade

The Transtec Group, Inc., used with permission

Figure 5.3. Proof rolling of recycled base material

Table 5.2. Subgrade QC—inspection items, QC measurements, and checklists

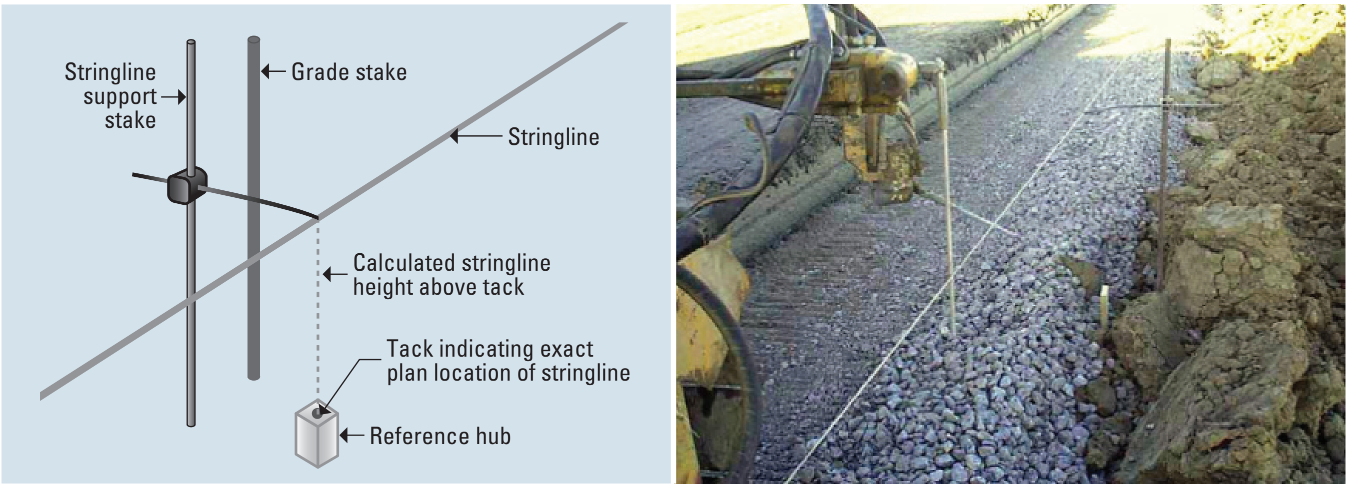
Key inspection items—Subgrade	QC measurements—Subgrade
• Visually monitor for changes in soil type and content. • Identify nonuniformity and instability; repair or undercut and replace subgrade/subbase failures before proceeding to construct the next layer of the pavement structure.	• Moisture and density: Measured per AASHTO T 310 at a recommended frequency of 1 test per 2,000 yd^2 • Intelligent compaction systems: Continuous measurement
Checklist—Natural subgrade	
✓ Verify that Proctor densities and optimum moisture contents correspond to soil type(s) found in the field. ✓ Establish a rolling pattern and verify that desired objectives are achieved with QC measurements (moisture and density). ✓ Proof roll or use intelligent compaction methods to identify nonuniformity. ✓ Remediate areas identified by proof rolling or intelligent compaction.	
Checklist—Chemically modified subgrade	
✓ Verify that Proctor densities and optimum moisture contents correspond to soil type(s) found in the field. ✓ Calculate spread rate (lb/yd^2) for modifying material. ✓ Verify spread rate for each truckload of modifying material. ✓ Establish a rolling pattern and verify that desired objectives are achieved with QC measurements (moisture and density). ✓ Verify thickness. ✓ Proof roll or use intelligent compaction methods to identify nonuniformity. ✓ Remediate areas identified by proof rolling or intelligent compaction.	

Source: Fick et al. 2012

Like subgrade inspection, subbase inspection should include monitoring for segregation and changes in moisture content and, when appropriate, monitoring the lift thickness. Nonuniform and/or unstable areas should be repaired, and moisture content should be controlled. Recommended inspection items, QC measurements, and checklists for the inspection of granular subbases, stabilized bases/subbases (cement-treated permeable aggregate or asphalt), drainable subbases, and lean concrete are presented in Table 5.3.

Staking and Stringline or Stringless Paving

The processes of construction staking include establishing reference hubs for alignment and elevation of the pavement. Whether the stringline process (Figure 5.4) or stringless paving (Figure 5.5) is used, the offset and grade at which the paving hubs are set are critical to achieving the desired result and meeting specifications. Communication between the contractor and surveyor is critical to ensure that the paving hubs are not placed in a manner that will be disturbed by the paving operation and that they provide the appropriate grades (flat or projected) to support the work. Recommended inspection items, QC measurements, and checklists for both the staking and stringline system and the stringless paving system are presented in Table 5.4.



Adapted from Kevin W. McMullen, Wisconsin Concrete Pavement Association, used with permission

Figure 5.4. Stringline and paving hub alignment

Table 5.3. Subbase QC—inspection items, QC measurements, and checklists

Key inspection items—Subbase	QC measurements—Subbase
• Visually monitor for segregation and changes in moisture content. • Monitor lift thickness when appropriate. • Protect drainable subbases from infiltration of fines, which can reduce drainage capacity. • Identify nonuniformity and instability. • Assure that construction and material hauling equipment are not rutting underlying layers, thereby adversely affecting lateral drainage through the pavement section.	• Moisture and density: Measured per AASHTO T 310 at a recommended frequency of 1 test per 2,000 yd^2 • Intelligent compaction systems: Continuous measurement • Gradation: Measured per AASHTO T 27 at a recommended frequency of 1 test per 8,000 yd^2 • Strength for lean concrete subbase: Measured per AASHTO T 22 at a recommended frequency of 1 test per 4,000 yd^2 • Grade tolerance: Verified during production with respect to grade stakes at a recommended frequency of 1 check per 100 lineal feet • On projects using automatic machine controls (e.g., global positioning systems [GPS], laser guidance, or other technologies), grade tolerance should be checked at least every 100 lineal feet
Checklist—Granular subbase	
✓ Verify that Proctor densities and optimum moisture contents correspond to delivered aggregate materials. ✓ Establish a rolling pattern and verify that desired objectives are achieved with QC measurements (moisture and density). ✓ Verify that spreading techniques do not contribute to segregation. ✓ Proof roll or use intelligent compaction methods to identify nonuniformity. ✓ Remediate areas identified by proof rolling or intelligent compaction.	
Checklist—Stabilized base/subbase (cement-treated permeable aggregate or asphalt)	
✓ Verify that mixtures conform to the job mix formula (JMF). ✓ Verify that placement, consolidation, and finishing operations produce a uniform, nonsegregated product. ✓ Verify that controls are in place to meet minimum thickness and smoothness tolerances. ✓ Establish a rolling pattern and verify that desired objectives are achieved with QC measurements (moisture and density). ✓ Verify thickness. ✓ Proof roll or use intelligent compaction methods to identify nonuniformity. ✓ Remediate areas identified by proof rolling or intelligent compaction.	
Checklist—Drainable subbase	
✓ Verify that mixtures conform to the JMF. ✓ Verify that placement, consolidation, and finishing operations produce a uniform, nonsegregated product. ✓ Verify that controls are in place to meet minimum thickness and smoothness tolerances. ✓ Protect from infiltration of fine materials. ✓ Verify thickness.	
Checklist—Lean concrete	
✓ Refer to checklists for concrete paving.	

Source: Fick et al. 2012

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Figure 5.5. Stringless paving system guidance using total stations

Fine Grading

Fine grading of the subgrade and subbase to the appropriate cross slope and elevation should be performed using trimmers and/or motor graders that have automatic machine control to guide the work. Without appropriate control of the elevation and cross slope of the foundation layers, the contractor will find it challenging to construct the concrete pavement to the required thickness and smoothness. Approaches used to check the cross slope and elevation, such as stringlines, levels, and/or laser levels, should comply with agency specifications, if applicable. A summary of recommended inspection items, QC measurements, and checklists for fine grading is presented in Table 5.5.

Table 5.4. Staking and stringline or stringless paving QC—inspection items, QC measurements, and checklists

Key inspection items—Staking and stringline or stringless paving	QC measurements—Staking and stringline or stringless paving
• Spot check paving hubs and grades for accuracy by checking against a known benchmark. • Visually inspect stringline for abrupt changes and/or discontinuities (stringline only). • Check that pins and wands are solid and resistant to moving (stringline only). • Depending on the offset used, check whether subgrade and subbase has pumped and the paving hub has moved from its surveyed elevation and alignment. Correct the subgrade/subbase and resurvey.	• Paving hubs: Random survey check • Random check of stringline elevation and alignment relative to paving hub information (not applicable to string that has been eyeball adjusted for smoothness)
Checklist—Staking and stringline	
✓ Verify that the survey has provided the correct grades for the requested offset and grade type (projected or level). ✓ Verify that pins are placed at appropriate intervals (25 ft or less in tangent sections, closer spacing through tight curves). ✓ Verify that wands are adjusted for alignment (stringline should be directly above the hub). ✓ Verify that stringline is set to the correct elevation with respect to the hub. ✓ Verify that stringline is uniformly taut. ✓ Verify that stringline is marked for visibility to prevent accidental bumping.	
Checklist—Stringless paving	
✓ Verify that models (data) used for stringless machine control are prepared in accordance with the manufacturer's recommendations. ✓ Verify that models are complete and accurate with enough points and free of errors. ✓ Verify that stringless model is set to correct alignment and elevation and checked for accuracy.	

Source: Fick et al. 2012

Table 5.5 Fine grading QC—inspection items, QC measurements, and checklists

Key inspection items—Fine grading	QC measurements—Fine grading
• Check the finished grade to verify that subgrade or subbase is ± 0.02 ft from plan elevation. • Blend and compact trimmed material into low spots uniformly. Fine materials that are trimmed from high spots should be re-used in a manner that does not result in segregated pockets of granular materials. • Visually identify areas of segregation in granular subbases. Reblend segregated materials and recompact when feasible; otherwise, remove and replace segregated material.	• Grade tolerances: Measured, logged, and analyzed at 50 ft intervals (3 to 5 places across the width of the roadway); highs and lows should be corrected • Subbase thickness: Checked at 50 ft intervals in 3 locations across the width of the layer
Checklist—Fine grading	
✓ Maintain the moisture in subgrade and subbase during fine grading operations and until the next layer is placed. ✓ Re-use trimmings in a manner that does not result in segregated pockets of granular material. ✓ Verify that the stringline or stringless model is set to correct alignment and elevation.	

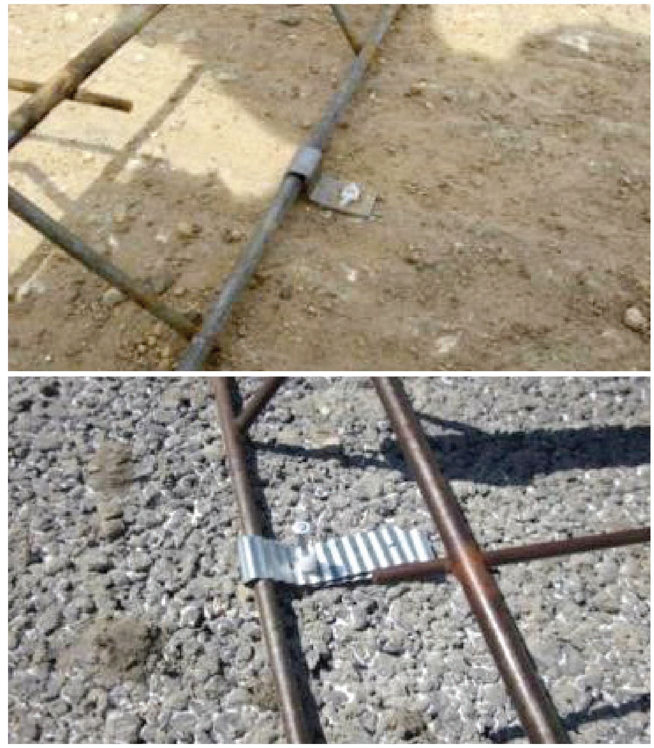
Source: Fick et al. 2012

Dowel Basket Placement

The QC plan should include provisions to ensure that the correct dowel basket components are used and that the assemblies or single units are installed properly and are secured to ensure that they remain in the appropriate position (within tolerances) both before and after paving (Figure 5.6) (ACPA 2019). An adequate amount of bond breaker should be applied to the bars, if specified. The QC plan should include the proposed type and number of fasteners, the proposed installation equipment, the dowel basket assembly anchoring plan, and a description of the process used to anchor basket assemblies (whether baskets will be anchored prior to or during concrete placement) (Masten 2020).

It is recommended that dowel basket shipping wires remain intact to provide additional stability during the paving process. Keeping the wires intact does not restrain the formation of transverse joints or joint movement (ACPA 2005). Additionally, contrary to some guidance, the use of a MIT SCAN device to locate dowels in the hardened concrete does not require cutting the shipping wires. While the image and data provided by a MIT SCAN device may have greater resolution when the shipping wires are cut than when the wires are intact, there are proven methods for evaluating dowel placement using a MIT SCAN device when the shipping wires are intact (CDOT 2020).

The contractor should also periodically verify the placement and location of dowel baskets during construction and adjust as necessary (Taylor et al. 2019). The location of the midpoint of each dowel (the center of the basket) should be clearly marked along the sides of the pavement and on the adjacent grade (Figure 5.7) to guide sawcutting of the joints. Many contractors embed a nail in both edges of the fresh concrete, which can be used by the saw crew to accurately mark the sawcuts at the center of the dowel bars.



Maria Masten, MnDOT, used with permission

Figure 5.6. Dowel basket anchored to subgrade (top) and existing asphalt (bottom)

The Lane Construction Corporation, used with permission

Figure 5.7. Preplaced dowel baskets fastened to asphalt base, with markings located on base to guide sawcutting

A summary of recommended inspection items, QC measurements, and checklists for dowel baskets is presented in Table 5.6. The QC plan should also include actions that will be taken if misaligned baskets are identified during or after concrete placement. The following publications can be consulted for additional guidance:

- *Guide to Dowel Load Transfer Systems for Jointed Concrete Roadway Pavements* (Snyder 2011)
- Dowel Bar Alignment: What Do We Need? What Should We Expect? (Snyder 2018)
- *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019)
- *American Concrete Pavement Association (ACPA) Guide Specification: Dowel Bar Alignment and Location* (ACPA 2018)

Steel Placement for Continuously Reinforced Concrete Pavement

Construction of continuously reinforced concrete pavement (CRCP) requires placement of steel reinforcing bars of the appropriate size and spacing at the correct depth within the pavement slab. Prior to paving, the reinforcing bars should be placed on supports at the appropriate locations, within tolerances, and anchored appropriately (Figure 5.8). Attention should be paid to bars near the edge of the pavement because these bars can potentially be hit by paving equipment. Tube feeders should not be used for longitudinal steel placement because this approach has been shown to have issues maintaining placement at mid-slab depths (Fick et al. 2012). Recommended inspection items, QC measurements, and checklists for reinforcing steel for CRCP are presented in Table 5.7.

Table 5.6. Dowel basket QC—inspection items, QC measurements, and checklists

Key inspection items—Dowel baskets	QC measurements—Dowel baskets
• Check transverse spacing and offset from the edge of the pavement. • Verify that bond breaker has been applied, if applicable. • Visually inspect for alignment and correct misaligned bars. • Verify that basket locations are marked on both sides of the pavement. • Anchor baskets so that the stake is on the downstream side of the basket frame. • Check the stability of the baskets and verify that they are anchored adequately to withstand the force of a slipform paver pushing concrete over them.	• None during prepaving • Embedment of the cover of bars: Verified by probing behind the paver at 300 ft intervals (locating at least 1 bar for each basket across the width of the slab) • Dowel/joint placement: Evaluated using nondestructive devices such as MIT SCAN, MIT SCAN-T2, ground penetrating radar, or pachometer (cover meter)
Checklist—Dowel baskets	
✓ Verify that dowel dimensions (diameter and length) are correct. ✓ Verify that basket height is appropriate for the pavement thickness. ✓ Verify that bar spacing is as specified. ✓ Verify that bar coating is as specified and not damaged. ✓ Verify that bond breaker is adequate. ✓ Verify that the midpoint of each dowel location (the center of the basket) is marked adequately on both sides of the slab to ensure proper joint sawing.	

Source: Fick et al. 2012

TxDOT, used with permission

Figure 5.8. Verification of positioning of reinforcing bars for CRCP and support conditions (left) and staking of reinforcing bars to subgrade (right)

Table 5.7. CRCP reinforcing steel QC—inspection items, QC measurements, and checklists

Key inspection items—CRCP reinforcing steel	QC measurements—CRCP reinforcing steel
• Check bar spacing and offset from the edge of the pavement. • Verify that laps are staggered. • Periodically anchor the mat using a bar driven into the subgrade to help prevent the entire mat from falling off the supports if the outside bars are caught by the spreader or paver. • Check the stability of the bar mat to ensure that it is tied and supported adequately to withstand the force of concrete spreader dumping concrete on it and a slipform paver pushing concrete over it. • Ensure that the concrete is adequately consolidated around heavily reinforced transverse construction joints.	• None during prepaving • Steel location: Verified by probing behind the paver at 300 ft intervals
Checklist—CRCP reinforcing steel	
✓ Verify that the diameter and grade of the steel are correct. ✓ Verify that the bar support height is correct for the thickness of the concrete pavement. ✓ Verify an adequate supply of bar supports and tie wire. ✓ Verify proper consolidation at headers.	

Source: Fick et al. 2012

Paver Preparation

To construct quality concrete pavement, the slipform paver should be properly maintained and should be prepared prior to each day's paving. The paver should be free from dried concrete from previous work, and all mechanical and electrical systems should be verified to be operational. Particular attention should be paid to hydraulic systems and other fluids, and leaks should be fixed. Prior to paving, the following should be performed (Fick et al. 2012):

- Check vibrator spacing, operation, and frequency.
- Adjust the extrusion pan to the correct width and shape (cross slope and crown).
- Set the paver parallel to the stringline.
- Set the height relative to the string to provide the correct pavement thickness.
- Run the paver on the string or with the correct stringless model for approximately 50 ft and recheck alignment, elevation, and crown/cross slope.
- Check that the tie bar inserter(s) are set to ensure that the tie bars are located correctly in the pavement.
- If an integral curb is being placed, confirm that the curb mold matches the curb design.

A summary of recommended inspection items, QC measurements, and checklists for paver preparation is presented in Table 5.8.

The QC plan should also address the mixing and delivery processes and include provisions to address potential issues that may arise. The mixing process used for a given project will vary based on whether the concrete is mixed at a central mix plant or is shrink mixed or truck mixed. The required mixing time will vary based upon the mixture and plant characteristics. However, mixing time is a variable that can be measured and adjusted when problems with the mixture arise. Issues such as segregation, bleeding, and finishability can be addressed by changing the mixing time (Taylor et al. 2019).

Table 5.8. Paver preparation QC—inspection items, QC measurements, and checklists

Key inspection items—Paver preparation	QC measurements—Paver preparation
• Set the paver width to provide a slab width equal to or greater than the plan width. • Verify the crown and cross slope. • Verify that vibrators are operable and spaced appropriately.	• Vibrator frequency: Constant data collection if monitors are used; measured at least twice daily if data collected manually
Checklist—Paver preparation	
✓ Verify that the paver is clean. ✓ Verify that vibrators are working. ✓ Verify that vibrator spacing, height, and orientation are correct. ✓ Verify that the hydraulic system and other fluids are not leaking. ✓ Verify that the width, crown, and cross slope are correct. ✓ Perform a dry run on the string or with the correct stringless model (data). ✓ Double check crown, cross slope, and thickness after the dry run.	

Source: Fick et al. 2012

Daily QC at the Paver

QC activities should adhere to the QC plan and specifications. *At a minimum*, daily prepaving measurements and checklists should include the following:

- Inspect the base course for adequate stability.
- Identify all areas that need to be repaired prior to concrete paving.
- Inspect and measure all steel reinforcement and load transfer dowels that are installed before paving.
- Verify that haul road conditions are acceptable.
- Verify that adequate material inventory is available and that materials are prepared for paving operations:
  - Aggregates
  - Cementitious materials
  - Admixtures
  - Tie bars
  - Dowel bars
  - Dowel baskets
  - Curing compound
  - Saw blades and other tools
  - Other tools and materials as needed or required
- Verify stringline or three-dimensional (3D) machine controls.
- Verify that paving equipment is prepared and operational:
  - Spreader
  - Paver
  - Vibration equipment
  - Texture/cure equipment
  - Saws
  - Other equipment if needed
- Perform all fresh concrete testing at the frequency and locations detailed in the QC plan.

Daily QC at the Plant

QC activities should adhere to the QC plan and specifications. *At a minimum*, daily checklists and measurements should address the following items using the appropriate test methods at the appropriate frequencies:

- Aggregate gradations
- Aggregate moisture contents and appropriate batch weight compensations
- Concrete workability (Box, VKelly, or slump test)
- Concrete temperature
- Concrete unit weight
- Concrete air content
- Concrete compressive or flexural strength

Daily QC Behind the Paver

QC activities should adhere to the QC plan and specifications. *At a minimum*, daily checklists and measurements should address the following items using the appropriate test methods at the appropriate frequencies:

- Pavement thickness
- Pavement smoothness
- Uniformity of texture (drag and/or tining)
- Coverage of curing compound
- Sawcut depth and timing

If validated QC data are used for acceptance, the random sampling locations should be the same as those used for agency tests. QC activities may include tests for temperature, air content, strength, or other properties as specified.

Plant Site and Mixture Production

Equipment and Laboratories

In addition to the quality of the materials used, the quality of a concrete batch is also highly dependent on the adequacy and accuracy of the equipment used to produce the concrete. Concrete production facilities used for concrete paving projects should conform to the requirements of ASTM C94, Standard Specification for Ready-Mixed Concrete. All plants and equipment should either have a current certification from the National Ready Mixed Concrete Association (NRMCA) or be on the current approved list of the agency overseeing the project. Certification programs administered by both the NRMCA and various agencies prescribe many provisions and requirements that help demonstrate that a concrete batching operation has the necessary equipment, people, and processes to consistently produce and deliver quality concrete (Obla and Lobo 2014).

Some items that may be included in a certification program are listed below. Although this is not a complete list of all provisions covered by NRMCA or agency certification programs, the list indicates the types of provisions that certification programs include to help ensure that a batch plant is capable of producing concrete of consistent quality.

- Frequency of accuracy checks of scales and volumetric measuring devices
- Qualification, education, and experience of quality control personnel
- Laboratory testing capabilities
- QC processes used for monitoring the quality and uniformity of material ingredients and the finished product
- Process for identifying nonconforming materials and taking the appropriate corrective action
- Measurement systems for tracking specific quality objectives

The equipment used at the batching facility should be in good condition and well maintained. Personnel should measure the important characteristics of the concrete produced and use those measurements to adjust the equipment as necessary to provide concrete of consistent quality. The QC program for the production facility should include provisions for regular maintenance, calibration, and care of the equipment used at the batch plant and in the QC laboratory, and a process for recordkeeping and continuous improvement should be in place.

If required, the laboratory (or laboratories) used for QC testing should be approved by the agency or, if applicable, the appropriate regional certification group. In certain cases, agencies may require that QC laboratories be accredited by AASHTO or an equivalent entity. QC laboratories should meet the requirements of ASTM C1077, Standard Practice for Agencies Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Testing Agency Evaluation.

The setup of the plant should reflect the logistics of material delivery and storage, plant placement and orientation, and traffic flow (Figure 5.9). The plant should be maintained in good working order, and the manufacturer's directions for transport, setup, and maintenance of the equipment used at the plant should be followed. The appropriate components of the plant should be calibrated and certified. Prior to batching concrete for the project, trial batching should be performed to ensure that the plant is operating properly and producing the desired concrete consistently. Recommended inspection items, QC measurements, and checklists for plant setup and calibration are presented in Table 5.9.

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Figure 5.9. Layout of a concrete batching plant

Table 5.9. Plant setup and calibration QC—inspection items, QC measurements, and checklists

Key inspection items—Plant setup and calibration	QC measurements—Plant setup and calibration
• Check for scale calibration and certification. • Check accuracy of water meters, admixture dispensers, and moisture probes, where used. • Review the trial batch ticket for the proper proportions. • Check admixture and cementitious material delivery tickets to ensure that they match the approved mixture design.	• Mixer uniformity: Testing performed for centrally mixed concrete

Checklist—Plant setup and calibration
✓ Check all bins and belts to prevent intermingling of aggregates. Scalping screens can help ensure that oversized material is removed. ✓ Verify that scales are calibrated and certified. ✓ Verify that the water meter is calibrated. ✓ Verify the admixture dispensing system for accuracy. ✓ Verify that the mixing blades are not worn out. ✓ Remove any excessive buildup in the mixer. ✓ Verify that proper mixture proportions are programmed into the plant control system. ✓ Verify that the batching sequence is correct.

Source: Fick et al. 2012

Personnel

Most manufacturing industries have a high degree of standardization in their processes. However, due to the nature of concrete construction, concrete producers need to modify and adjust their mixtures based on the application and in response to variations in location, weather, delivery distance, and local materials. Because knowing when and how to make these adjustments is critical to the success of a project, personnel should be trained to control concrete quality within their respective areas of responsibility in the concrete production process. Additionally, all personnel should know their roles and responsibilities in a company's QC program, in project management, and in the QC plan for a given project.

The personnel who perform testing should receive appropriate training and, if required, be certified through state or regional certification programs or by industry organizations. The NRMCA, ACPA, and ACI, for example, offer training classes and certification programs that provide industry personnel with the skills necessary to produce a quality product consistently. A QC plan may require various project personnel to have the following certifications and qualifications (NRMCA 2016):

- Quality manager:
  - NRMCA Concrete Technologist certification (several levels can be achieved)
  - ACI Concrete Quality Technical Manager certification
  - Licensed engineer with several years of experience in specification review and mixture proportioning
- Plant operator:
  - ACPA Plant Manager certification
  - NRMCA Concrete Plant Operator Manager certification
  - Plant operator or batchman certification through an agency program
  - A sufficient number of years of work experience and technical education related to batching concrete
- Field testing technicians:
  - ACI Field Grade 1 certification
  - Concrete field technician certification through an agency program
  - Aggregate sampling and testing certification through an agency program
- Truck mixer operators:
  - NRMCA Concrete Delivery Professional certification
  - Statement of qualifications that documents training

Materials

The quality of the materials used to produce concrete heavily influence the quality of the final product. Contractor QC provisions should address the management of each material throughout a project, from delivery to storage to loading into the plant (Taylor et al. 2019). It is also important to have accurate, timely, and useful information on the products provided by each of the materials suppliers. Clear, well-timed communication and collaboration between suppliers and contractors is critical to mitigating and addressing problems.

The QC plan should include provisions on inspecting the materials, reporting conditions, and correcting issues. The QC plan should also guide personnel in identifying changes to the materials and communicating these changes to the plant foreman or other appropriate personnel.

The following sections discuss items to consider for the different types of materials involved in concrete paving.

Cement and Cementitious Materials

Whenever possible, the concrete producer should request that each of the materials comes from a single source for the duration of the project. Source changes during a project should require additional testing to verify that the new materials will produce a mixture of equivalent quality to the original mixture. At a minimum, the concrete producer should request the following information from suppliers of cements and SCMs:

1. Cement. A monthly mill certificate (Figure 3.2) showing compliance with the appropriate specification and an ASTM C917 report showing the strength uniformity of concrete produced using cement from the source supplying cement for the project.
2. Slag. A monthly mill certificate showing compliance with the appropriate specification.
3. Fly ash and pozzolans. A monthly mill certificate showing compliance with the appropriate specification. The specification for fly ash and pozzolans contains uniformity requirements, and information pertaining to these requirements should be included in the mill certificate.

Whenever possible, and especially when issues arise, the concrete producer should work closely with suppliers to obtain additional information beyond that which is typically included on a typical mill certificate, as described in Chapter 3.

Cement and cementitious materials should be stored in a manner that allows easy access for inspection in separate, suitable, weathertight storage silos or other containment units to protect these products from dampness and minimize quality deterioration. The QC plan should include provisions that detail the procedures for material delivery and silo loading. Periodic inspection of stored materials should also be included in the QC plan, along with provisions for identification and disposition of materials that may have been subjected to adverse conditions in storage.

Aggregates

Information to support an understanding of and confidence in the aggregates used on the project should be obtained from the aggregate supplier. ASTM C33, Standard Specification for Concrete Aggregates, defines the requirements for the grading and quality of fine and coarse aggregates for use in concrete. However, in many parts of the country, good-quality aggregates meeting the requirements of ASTM C33 are scarce and expensive. While the individual aggregates should meet the specified durability requirements, gradation should be based upon the combination of all aggregates used in the mixture. This allows the concrete producer to use the most economical combination of approved aggregates that meets both the durability and combined gradation requirements for the project.

The frequency of testing for aggregate characteristics should be included in the specification to ensure the consistency of the concrete. All quality characteristics (gradation, absorption, deleterious materials, etc.) of aggregates should be clearly agreed upon by the supplier and purchaser but may vary from the requirements of ASTM C33. It should be noted that the frequency of testing in the QC plan may need to be greater than that required by the specification depending on the observed variability of the aggregate properties.

Aggregates are the only product supplied to a project that are open to the environment. As a result, the moisture content will vary after delivery, and contamination can occur. Selection of an appropriate location for aggregate stockpiles is therefore critical. The site should be relatively flat but sloped to drain. Prior to the initial delivery of materials, an appropriate concrete slab or aggregate separation layer should be placed. This will help ensure that contaminants are not introduced to the aggregate stockpiles and that the underlying soils are not intermixed with the aggregates. One strategy successfully used by paving contractors with portable plant sites is to use the concrete produced during the early stages of plant setup and mixture design/verification to pave slabs in stockpile areas. Other strategies have included the use of cement-stabilized base beneath stockpiles (as shown in Figure 5.10). Fabric barriers have also been successfully used to separate stockpiles (Figure 5.10) and can serve as a best management practice (BMP) for stormwater management.

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Figure 5.10. Aggregate stockpiles

The QC plan should include procedures detailing the management of aggregate stockpiles to maintain uniform gradation (minimize segregation), maintain uniform moisture content, and minimize the potential for contamination of the stockpiles. The following strategies support proper stockpile management (Taylor et al. 2019):

- Piling the material in lifts
- Completing each lift before beginning the following lift
- Maintaining a clear separation between materials
- Ensuring that the material is not dumped over the edges of a stockpile
- Minimizing free fall heights of aggregates to avoid segregation
- Maintaining appropriate stockpile sizes to allow for adequate gradation and moisture testing before incorporation into the mixture
- Minimizing crushing of the aggregates by the loader
- Sprinkling water on or otherwise adding moisture to stockpiles as needed in a manner that provides uniform moisture within the area(s) of the stockpiles that are being used for production of concrete
- Managing the stockpiles carefully and using materials that have known moisture contents
- Monitoring the moisture content of the aggregate in the stockpile and adjusting the mixing water required accordingly

A summary of recommended inspection items, QC measurements, and checklists for aggregate stockpiles is presented in Table 5.10. Particular care should be taken to ensure that the moisture content of the aggregates is accounted for in each and every concrete mixture. During production for paving, aggregate moisture contents should be continuously monitored and real-time adjustments made to the batching process.

Steel Reinforcement, Dowels, and Other Embedded Items

Steel materials should be stored in a manner that prevents excessive rust or damage to the steel or coatings. Other items should be stored in accordance with the manufacturer's instructions or agency specifications.

Mixture Design (Prequalification)

QC activities during the mixture design and prequalification stage of the project should include all required actions to develop and evaluate the concrete mixtures for conformance with the specified acceptance criteria. The materials that will supply the project should be used when batching and testing trial mixtures during the design process and when preparing mixtures for prequalification testing.

Although the specific requirements for QC testing during the mixture design and prequalification stage will vary based on agency specifications and project requirements, a summary of recommended laboratory tests for use during prequalification of a mixture is presented in Table 5.11 (Taylor et al. 2019).

One of the intents of the PEM initiative and recommendations is to ensure that the contractor understands how a mixture will perform during the mixture design/proportioning and prequalification stage of the work.

Table 5.10. Aggregate stockpile QC—inspection items, QC measurements, and checklists

Key inspection items—Aggregate stockpiles	QC measurements—Aggregate stockpile
• Visually inspect the stockpile for segregation. • Watch for rutting and pumping at the edges of the stockpile, which suggests that mud balls may be a concern.	• Sieve analysis: Performed during stockpiling; out-of-tolerance aggregates should be rejected • Aggregate moisture content
Checklist—Aggregate stockpiles	
✓ Verify that stockpile foundations have been stabilized. ✓ Verify that aggregate sources match the approved mixture design. ✓ Verify that aggregate gradation is within action limits.	

Source: Fick et al. 2012

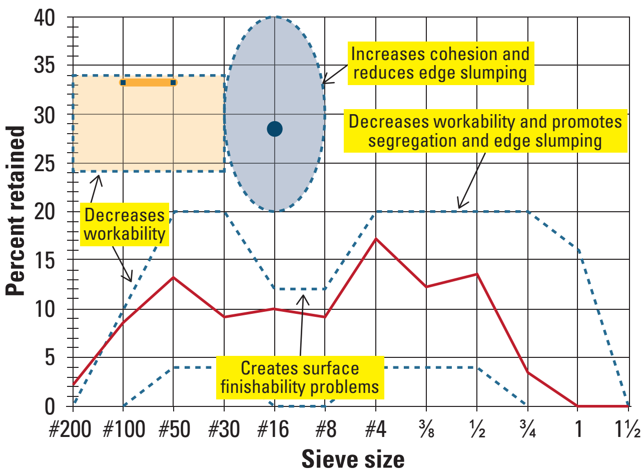
Table 5.11. Recommended laboratory tests during prequalification of a mixture

Concrete property	Test description	Test method	Comments
Workability	Aggregate gradation	ASTM C136 / AASHTO T 27	• Use individual gradations and proportions to calculate combined gradation.
	Combined gradation	Tarantula curve (Table 5.12 and Figure 5.11)	• Adjust combined gradation to achieve optimum workability.
	Paste content	Batch sheet	• Adjust paste content to find minimum paste needed while still workable. • Confirm that total is below maximum permitted for shrinkage.
	VKelly or Box Test	AASHTO TP 129 / AASHTO PP 84	• Confirm that the mixture responds well to vibration. • Adjust aggregate gradation and water content to achieve desired performance.
	Slump at 0, 5, 10, 15, 20, 25, and 30 minutes	ASTM C143 / AASHTO T 119M/T 119	• Look for excessive slump loss due to incompatibilities, which is more likely at elevated temperatures. • Determine approximate WRA dosage.
	Segregation	—	• Look for signs of segregation in the slump samples.
Air void system	Foam drainage	—	• Assess stability of the air void system for the proposed combination of cementitious materials and admixtures. • Select alternative admixture combinations if instability is observed.
	Air content	ASTM C231 / AASHTO T 152, T 196M/T 196	• Determine approximate air-entraining admixture (AEA) dosage.
	SAM	AASHTO TP 118	• Target value established by the agency and/or QC plan.
	Clustering	Retemper a sample and use optical microscopy to assess clustering	• This can affect strength. • Air content can also jump with retempering.
	Hardened air	ASTM C457	• Assess compliance with specification.
Unit weight	Unit weight	ASTM C138 / AASHTO T 121M/T 121	• Indicates yield of the mixture and provides a rough estimate of air content. • Establish a basis for QC monitoring.
Strength development	Compressive or flexural strength	ASTM C39 / AASHTO T 22 and/or ASTM C78 / AASHTO T 97 at 1, 2, 7, 28, and 56 days	• Calibrate strength gain for early-age QC. • Calibrate flexural with compressive strengths. • Adjust w/cm ratio to ensure sufficient strength.
	Maturity (Figure 5.12)	ASTM C1074	• Calibrate the mixture so maturity can be used in the field to determine opening times.
Transport	Resistivity / F-factor	AASHTO TP 119 and AASHTO T 358	• Sample conditioning per AASHTO TP 119 (Option A) is preferred. • Determine development of F-factor over time. • Adjust w/cm ratio to achieve required performance.
	Sorption	ASTM C1585	• Determine time to critical saturation.
	w/cm ratio	Microwave (Figure 5.13)	• Calibrate microwave test with batch data.
	Rapid chloride penetrability	ASTM C1202 / AASHTO T 277	• Evaluate chloride ion penetrability using the table provided in ASTM C1202 / AASHTO T 277. • Adjust w/cm ratio to achieve required performance.
Other	Hydration	Semi-adiabatic calorimetry	• Determine hydration rates of mixture. • Set a baseline for QC. • Assess risk of incompatibilities if SCMs/admixtures/ temperatures change. • Adjust SCM source, WRA type, or operating temperature if incompatibility is observed.
	Oxychloride risk	LT-DSC on paste	• Assess risk of joint deterioration if salts are used. • Increase SCM dose if risk is excessive.
	Coefficient of thermal expansion (CTE)	AASHTO T 336	• Confirm that assumptions used in structural design are appropriate.
	Mortar content	Vibrate a container (air pot) for 5 minutes and measure depth of mortar at the top surface	• This provides information on the coarse aggregate content; maximum is ~¼ in.

Source: Taylor et al. 2019

Table 5.12. Example sieve analysis results

Sieve size	Sand (% passing)	Concrete stone (% passing)	Combined % passing
2 in.	100	100	100
1.5 in.	100	100	100
1 in.	100	100	100
¾ in.	100	93	97
½ in.	100	65	83
⅜ in.	100	40	71
No. 4	98	7	53
No.8	84	3	44
No.16	67	0	34
No.30	49	0	25
No.50	23	0	12
No.100	6	0	3
No.200	2	0	1
Aggregate Proportions	51%	49%	100%



FHWA Mobile Concrete Technology Center, used with permission

Figure 5.11. Tarantula curve analysis

University of North Carolina at Charlotte, used with permission

Figure 5.12. Maturity meter (left) and sensor (right)

MnDOT, used with permission

Figure 5.13. Microwave test to determine w/cm ratio of mixture in the field

It is important to remember the variability inherent in measurements due to variations in materials, processes, sampling, and testing (as discussed in Chapter 2). This variability inevitably leads to test results that differ, whether among tests performed in the QC laboratory, between tests performed during mixture design and production, or between tests performed in a contractor's laboratory and an owner's laboratory once production begins. During the mixture design process and, in fact, throughout production, the contractor should be mindful of the precision and bias of each test method used, as well as the specification requirements. The mixture should be designed in a manner that accounts for and adequately accommodates the variability in test results to ensure that the constructed pavement meets the specified tolerances (Taylor et al. 2019). During this stage, the QC team should also perform testing to determine whether mixtures are workable at the anticipated placement temperatures.

Mixture Verification (Field Setup and Trial Batches)

Trial batches are essential for concrete producers to understand their mixtures, ensure that their mixtures meet the specification requirements, and verify their equipment calibration and testing procedures. Trial batches also provide baseline properties for mixtures to support optimization and the development of process control provisions. The test results from a trial batch provide a basis for comparing the performance of mixtures after changing a process and for monitoring for changes that may have occurred during a process.

The QC plan should describe the process for establishing concrete mixture proportions for each mixture design planned for use on the project. The plan should define who has responsibility for the trial batching process and whether it is performed in-house or under contract with a third party. The process used for establishing the target strength of the mixtures should also be described.

The information included on each mixture submittal should comply with agency requirements and, at a minimum, include a list of materials, their sources and characteristics, the mixture proportions used, and the test results describing the fresh properties and strength of the mixture.

Prequalification testing required by agencies can include, but is not limited to, alkali aggregate reactivity, shrinkage, permeability, setting time, and ingredient material compatibility. Contractor QC personnel should address all requirements included in the appropriate specification. A list of recommended field setup tests is provided in Table 5.13.

It is highly recommended that each mixture submitted for use on a project be tested at the plant where it will be produced. During these trials, a mixture can be optimized for performance in hot and cold weather, and all ingredients can be confirmed to be compatible in terms of workability, air content, and set time. Workability can be established using the VKelly (AASHTO TP 129) or Box Test (Ley et al. 2012, Cook et al. 2014).

The procedures used for concreting in hot and cold weather and adjusting concrete mixtures should be established and formalized in the QC plan. The QC plan should also identify the personnel responsible for adjusting concrete mixtures and define the processes used to inform the specifier or purchaser. When changes are made to a mixture, it is important to inform all parties that could be affected by those changes.

Mixture Production

The QC plan should guide all mixture production processes from the start of construction until completion. The batching process, including measurement of materials and introduction of the materials into the mixer, should be addressed in the QC plan. The batching sequence may vary depending on the materials and type of mixer used (stationary or truck mixer), and more extensive guidance on developing an appropriate batching sequence is presented in Chapter 8 of the IMCP manual (Taylor et al. 2019).

Critical to the success of any batching process is control of the water added to the mixture, including both the batch water and the water introduced into the mixture with the aggregates. Note that aggregates batched below saturated surface dry (SSD) can absorb water during the mixing operation. The QC plan should include provisions to ensure that water added to the mixture during batching is controlled. These provisions should outline the means to monitor and maintain moisture in the stockpiles and to adjust for stockpile measurements during batching. Provisions to control aggregate uniformity and prevent contaminants are provided in ASTM C94 and are further detailed in ACPA (2004). The batching tolerances provided in ASTM C94, shown in Table 5.14, should be included in the QC plan.

Table 5.13. Field setup tests

Concrete property	Test description	Test method	Comments
Workability	Aggregate gradation	ASTM C136 / AASHTO T 27 ASTM C566 / AASHTO T 255	• Use individual gradations and proportions to calculate combined gradation.
	Combined gradation	Tarantula curve (Ley 2020)	• Adjust combined gradation to achieve optimum workability.
	Slump	ASTM C143 / AASHTO T 119M/T 119	• Determine WRA dosage range.
	Segregation	—	• Look for signs of segregation in the slump samples.
Air void system	SAM	AASHTO TP 118	• Determine AEA dosage range.
Unit weight	Unit weight	ASTM C138 / AASHTO T 121M/T 121	• Confirm basis for QC monitoring.
Strength development	Compressive or flexural strength	ASTM C39 / AASHTO T 22 and/or ASTM C78 / AASHTO T 97	• Confirm strength development.
Transport	Resistivity / F-factor	AASHTO TP 119 and AASHTO T 358	• Sample conditioning per AASHTO TP 119 (Option A) is preferred. • Confirm development of F-factor over time.
	Rapid chloride penetrability	ASTM C1202 / AASHTO T 277	• Evaluate chloride ion penetrability using the table provided in ASTM C1202 / AASHTO T 277. • Adjust w/cm ratio to achieve required performance.
Other	Hydration	Semi-adiabatic calorimetry	• Confirm baseline for QC.

Source: Taylor et al. 2019

Table 5.14. Required batch tolerances for ready-mixed concrete

Constituent	Individual (%) *	Cumulative (%) **
Cementitious materials	±1	±1
Aggregates	±2	±1
Admixtures	±3	Not permitted
Water	Batch water should be ±1% of mixing water. Total mixing water should be within ±3%.	

Batch weights should be greater than 30% of scale capacity.

** Individual refers to separate weighing of each constituent.*

*** Cumulative refers to cumulative weighing of cement and pozzolan, of fine and coarse aggregate, or water from all sources (including wash water).*

Source: ASTM C94

One of the primary QC activities during this stage of work is to test the concrete mixtures used for the project in the QC laboratory. Recommended inspection items, the *minimum* QC measurements that should be performed, and checklists for mixture production are provided in Table 5.15.

Tests recommended for mixture QC during production are listed in Table 5.16. However, even if not specified by an agency, contractors can also use the PEM tests and approaches listed in Table 4.1 and described in AASHTO PP 84 to improve their QC and achieve the benefits associated with more reliable production of quality concrete. As described in Chapter 4, the PEM guidance provided in AASHTO PP 84 allows agencies flexibility in their approach to using alternative performance measures. As agencies move towards PEM specifications, contractors will increasingly need to adapt their QC measurements during mixture production to include performance-related tests.

Table 5.15. Mixture production QC—inspection items, QC measurements, and checklists

Key inspection items—Mixture production	QC measurements—Mixture production
• Review aggregate moisture testing results and moisture compensation on the batch tickets. • Periodically monitor mixing time. • Check that the aggregate moisture contents used for adjusting batch proportions is representative of the material being taken from the stockpiles.	• Sieve analysis and combined gradation • Aggregate moisture content • Concrete temperature* • Unit weight* • Air content* ** At a minimum, concrete temperature, unit weight, and air content should be checked once per day and then randomly every additional 1,000 yd^3 at the plant site, and these measurements should be compared to those taken from samples obtained at the point of delivery. Other PEM tests should be included to ensure that agency specifications are met or at the discretion of the contractor.*
Checklist—Mixture production	
✓ Verify that batch proportions match the approved mixture design (daily). ✓ Verify that moisture compensation is representative of the aggregates being batched (at least 2 times per day, more if necessary). ✓ Verify that material inventories are adequate. ✓ Verify that mixing drum is clean of dried materials that could break loose. ✓ Verify that mixing blades are not overly worn.	

Source: Fick et al. 2012

Table 5.16. Concrete mixture QC tests

Concrete property	Test description	Test method	Comments
Workability	Aggregate gradation	ASTM C136 / AASHTO T 27 ASTM C566 / AASHTO T 255	• Use individual gradations and proportions to calculate combined gradation.
	Combined gradation	Tarantula curve (Ley 2020)	• Monitor uniformity.
	Aggregate moisture content	ASTM C29	• Affects w/cm ratio and workability.
	Slump	ASTM C143 / AASHTO T 119M/T 119	• Indicates uniformity batch to batch.
Air void system	SAM	AASHTO TP 118	• Indicates uniformity batch to batch.
Unit weight	Unit weight	ASTM C138 / AASHTO T 121M/T 121	• Indicates uniformity batch to batch.
Strength development	Compressive or flexural strength	ASTM C39 / AASHTO T 22 and/or ASTM C78 / AASHTO T 97	• Indicates uniformity batch to batch.
	Maturity (Figure 5.14)	ASTM C1074	• Opening times.
Transport	Resistivity / F-factor	AASHTO TP 119 and AASHTO T 358	• Sample conditioning per AASHTO TP 119 (Option A) is preferred.
	Rapid chloride penetrability	ASTM C1202 / AASHTO T 277	• Indicates uniformity.
Other	Hydration	Semi-adiabatic calorimetry	• Indicates uniformity batch to batch.

Source: Taylor et al. 2019

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Figure 5.14. Maturity testing of concrete pavement

Information on the items to be tested, the tests to be performed, the sampling protocol, testing frequencies, and replicates for testing during mixture production should be provided in the QC plan. FHWA regulations on QA require that acceptance testing be conducted on independent random samples, not fixed-interval samples (such as a set number of square yards or cubic yards), because the latter may introduce bias into the test results. Contractors should be aware of agency requirements when developing a QC plan and should include QC provisions that support the agency's process.

The QC plan should also include a random sampling plan, a description of sample identification and storage systems, and a QC sampling and testing table. If presented in table format, the information on sampling and testing is easily referenced within the plan. An example of a QC sampling and testing table that includes PEM tests is presented in Table 5.17. **Note that the information presented in Table 5.17 is shown as an example only. The table should not be used for any other purpose than to develop a project-specific schedule of testing to be incorporated into a QC plan.**

Appropriate details for specific items such as lot sizes, numbers of sublots, and sampling and testing frequencies will vary based on agency requirements and project characteristics such as size, duration, staging, the type of work being performed, and other factors. In developing a QC plan for a given project, contractors should consider these factors and adjust the QC plan accordingly. ACPA publication EB238P, *Concrete Pavement Field Reference: Paving*, provides a table of QC tests, procedures, and testing frequencies that can be used for roadways of different types (ACPA 2010).

Table 5.17. Example QC sampling and testing table

Material	Test/Test method	Lot size	No. of sublots	Testing frequency	Sampling location	Sampling method	Report type
Coarse and fine aggregates	• Gradation: ASTM C136	5,000 yd^2	5	1 per sublot and/or minimum 1 per day	Stockpile	Random, per agency specification	Tabular and graphical: percent retained, Tarantula curve
Fresh concrete	• Air content: ASTM C231	5,000 yd^2	5	First 3 loads per day and for 3 loads whenever admixture dosages are adjusted	Plant, grade, and behind paver	Biased, start of day	Tabular and control chart
	• SAM: AASHTO T 152 • VKelly: AASHTO TP 129	N/A	5	First 3 loads per day and for 3 loads whenever admixture dosages are adjusted	Plant	Biased, start of day	Tabular and control chart
Fresh concrete at grade	• Temperature: ASTM C1064 • Air content: ASTM C231 • Air void system: AASHTO T 152 • Unit weight: ASTM C138 • Water content: AASHTO T 318	5,000 yd^2	5	1 per sublot	Grade	Random, per agency specification	Tabular and control chart
Hardened concrete	• Compressive strength: ASTM C39 • Resistivity: AASHTO T 358	5,000 yd^2	5	1 set of 3 replicates per lot and/or minimum set of 3 replicates per day	Plant	Random, per agency specification	Tabular and control chart
Concrete pavement	• Thickness probe: per agency specification	5,000 yd^2	5	1 per sublot	Grade	Random	Tabular and control chart
	• Maturity: ASTM C1074	5,000 yd^2	5	1 per sublot	Grade	Random	Tabular and control chart
	• Thickness: ASTM C174 • Thickness: MIT SCAN-T3	5,000 yd^2	5	1 per sublot	Pavement cores	Random	Tabular and control chart
	• Dowels: MIT-DOWEL-SCAN	N/A	N/A	All dowelled joints	All dowelled joints	N/A	N/A

Source: Fick et al. 2012

For perspective, the QC sampling and/or testing frequencies from some agencies are shown below. It is noted that the examples provided below include contractor QC testing, agency acceptance testing, and a combination of both. Additional information can be found in the specifications referenced for each agency.

Iowa Department of Transportation. *Developmental Specifications for Quality Management Concrete (QM-C)* (DS-15084) (Iowa DOT 2020):

- Unit weight: Twice per day
- Gradation and aggregate moisture contents: One per 1,500 yd^3
- Air content at discharge: One per 350 yd^3
- Air content behind the paver: Two per day for the first three days of paving and one per week thereafter
- w/cm ratio: Two per day
- Vibrator frequency: Two per day if electronic monitors are in use, otherwise two per day per vibrator

Oklahoma Department of Transportation. *2019 Standard Specifications for Highway Construction* (ODOT 2019):

- Gradation, air content, compressive strength, and thickness: one per 2,500 yd^2

Kansas Department of Transportation. *Standard Specification Book for State Road and Bridge Construction, Edition 2015*. 501 - Portland Cement Concrete Pavement (QC/QA) (KDOT 2015):

- Lot and sublot size vary by daily production:
  - Under 1,000 yd^2 (urban) = two sublots
  - 1,001 to 2,000 yd^2 = three sublots
  - 2,001 to 4,000 yd^2 = four sublots
  - 4,001 yd^2 and greater = five sublots

Wisconsin Department of Transportation. *Standard Specifications for Highway and Structure Construction* (WisDOT 2021):

- Slipformed: One paver width, with four to eight sublots with a length of 1,000 ft for a single lane and 500 ft for two-lane paving

  OR

- One lot per 2,000 yd^3 with sublots of a maximum of 250 yd^3

North Carolina Department of Transportation. *Aggregate Quality Control/Quality Assurance Program (NCDOT 2020) and Standard Specifications for Roads and Structures* (NCDOT 2018):

- Aggregates: Lot sizes shall be 2,000 tons for each size of materials shipped to the Department, or a minimum of one sample per week for each size of material, whichever comes first.
- Concrete pavement (mainline, shoulders, ramps, tapers, intersections, entrances, crossovers, and irregular areas not otherwise defined): A lot consists of 1,333.3 yd^2 or fraction thereof placed within 28 calendar days.

Test Strips

Whenever test strips are specified, the intent should be to evaluate all materials, construction, and QC processes. A test strip should be of sufficient length/volume to allow a thorough evaluation of all specification requirements. With the approval of the project engineer, the test strip may be placed as part of the planned area of paving.

Placement, Finishing, Texturing, Curing, and Sawing

Transportation and Spreading of Concrete

Delivery of the concrete to the paver in a consistent fashion helps minimize problems with the paving operation (ACPA 2003), and provisions in the QC plan regarding delivery should consider the haul route, site conditions, and mixture characteristics. Timing of delivery trucks to ensure a constant supply of concrete to the paving operation should also be considered, and if the travel time is anticipated to vary during the project, provisions should be included in the QC plan to ensure that the delivery schedule is appropriate for the set time of the mix. The QC plan should also include provisions outlining changes that may be required to the mixing operation, the number of haul trucks, the paving operation, or the haul route to ensure that the operation is coordinated in a manner that provides a consistent supply of concrete and an acceptable placement or slipform speed (Taylor et al. 2019). Haul units should be cleaned to remove dried concrete and other contaminants, and an adequate washout area should be provided and maintained.

Recommended inspection items, QC measurements, and checklists for the transportation of concrete are presented in Table 5.18.

Table 5.18. Transportation of concrete QC—inspection items, QC measurements, and checklists

Key inspection items—Transportation of concrete	QC measurements—Transportation of concrete
• Look for segregation in the mixture, including wet spots, dry clumps, areas of paste concentration, etc. • Check the haul road for smoothness. • Watch for dried concrete in the haul units. • Ensure that an adequate number of haul units are on the project.	• Visual inspection
Checklist—Transportation of concrete	
✓ Verify that haul route is maintained. ✓ Verify that washout area is adequate. ✓ Verify that that an adequate number of trucks are on site. ✓ Verify that vibrators on truck beds are operational.	

Source: Fick et al. 2012

University of North Carolina at Charlotte, used with permission

Figure 5.15. Uniform deposition of concrete in front of the paver

After being transported, the concrete should be deposited/spread in a manner that maintains a uniform head of concrete in front of the paver (Figure 5.15). Maintaining a uniform head of concrete becomes challenging if the subbase deviates from the plan because the volume of concrete required for paving will vary. This illustrates the compounding nature of QC issues, in that inadequate QC for the base/subbase leads to additional QC issues during paving; when effective QC is practiced throughout all stages of a project, subbase profiles should be corrected before paving to minimize variability in the concrete paving process and slab thickness. If the concrete head in front of the paver is too small or too large, the smoothness of the pavement will be affected.

The QC plan should include provisions to guide the paving operation and to indicate how problems arising at the paver will be addressed. Problems may include issues with the deposition of concrete ahead of the paver, surges of excess concrete or shortages of material in front of the machine, and mechanical issues that can occur with the paver itself (Figure 5.16). Recommended inspection items, QC measurements, and checklists for the spreading of concrete are presented in Table 5.19.

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Figure 5.16. Maintenance truck (at left) with tools and equipment available to address issues with the paver during paving

Slipforming (Extrusion)

The paver operator will need to adjust the paver speed to match the concrete delivery rate. However, in planning and executing paving operations, the contractor should aim to keep the paver moving at a uniform speed. When a slipform paving machine is used, the primary items that can be adjusted to improve the quality of paving include paving speed, vibrator frequencies and heights, elevation, angle of the pan, and amount of concrete head in the grout box (Taylor et al. 2019). Vibrator monitors should be used to control the amount of vibration in a manner that provides suitable consolidation without causing segregation or issues with the entrained air void system. Chapter 8 of the IMCP manual (Taylor et al. 2019) provides guidance on managing the paving operation and preventing/mitigating issues associated with consolidation (for both slipformed and hand-placed concrete pavement) and horizontal and vertical control (for both stringline and 3D machine-controlled paving). In all cases, control of the paving operation is much easier to achieve if uniform concrete is provided to the paver.

Table 5.19. Spreading of concrete QC—inspection items, QC measurements, and checklists

Key inspection items—Spreading of concrete	QC measurements—Spreading of concrete
• Sprinkle subgrade/subbase with water and ensure that it remains damp before concrete spreading occurs. • Reject pavement in areas where the grout box empties. • Monitor the amount of concrete in front of the paver; note the time and location of extremes and correlate these events to the smoothness profile. • Visually inspect the concrete for nonuniformity (e.g., segregation, unmixed materials) before it is extruded through the paver.	Testing performed on QC and acceptance samples taken at the point of delivery: • Concrete temperature • Subbase temperature • Slump • Unit weight • Air content • Strength
Checklist—Spreading of concrete	
✓ Verify that spreader, if used, is set narrower than the paver. ✓ Verify that spreader, if used, has automatic control for steering and elevation (stringline or stringless). ✓ Verify that water truck is available for sprinkling grade.	

Source: Fick et al. 2012

The plastic concrete should be confirmed to be as thick as or thicker than the thickness specified in the paving plan. Approaches for obtaining thickness measurements should be included in the QC plan and should reflect the methods and frequencies specified by the agency. During paving, a probe should be used to confirm the slab thickness in real time behind the paver at a recommended frequency of approximately every 200 to 500 ft. The MIT SCAN-T3 device, discussed below under Acceptance, provides thickness data for both QC and acceptance purposes.

A summary of key inspection items, QC measurements, and checklists for the slipforming of concrete is presented in Table 5.20.

Insertion of Dowels and/or Tie Bars

Instead of being preplaced in baskets, dowel bars can be inserted during the paving process (Figure 5.17) using automatic insertion equipment. If automatic insertion equipment is used, the mixture must be sufficiently workable and the equipment must be operating correctly. Regardless of the approach used, dowel bars must be aligned within tolerances to ensure that they efficiently transfer loads.

When automatic insertion equipment is used, one practice that has resulted in improved dowel alignment is the use of a MIT SCAN device to check the alignment of dowel bars after the first day of paving or after a test section is paved. The MIT SCAN data can be analyzed, and a joint score can be computed for each joint. Using this process, the dowels contributing to a higher (i.e., less desirable) joint score can be identified, and the forks of the dowel bar inserter equipment used to place those dowels can be adjusted or replaced as needed to provide better alignment.

Tie bars are typically placed after paving and should be positioned at the appropriate location, at the appropriate depth within the slab, and in the correct alignment (Figure 5.18). Adequate spacing from the load transfer dowels is critical.

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Figure 5.17. Paver equipped with dowel bar inserter technology

Table 5.20. Slipforming of concrete QC—inspection items, QC measurements, and checklists

Key inspection items—Slipforming of concrete	QC measurements—Slipforming of concrete
• Visually inspect the edge for stability. Continued edge problems should not be tolerated because they indicate a nonuniform mixture, improper consolidation, or an out-of-adjustment paver. • Visually inspect the pavement for surface tears directly behind the paver before any hand finishing has occurred. Tears in the surface may indicate that the paver needs to be adjusted and/or the mixture needs to be modified. • Look for concrete buildup in the grout box and clean out any hardened concrete from the grout box. • Adjust the vibrator frequency for the paver speed; the vibrators should stop whenever the paver stops.	• Vibrator frequency: Measured automatically when monitors are used or manually at least twice per day • Paver speed: Log maintained of paver speed, noting start and stop locations • Smoothness profiles: Roughness correlated to any events noted during paving • Thickness measurements
Checklist—Slipforming of concrete	
✓ Verify that vibrators are operable before starting. ✓ Monitor vibrator operation at least hourly. ✓ Check stringline or stringless models for accuracy. ✓ Verify that paver and all associated equipment are fueled and ready for uninterrupted operation.	

Source: Fick et al. 2012

MnDOT, used with permission

Figure 5.18. Preplaced tie bars supported and fastened to the grade

Kevin W. McMullen, Wisconsin Concrete Pavement Association, used with permission

Figure 5.19. Verification of dowel bar location by probing behind the paver

Some agencies require the contractor to verify the location of dowels after the pavement is placed (Figure 5.19). The procedure for verifying the location of dowels should be documented in the QC plan and should, at a minimum, conform to agency requirements. Information provided in the QC plan to support verification should include the number of dowels per interval verified by probing or, if nondestructive test methods are used, a procedure for using a scanning device to confirm placement at an established frequency (described in Table 5.21).

Recommended inspection items, QC measurements, and checklists for the placement of inserted dowels and tie bars are presented in Table 5.21.

The Transtec Group, Inc., used with permission

Figure 5.20. Hand finishing

Hand Finishing

Hand finishing (Figure 5.20) should be minimized on concrete paving jobs to avoid bringing excess paste to the surface, which may lower the surface's durability.

Ensuring that the paving equipment is properly adjusted and the concrete mixture provides good finishing characteristics should help minimize the effort required to produce an acceptably closed surface (Taylor et al. 2019).

Table 5.21. Insertion of dowels and tie bars QC—inspection items, QC measurements, and checklists

Key inspection items—Inserted dowels and tie bars	QC measurements—Inserted dowels and tie bars
• Check transverse spacing and offset from the edge of the pavement. • Verify that dowel locations are marked on both sides of the pavement and correspond to the center of the dowel bar. • Monitor consolidation above and around the dowels by coring after each day of paving.	• None during prepaving • Embedment and cover of bars: Verified by probing behind the paver at 300 ft intervals (locating at least 1 bar for each basket across the width of the slab) • Dowel/joint placement: Evaluated using nondestructive devices such as ground penetrating radar, MIT SCAN, or pachometer (cover meter)
Checklist—Inserted dowels and tie bars	
✓ Verify that dowel dimensions (diameter and length) are correct. ✓ Verify that bar spacing is as specified. ✓ Verify that equipment is set up to insert the dowels to the specified tolerances. ✓ Verify that bar coating is as specified and not unduly damaged. ✓ Verify that bond breaker is adequate. ✓ Verify that the midpoint of each dowel location is marked adequately on both sides of the slab to ensure proper joint sawing.	

Source: Fick et al. 2012

The QC plan should include provisions for checking the surface behind the paving equipment and addressing bumps and high/low spots. Using a straightedge, bumps and dips should be identified and corrected by experienced concrete finishers. In making corrections, water should not be added to the surface because, as with hand finishing, doing so will reduce the surface's durability. If repairs to the edges of the newly placed pavement are required, the concrete should be supported with a board, reconsolidated, and finished by experienced concrete finishers. Issues with slumped or fallen edges often indicate that adjustments to the mixture or paver are needed (Fick et al. 2012).

Procedures for forming headers (transverse construction joints) at the end of a workday or during an interruption in paving should also be included in the QC plan. Guidance on forming headers, which often contribute to pavement roughness if not constructed properly, is provided in the IMCP manual (Taylor et al. 2019).

A summary of recommended inspection items, QC measurements, and checklists for hand finishing is presented in Table 5.22.

Texturing

Guidance on applying various textures to the pavement to improve friction and skid resistance is presented in Rasmussen et al. (2012). Procedures used to texture the concrete should be included in the QC plan. The texturing machine (Figure 5.21) should be operated at a constant speed using adequate steering and elevation controls (e.g., stringline, 3D machine control, or referencing of the slab). Tines should be clean and straight to produce acceptable tining (Figure 5.22), and their length and angle should be adjusted to ensure that the texture depth is appropriate. Texturing should not impede or delay the use and application of curing provisions (Fick et al. 2012).

Recommended inspection items, QC measurements, and checklists for texturing are presented in Table 5.23.

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Figure 5.21. Texturing machine

The Transtec Group, Inc., used with permission

Figure 5.22. Longitudinal tining

Table 5.22. Hand finishing QC—inspection items, QC measurements, and checklists

Key inspection items—Hand finishing	QC measurements—Hand finishing
• Ensure that water is not added to the pavement surface; instead, adjust the mixture and/or the paver. • Note locations where finishers cut bumps or fill dips. • Monitor wetting/rewetting of the burlap; overspray may accidentally add water to the pavement surface. • Monitor consolidation at end-of-day headers.	• Smoothness profiles: Correlated to events noted during paving
Checklist—Hand finishing	
✓ Verify that finishing tools are straight and true. ✓ Verify that header supplies and tools are on hand.	

Source: Fick et al. 2012

Table 5.23. Texturing QC—inspection items, QC measurements, and checklists

Key inspection items—Texturing	QC measurements—Texturing
• Check tine spacing. • Observe the nominal texture depth. It is impractical to measure texture depth, but look for texture that is obviously too deep or too shallow.	• None

Checklist—Texturing
✓ Verify that tine spacing is as specified. ✓ Replace broken tines. ✓ Clean tines.

Source: Fick et al. 2012

Table 5.24. Curing QC—inspection items, QC measurements, and checklists

Key inspection items—Curing	QC measurements—Curing
• Visually inspect for complete and uniform coverage of curing compound; the surface should be similar in appearance to a white sheet of paper (no gray streaks). • Ensure that curing compound is applied before any surface drying can occur. • Ensure that curing compound is not applied until bleed water is gone.	• Record of start and stop locations and times • Average coverage rate: Calculated each time curing compound is added to the tank

Checklist—Curing
✓ Verify that curing materials are on the job and meet specifications. ✓ Verify that curing tanks are full and material has been agitated. ✓ Verify that pump for refilling is operable. ✓ Verify that nozzles are clean and functioning. ✓ Verify that wind screen is adjusted properly.

Source: Fick et al. 2012

Curing

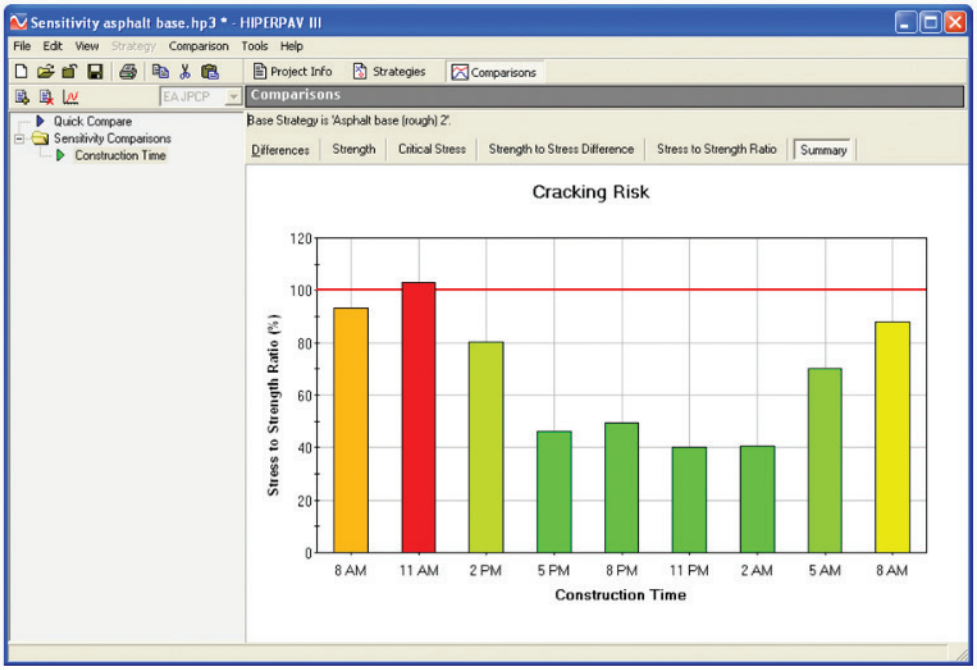
Curing is essential to the development of strength in concrete and helps ensure the durability of a pavement (Taylor et al. 2013). Maintaining adequate moisture and temperature conditions from placement until a suitable time has elapsed is critical to ensure that the quality of the pavement surface is maintained and hydration and pozzolanic reactions are supported (ACI Committee 308 2016).

The methods and materials involved in the curing regimen should be described in the QC plan, with provisions included to address potential problems. Like for the other pieces of equipment in the paving train, the QC plan should include provisions to ensure the correct operation of the equipment used for curing (such as a curing compound application machine, shown in Figure 5.23), as well as measures to prevent problems and address them as they arise. A detailed discussion on concrete pavement curing is presented in Taylor et al. (2013), Saeed et al. (2003), ACI Committee 308 (2016), and the IMCP manual (Taylor et al. 2019).

A summary of recommended inspection items, QC measurements, and checklists for curing is presented in Table 5.24.

University of North Carolina at Charlotte, used with permission

Figure 5.23. Curing machine applying curing compound



https://www.thetranstecgroup.com/hiperpav/

Figure 5.24. Screenshot of HIPERPAV software showing cracking risk at different times of day

Sawing

The QC plan should include measures to prevent drying shrinkage cracking, which is affected by the characteristics of the mixture, weather conditions, and the restraint acting on the concrete. The HIPERPAV software program (Figure 5.24) can be used as a QC tool to provide insight into the risk of early-age cracking for a concrete pavement mixture in a particular setting and in the absence of loading. Information on this QC tool is available in FHWA (2020) and in McCullough and Rasmussen (1999).

In addition to predicting the potential for early-age cracking, HIPERPAV can also help contractors determine the likely timeframe (window) for sawcutting. QC plan provisions for the sawcutting of joints should address the layout of the joints, the sawing equipment used, the sawcut timing and process, and the inspection of sawcuts. Provisions for sealing joints, including processes for cleaning joints and applying sealing products, should be included as appropriate to address specification requirements. The QC plan should also include provisions for the inspection of joints and, when warranted, remedial actions to be taken. Guidance on joint sawing is presented in Chapter 8 of the IMCP manual (Taylor et al. 2019). A summary of key inspection items, QC measurements, and checklists for sawing is presented in Table 5.25.

Table 5.25. Sawing QC—inspection items, QC measurements, and checklists

Key inspection items—Sawing	QC measurements—Sawing
• Verify that each sawcut location is centered on a dowel or tie bar. • Check that sawcut depths are in compliance with specifications at mid-slab locations. • Visually inspect the pavement for uncontrolled cracks. • Check whether raveling is excessive (if sawing is performed too early) or minimal (if sawing is performed too late).	• Log of time of paving, time of sawing, and slab temperature • Temperature: Monitor every hour via sensors installed in the pavement and correlate with the time of sawing relative to the time of placement • Early-age stress and strength behavior: Can be modeled in HIPERPAV to evaluate the potential for uncontrolled cracking and the effectiveness of sawing operations
Checklist—Sawing	
✓ Verify that an adequate number of saws and blades are available on the project. ✓ Verify that saw blades are the correct diameter for the required sawcut depth. ✓ Verify that water trucks are available to support the saw crews. ✓ Verify that lights, if necessary, are available and operable for the saw crews.	

Source: Fick et al. 2012

Temperature and Weather Adjustments

Temperature and weather conditions change during the course of a project, and these daily changes affect the paving operation. The QC plan should establish methods to adjust operations to accommodate changes in both temperature and weather conditions. Hot and cold weather extremes should be addressed, with provisions for materials management, batching and mixing, hauling, and paving in extreme temperatures. Regardless of weather conditions, the temperature of the concrete affects its workability and cracking potential and, as such, should be monitored and controlled. A description of the types of issues that can arise due to various temperature and weather conditions is presented in Chapter 8 of the IMCP manual, along with means to address these issues (Taylor et al. 2019).

In hot weather, the high temperatures speed the hydration process, subsequently impacting the timing of virtually all aspects of the paving operation. The mixture temperature should be kept below 90°F (Taylor et al. 2019). Paving during cooler times of day (such as overnight) can help ensure that adequate concrete temperatures are maintained during placement. Adjustments can also be made to the materials handling and batching processes, including the use of cooled water or ice, as well as provisions for sprinkling stockpiles to cool aggregates.

In cold weather, the concrete should be protected from freezing for at least 48 hours after placement using coverings (Fick et al. 2012). Cold temperatures slow the hydration process, which delays the sawing window. The coverings will need to be removed briefly to allow sawing to be performed but should subsequently be replaced to protect the concrete. Rapid cooling of the pavement may result in the formation of cracks.

The QC plan should include provisions for the use of accelerating or retarding admixtures to accommodate temperature and weather conditions, and these provisions should reflect agency requirements associated with use of these materials. Provisions for adding water and remixing concrete should follow ASTM C94/AASHTO M 157 and agency requirements.

If rain is forecast, adequate amounts of plastic sheeting should be on hand to cover the fresh concrete and protect it from rain. Paving operations could also be adjusted to include smaller pours, or paving could be postponed. If the finish of unprotected concrete pavement has been damaged by rain, it should not be refinished but should instead be grooved using saws (Fick et al. 2012).

The QC plan should include a comprehensive weather management plan that addresses the following:

- Hot weather concreting
- Cold weather concreting
- Protection from rain
- Adjustments to paving processes and joint sawing when sudden changes in temperature occur

An example weather management plan is provided in Fick et al. (2012), Appendix B.

Smoothness

Ensuring the smoothness of concrete pavement is becoming an increasingly important aspect of contractor QC because agencies are increasingly utilizing this measure as a primary indicator of pavement condition and quality. Pavement smoothness is influenced by many specification and construction factors, including those shown in Table 5.26. Provisions addressing the items in this table that are appropriate for a given project should be included in the project's QC plan. The IMCP manual (Taylor et al. 2019) provides guidance on addressing each of these factors, and other guidance is presented in *Implementation of Best Practices for Concrete Pavements: Guidelines for Specifying and Achieving Smooth Concrete Pavements* (Fick et al. 2019).

Table 5.26. Factors influencing pavement smoothness that should be considered in development of a QC plan

Design/specification factor	Construction factor
• Base/subbase and trackline • Horizontal alignment, cross slope, and superelevated curves • Grade and staking calculations • Embedded reinforcement and fixtures • Concrete mixture characteristics • Access to businesses and local residences	• Preparation of the grade • Production of consistent concrete • Delivery of concrete • Setup of fixed forms • Setting and maintenance of the stringline • Operation of the paving machine • Paving on vertical grades and curves • Handling of dowel bars and reinforcement • Finishing of the surface and headers • Education and motivation of the crew

Source: Taylor et al. 2019

The QC plan should include provisions to measure the initial smoothness of the pavement using a lightweight inertial profiler with line lasers within the first 24 to 48 hours after paving, along with provisions for making adjustments to the process based upon issues that may be found during these measurements. A real-time smoothness measurement device mounted to the back of the paver is also a highly useful QC tool (Figure 5.25). Although the measurements will differ between the real-time smoothness measurement device and the lightweight inertial profiler (described in the following section), the measurements will be parallel, and real-time measurements offer contractors the opportunity to adjust their operations based on real-time data (Taylor et al. 2019).

University of North Carolina at Charlotte (top), used with permission; The Transtec Group (bottom), used with permission

Figure 5.25. Real-time smoothness measurement device mounted to the back of a paver

Acceptance

Acceptance Tests for Concrete Mixtures

Tests for mixture acceptance should be performed as specified by the agency. These tests may be performed by the agency or the agency's representative. As described above, the agency may also choose to use data from QC tests performed by the contractor in the acceptance process. The latter case further emphasizes the need for the contractor to ensure that appropriate QC provisions are in place to support the acceptance decision. A list of mixture acceptance tests is presented in Table 5.27. Note that the most commonly used tests currently include air content and strength, but agencies are increasingly moving towards the use of performance-based tests such as SAM and permeability.

Acceptance Tests for Concrete Pavement

QC and acceptance tests used during construction are summarized in Table 5.28.

FHWA Mobile Concrete Technology Center, used with permission

Figure 5.26. SAM testing at the paver

Table 5.27. Mixture acceptance tests

Concrete property	Test description	Test method
Air content	Air content by pressure method	ASTM C231
Air void system	SAM (Figure 5.26)	AASHTO TP 118
Strength	Compressive or flexural strength	ASTM C39 / AASHTO T 22 and/or ASTM C78 / AASHTO T 97
Permeability	Resistivity / F-factor	—
		• AASHTO TP 119 and AASHTO T 358 • Sample conditioning per AASHTO TP 119 (Option A) is preferred.
	Rapid chloride penetrability	ASTM C1202 / AASHTO T 277
Other	w/cm ratio	Microwave

Source: Taylor et al. 2019

Table 5.28. Construction QC and acceptance tests

Property	QC test method(s)	Acceptance test method(s)
Vibration	On-board monitors: • Monitor that all vibrators are operating • Ensure that vibrator speed is appropriate for paver speed	On-board monitors
Thickness	Probe behind paver	MIT SCAN-T3 (Figure 5.27) Cores
Smoothness	Real-time smoothness monitoring	Inertial profiler to measure hardened smoothness
Dowel alignment	Hand probe for dowel location behind the paver MIT-DOWEL-SCAN (Figure 5.28)	MIT-DOWEL-SCAN

Source: Taylor et al. 2019

Kessler Soils Engineering Products, Inc., used with permission

Figure 5.27. MIT SCAN-T3

Kessler Soils Engineering Products, Inc., used with permission

Figure 5.28. MIT-DOWEL-SCAN

Acceptance and the Percent Within Limits Approach

As defined in the seventh edition of TRB E-Circular E-C235, *Glossary of Transportation Construction Quality Assurance Terms* (TRB 2018), acceptance is "the process whereby all factors used by the agency (i.e., sampling, testing, and inspection) are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value for a given product." Acceptance measurements (including sampling, testing, and inspection) are always considered in the agency's acceptance decision, while QC measurements (including sampling, testing, and inspection) may be used in the acceptance decision depending on the agency's preferences and requirements. Process control measurements are not used in the agency's acceptance decision. When contractor QC measurements are used in the agency's acceptance decision, "the acceptance process includes contractor testing, agency verification and validation, and possibly dispute resolution" (TRB 2018).

AASHTO R 9, Standard Practice for Acceptance Sampling Plans for Highway Construction, provides guidance to agencies on developing acceptance plans that include the separate functions of QC and acceptance. For highway construction, acceptance plans should be statistically based on variables, not on pass/fail criteria using attributes.

Since the variability of most materials and construction products is unknown, AASHTO M 157 recommends that acceptance plans measure both the average and variability of the values for each inspection item as estimates of a population. Many statistically based acceptance plans are developed in terms of percent of material or constructed work within agency-determined limits. The main advantage of the PWL process is that it incorporates the mean, standard deviation, and size of a sample into the pay factor determination (Moulthrop et al. 2012).

Another key advantage is that the PWL process rewards the contractor for controlling variability and, as a result, should yield a pavement with uniform properties and performance (Russell and Frantzen 2008).

Corrective Actions

Issues inevitably arise during construction. A good QC plan includes (1) provisions to prevent and mitigate issues and (2) provisions to identify and address issues in a timely manner as they occur. For example, the plan should describe corrective actions to address issues such as excessive edge slump, embedded items that are out of tolerance, or problems that arise during the finishing operation. As part of the provisions on corrective actions, criteria for suspending or halting paving operations should be established and included in the QC plan, along with procedures for performing actions to support the stoppage of work. These criteria should include inclement weather or extreme temperatures, issues with the concrete mixture or other materials included in the pavement, issues with the equipment in the paving train, or problems associated with any hand-placed pavement operations.

In the QC plan, the contractor should also describe how operations will change when paving is suspended and when and how operations will recommence after suspension. This description should include information such as the corrective action plan and any associated documentation, the speed of operations when work is resumed after suspension, the tests to be performed and testing frequencies after suspension, and the criteria that must be met in order to resume full operations. The QC plan should indicate that when production is suspended due to materials and/or processes that have exceeded suspension limits, paving will not be resumed until appropriate adjustments have been made and approved by the appropriate individuals. The QC plan should also detail the additional (more frequent) sampling, testing, and inspection that will be performed until data are shown to be within control limits for a specified duration (or number of tests).

Problems inevitably arise during construction. When preparing the QC plan, the contractor should consider potential issues that may occur and include provisions in the QC plan that guide personnel in addressing those issues.

Chapter 6

Tools for Quality Control

"What gets measured gets managed" is a core principle of quality management. In previous chapters, guidance on what to measure at various stages in the concrete paving process was presented. This chapter provides information on several tools that can be used to help record, process, and use measurements to support decision-making and continuous improvement.

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 use of the vast amount of construction data that can be obtained using modern sensors, data collection devices, and models.

A variety of tools exist to support quality management. Many of these tools have their roots in the manufacturing sector and have been adapted for use in the construction setting. 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 quality control tools can be found in Wadsworth et al. (2001), Besterfield (2009), and Montgomery (2013), among other publications.

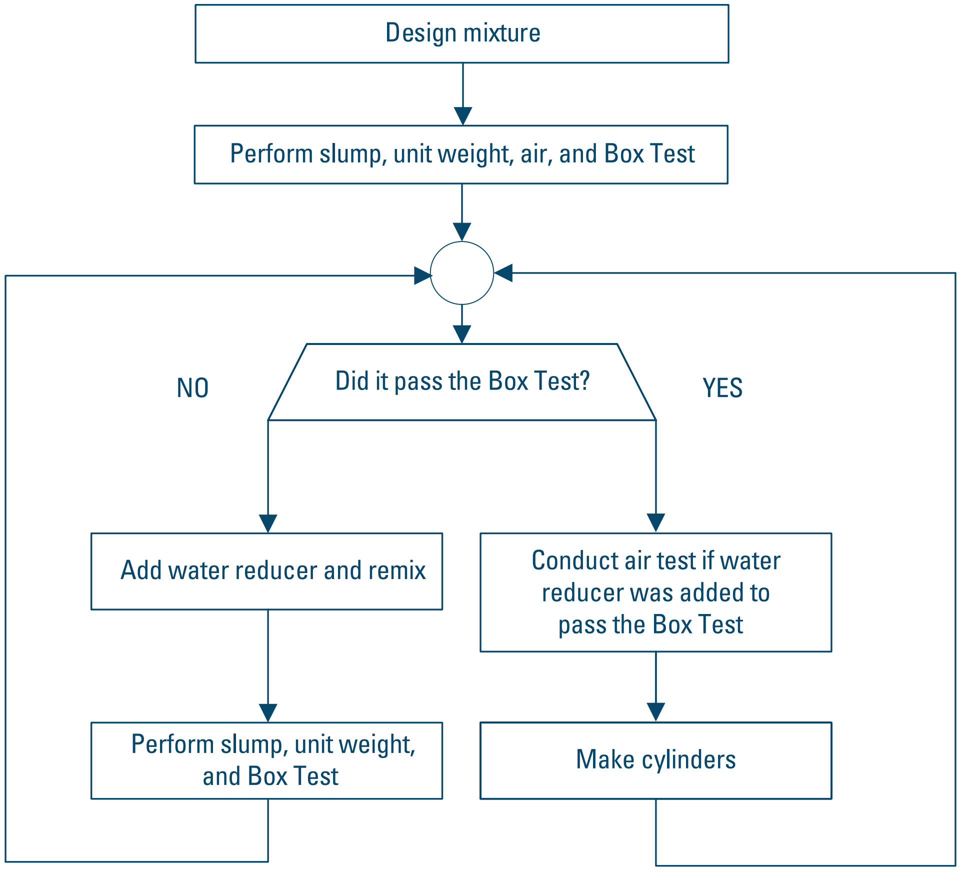
Process Diagrams, Check Sheets, and Other Tools

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 planning, communication, and improvement of a process. A flowchart can also be used 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 is shown in Figure 6.1. Like many QC tools and documents, a flowchart is a dynamic tool and will change as processes are modified, adapted, or enhanced. Once a flowchart is established, it can be appended with data useful to QC, such as measurement requirements, performance targets, and other information supporting quality control and improvement.

A large amount of data is collected as a project progresses, and some portions of the data are often more useful than others. One key QC task is developing 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 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.



Cook et al. 2013

Figure 6.1. Flowchart showing process for preparing and testing trial batches of concrete using the Box Test

Check sheets are extensively used 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 in QC processes and activities.

An example check sheet for the inspection of an aggregate base course prior to paving is shown in Figure 6.2, while an example data collection sheet that supports the testing of concrete properties is shown in Figure 6.3. Additionally, several simple checklists are provided throughout Chapter 5 for many concrete pavement construction processes. Although the checklists presented in this guide are simple, they can readily be enhanced to be highly useful and meet a contractor's needs.

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” lift, not to exceed 6”
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 6.2. 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 (lbs)				
Strength (psi)				
Cylinder IDs				
Test Age (days)				
Load (lbs)				
Strength (psi)				
Cylinder IDs				
Test Age (days)				
Load (lbs)				
Strength (psi)				
Cylinder IDs				
Test Age (days)				
Load (lbs)				
Strength (psi)				
Notes:				
	Signature		**Date**	
QC Inspector				
QC Supervisor				

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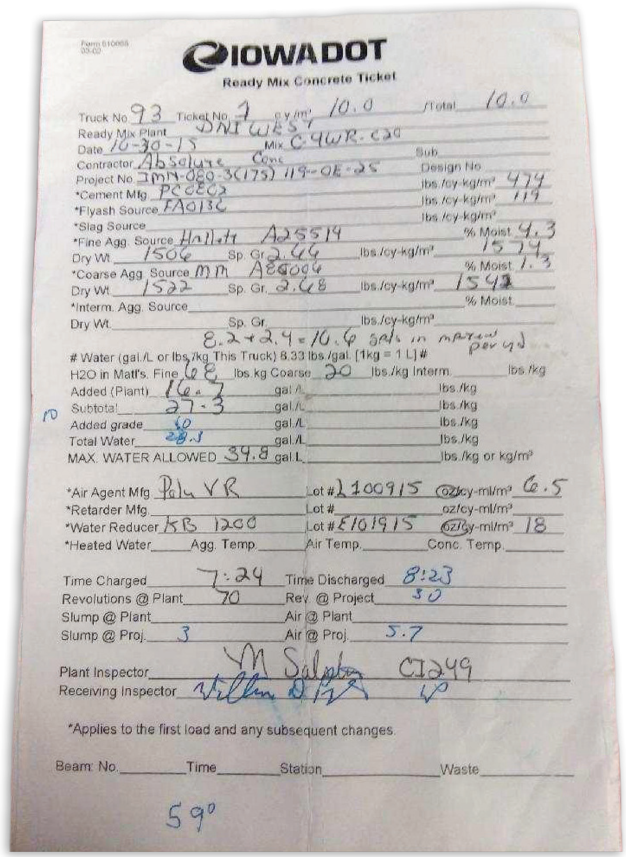
Figure 6.3. Data sheet showing compressive strength measurements

Historically, check sheets have been paper forms that were 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 transferring information 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.

QC check sheets can be used at a stationary point in the process (like those shown in Figures 6.2 and 6.3) 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 facilitates tracing later. Historically, paper materials tickets (Figure 6.4) have been used in concrete paving. However, e-ticketing systems (Figure 6.5) 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 the 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.

This section has provided a snapshot of tools that could (and often should) be utilized to support good QC practices. A range of other tools are used in QC, including histograms, scatter plots, Pareto charts, and other graphical and statistical tools. For more information on these tools, the reader is referred to the references listed at the beginning of this chapter.


IOWA DOT
Ready Mix Concrete Ticket

Truck No. 93 Ticket No. 7 c.y./m³ 10.0 /Total 10.0
Ready Mix Plant DNI West
Date 10-30-15 Mix C-4WR-C30
Contractor Absolute Conc.
Project No. IMN-080-3(175) 119-0E-25
Sub
Design No.
*Cement Mfg. PCGCC lbs./cy-kg/m³ 474
*Flyash Source FA013C lbs./cy-kg/m³ 119
*Slag Source lbs./cy-kg/m³
*Fine Agg. Source Hallett A25514 % Moist. 4.3
Dry Wt. 1506 Sp. Gr. 2.66 lbs./cy-kg/m³ 1571
*Coarse Agg. Source MM A86006 % Moist. 1.3
Dry Wt. 1522 Sp. Gr. 2.68 lbs./cy-kg/m³ 1542
*Interm. Agg. Source % Moist.
Dry Wt. Sp. Gr. lbs./cy-kg/m³
8.2+2.4=10.6 gals in material per yd
Water (gal./L or lbs./kg This Truck) 8.33 lbs./gal. [1kg = 1 L]
H2O in Mat'ls. Fine 68 lbs.kg Coarse 20 lbs./kg Interm. lbs./kg
Added (Plant) 16.7 gal./L lbs./kg
Subtotal 27.3 gal./L lbs./kg
Added grade 10 gal./L lbs./kg
Total Water 28.3 gal./L lbs./kg
MAX. WATER ALLOWED 34.8 gal./L lbs./kg or kg/m³

*Air Agent Mfg. Polu VR Lot # 2100915 oz/cy-ml/m³ 6.5
*Retarder Mfg. Lot # oz/cy-ml/m³
*Water Reducer KB 1200 Lot # E101915 oz/cy-ml/m³ 18
*Heated Water Agg. Temp. Air Temp. Conc. Temp.

Time Charged 7:24 Time Discharged 8:23
Revolutions @ Plant 70 Rev. @ Project 30
Slump @ Plant Air @ Plant
Slump @ Proj. 3 Air @ Proj. 5.7

Plant Inspector CI249
Receiving Inspector

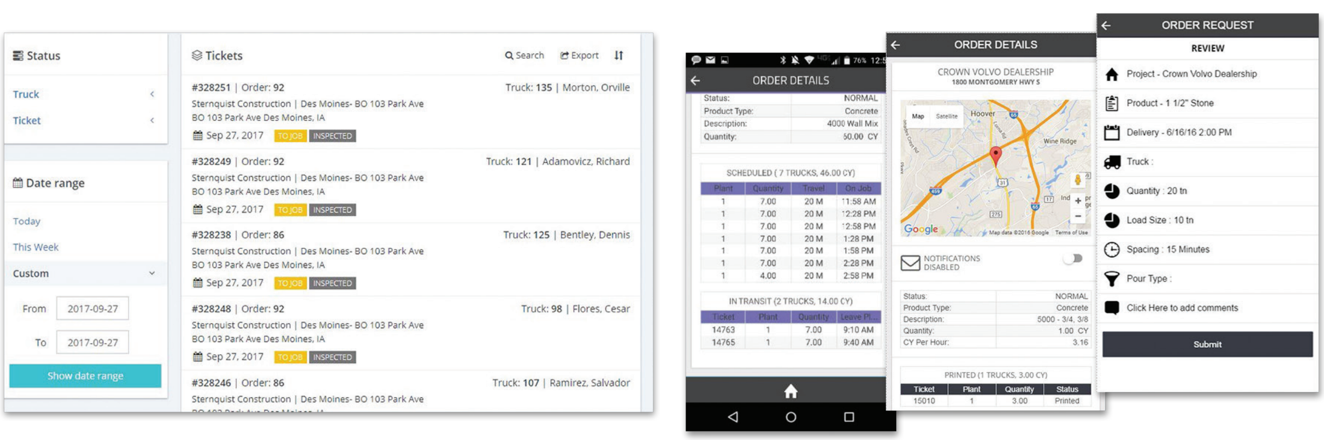
*Applies to the first load and any subsequent changes.

Beam No. Time Station Waste

59°

Greg Mulder, ICPA, used with permission

Figure 6.4. Paper materials ticket



Greg Mulder, ICPA, used with permission

Figure 6.5. E-ticketing system for concrete materials

Run Charts and Control Charts

Run charts and control charts are two process improvement tools that allow the user to gain insight into the performance of a process. A run chart (or 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 6.6. Although a run chart is useful for identifying trends in the data, it cannot be used to determine whether a measurement is influenced by chance or assignable cause variability.

Control charts are constructed similarly to run charts by plotting one or more quality characteristics 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 will also make it evident to the user when a process is experiencing unacceptable variability or when measurements are exceeding (or are trending towards) 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 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 control charts are constructed well and are reviewed periodically, issues with processes can be identified quickly and the user can respond to the issues in a timely manner. Contractor experience and companion records (if available) can be used to identify ways to address the issue(s) and bring the process back into control. Once corrective actions are taken or adjustments are made, continued use of the chart(s) 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.

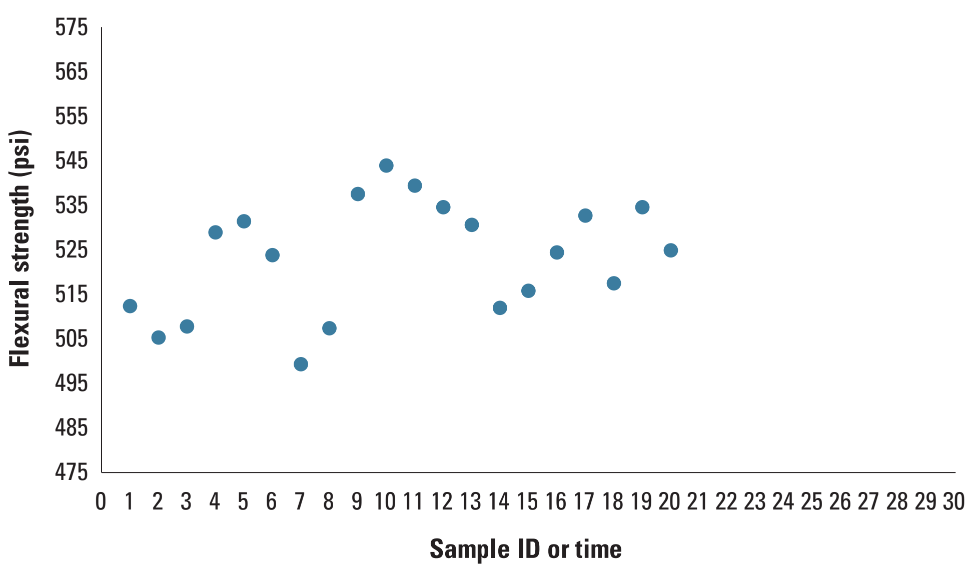


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Figure 6.6. Run chart for the flexural strength of a concrete mixture

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 provide insight for 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 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 a run chart or a control chart, if desired.

Once a quality characteristic is selected, a sampling plan should be determined. 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 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 samples 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, as well as correctly applying any corrective actions that may be needed. As noted in a previous chapter, the QC sampling plan should also be separate and independent from the agency's acceptance sampling plan.

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 limits 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 6.7), 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 $\pm 3\sigma$ from the average measurement. If a measurement is greater than $+3\sigma$ 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 $\pm 3\sigma$ 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 (such as after each set of 5 consecutive measurements is added to the control chart).

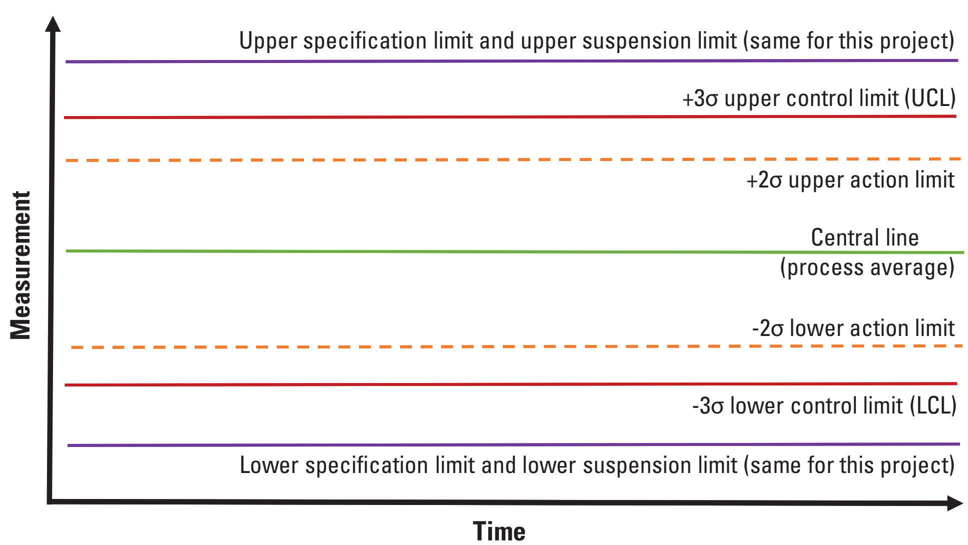

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Figure 6.7. Typical central line (process average) and limits on a control chart

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. An example calculation of control limits is presented below.

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 provides an additional, more detailed example of the use of statistical methods to assist in the development and use of a control chart. The reader is also referred to Besterfield (2009) and Montgomery and Runger (2014) for other detailed explanations of this process. ASTM publication MNL7-9TH, *Manual on Presentation of Data and Control Chart Analysis*, provides extensive guidance on the calculation and use of control chart limits (ASTM 2018).

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 6.7, 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 6.7, 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 6.8 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 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.

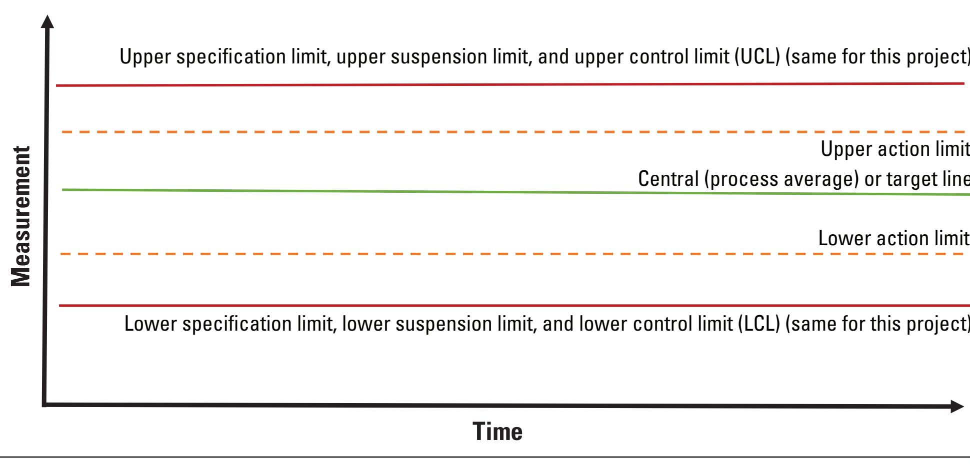

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Figure 6.8. Typical central line (target line or process average) and limits on a run chart, where statistical methods are not used to establish limits

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

Data collected for the average 7-day flexural strength of a concrete mixture are presented in Table 6.1. Note that these data are also shown in the example run chart in Figure 6.6. The data were tabulated in a spreadsheet, and the average and standard deviation were computed. Using the spreadsheet, an x-y scatter plot was produced for the two columns of data, resulting in the control chart shown in Figure 6.9.

Table 6.1. Measurements of concrete flexural strength

Time or sample ID	Flexural strength (psi)
1	512.4
2	505.3
3	507.8
4	528.9
5	531.4
6	523.8
7	499.3
8	507.4
9	537.5
10	543.9
11	539.4
12	534.6
13	530.6
14	512.0
15	515.8
16	524.4
17	532.7
18	517.5
19	534.6
20	524.9

Average	523.2
Standard deviation	12.8

		Upper	Lower
±2 standard dev.	Action limits	549	498
±3 standard dev.	Control limits	562	485

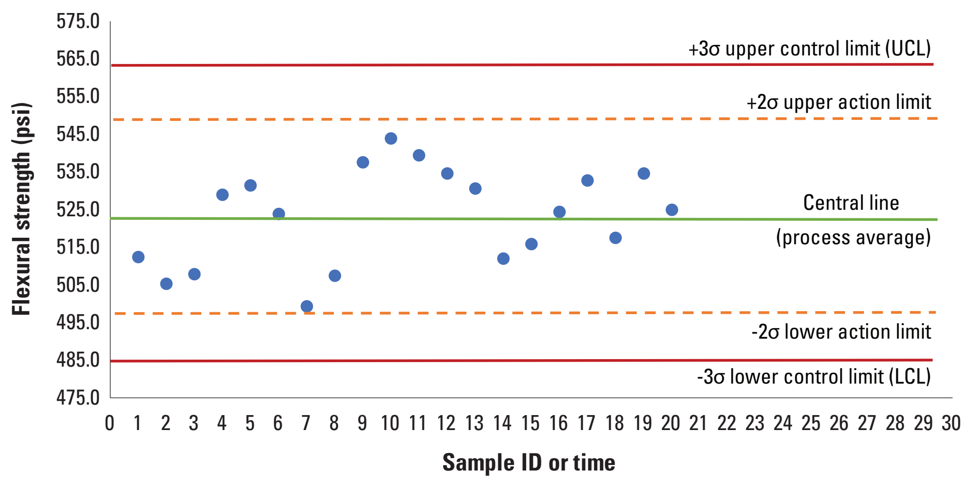

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Figure 6.9. Control chart for concrete flexural strength, with central line and control limits established using statistical methods

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 flexural strength of the 20 samples taken over time, 523.2 psi. The user decided that the control limits would be established at $\pm 3\sigma$ while the action limits would be established at $\pm 2\sigma$.

Using the standard deviation of the 20 measurements (12.8 psi), the upper and lower control limits were established at 562 psi and 485 psi, respectively. Flexural strength measurements greater than 562 psi or less than 485 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 549 and 498 psi, respectively. Measurements that trended above 549 psi or below 498 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 in Figure 6.9, 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 $\pm 3\sigma$ 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 (as shown in the example in Appendix E) 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.

Processes often become more stable over time. With experience and with efforts to address issues and implement improvements, there is a strong likelihood 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 6.10. 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 has time to make changes before the process trends in a direction that may exceed specification limits, upper and lower action limits were established at 0.5% within the specification limits, or at 7.0% and 5.0%, respectively.

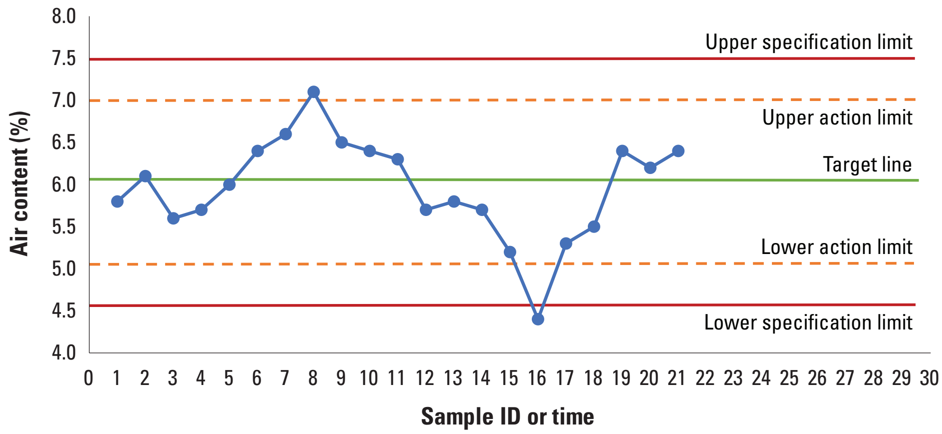

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Figure 6.10. Run chart for air content in fresh concrete, with control limits established using specification limits

In this example, the upper action limit was reached at Sample 8, and in response the AEA dosage was reduced slightly. As the process continued, the air content trended downwards 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 afterwards the air content trended towards a more stable reading by Samples 18 through 20.

Observing and Understanding Trends in Run Charts and Control Charts

To this point, this chapter has described the construction of run charts and control charts. To summarize, run charts represent a plot of data over time and are primarily useful for identifying trends (or runs) in the data and providing an early indication of a shift in a process. The central line is established based on a selected target value, and the limits are typically based on specification limits. Control charts use statistical methods to establish the center line and limits (preferably using a sample size greater than 1) and can differentiate whether data points are likely the result of chance cause or assignable cause and indicate whether a process is in or out of control. If variation in a process is the result of chance cause, the data points plotted on a control chart should fall at points evenly distributed above and below the statistically computed central line.

For both run charts and control charts, the data points for a process that is in control fall between the control limits and, hopefully, within the action limits. A process is considered to be in greater control if the data points tend to fall closer to the central or target line rather than further away.

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. If measurements exhibit concerning trends, such as several consecutive points trending upward or downward towards 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.

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 on a run chart or control chart as a measurement spike outside of the control limits.

Drift or other issue(s) 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 Figures 6.11 through 6.17 using unit weight as an example measurement. Note that in the previous example illustrating the use of specification targets to define the central line and limits on a run chart (Figure 6.10), seven points are decreasing prior to Sample 16 falling outside of the control limits. Using the rule of thumb listed above that states that assignable cause variability is likely present if six consecutive test results are increasing or decreasing, the user could have noticed the issue and potentially addressed it before concrete was produced that fell outside of the lower specification limit.

If run charts or control charts are developed using a spreadsheet, cells can be programmed (using conditional color formatting, IF statements that trigger pop-up alerts, or other means) to indicate to the user when trends suggesting assignable cause variability are present in the data.

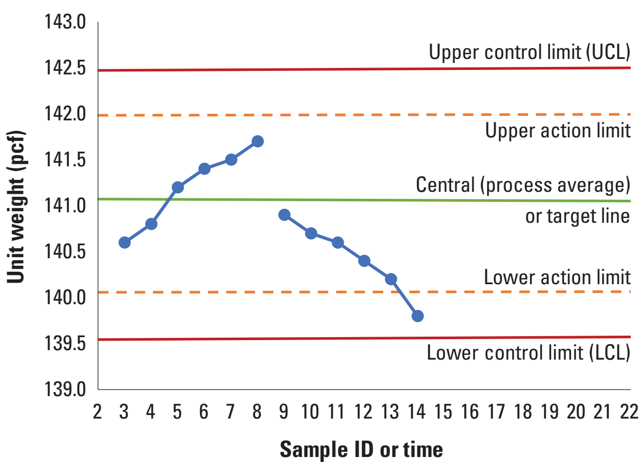

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Figure 6.11. Assignable cause variability suggested by six consecutive test results increasing or decreasing

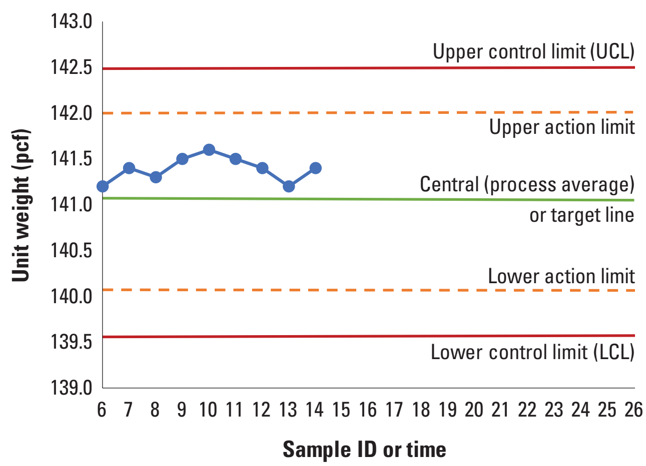

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Figure 6.12. Assignable cause variability suggested by nine consecutive test results on one side of the central line

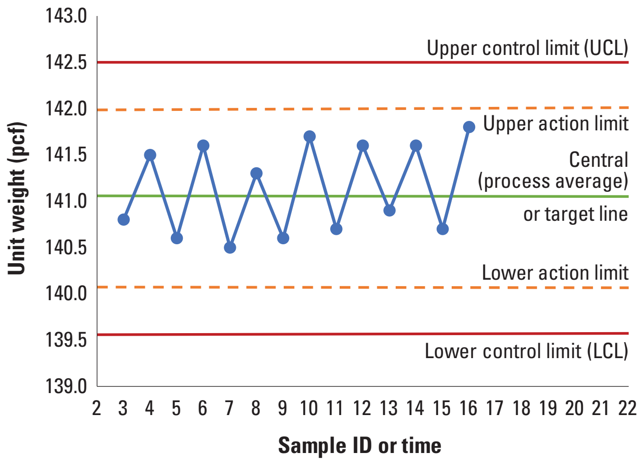

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Figure 6.13. Assignable cause variability suggested by 14 test results alternating above and below the central line (acting as two populations)

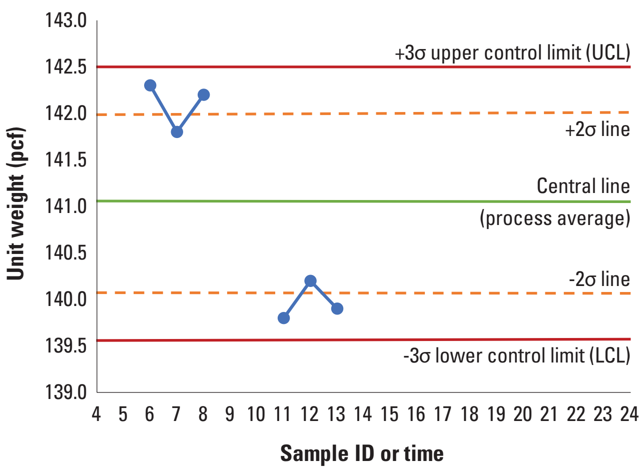

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Figure 6.14. Assignable cause variability suggested by two of three test results more than two standard deviations from the central line

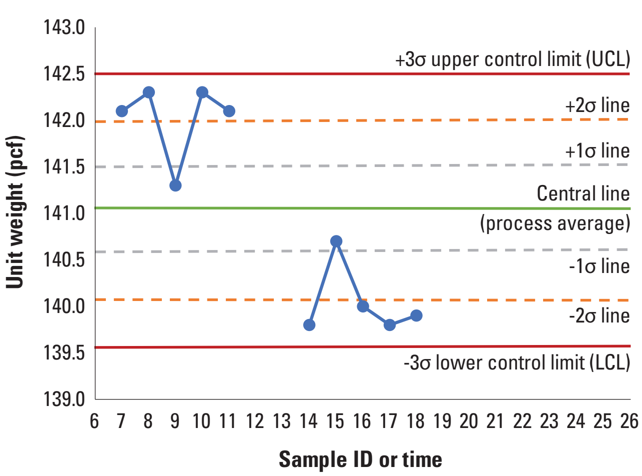

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Figure 6.15. Assignable cause variability suggested by four of five test results on the same side of the central line that are more than one standard deviation from the central line

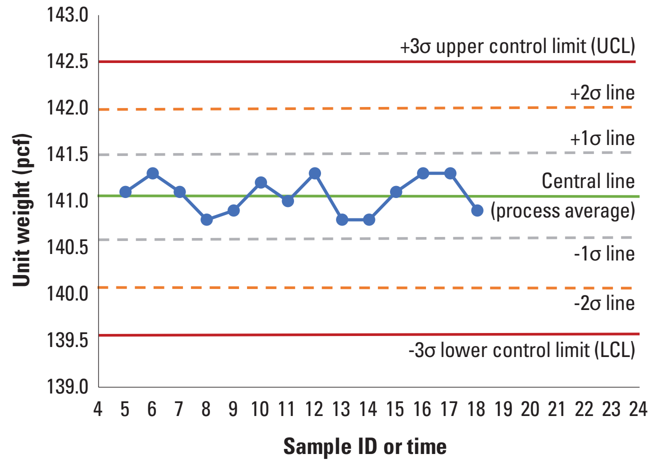

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Figure 6.16. Assignable cause variability suggested by 15 test results within one standard deviation from the central line

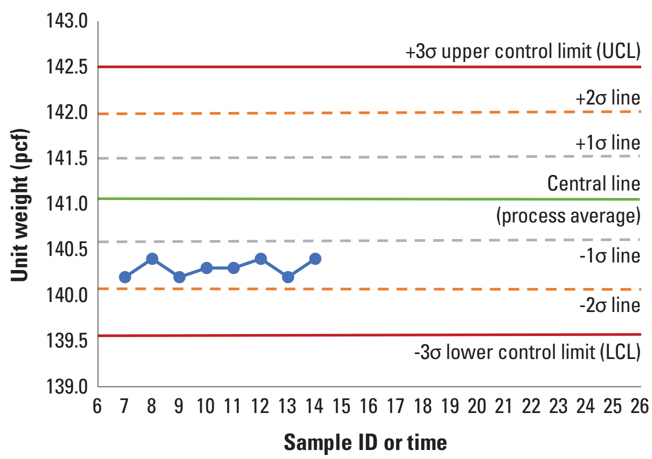

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Figure 6.17. Assignable cause variability suggested by eight consecutive test results more than one standard deviation from the central line

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 this section 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. This is illustrated in the run chart shown in Figure 6.18. Since these properties are inversely related, one axis can be inverted (or reversed) to show the relationship more directly, as demonstrated in Figure 6.19, where the secondary y-axis for unit weight has been inverted.

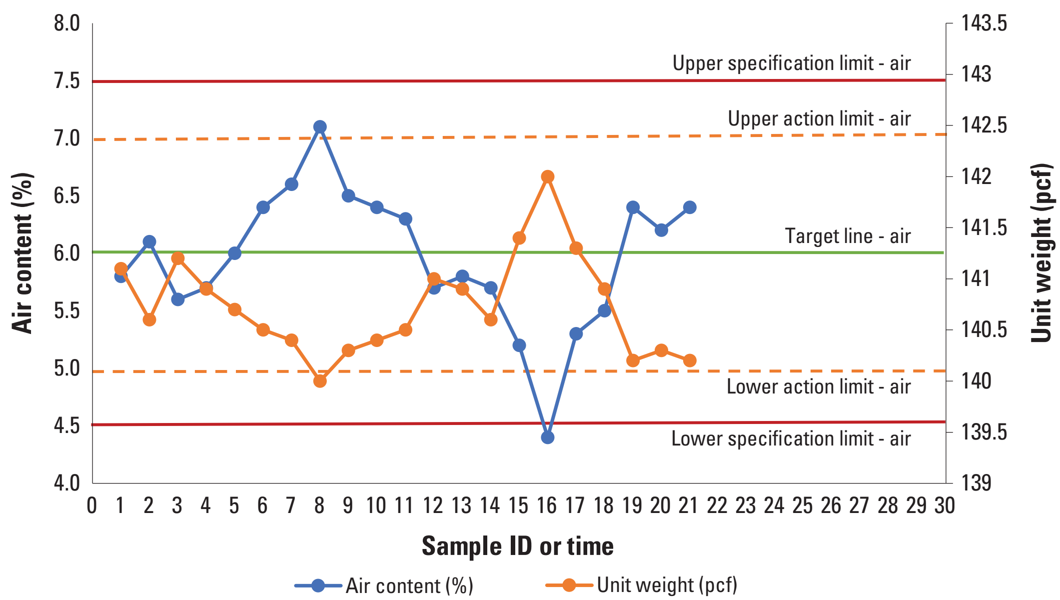

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Figure 6.18. Run chart for air content and unit weight

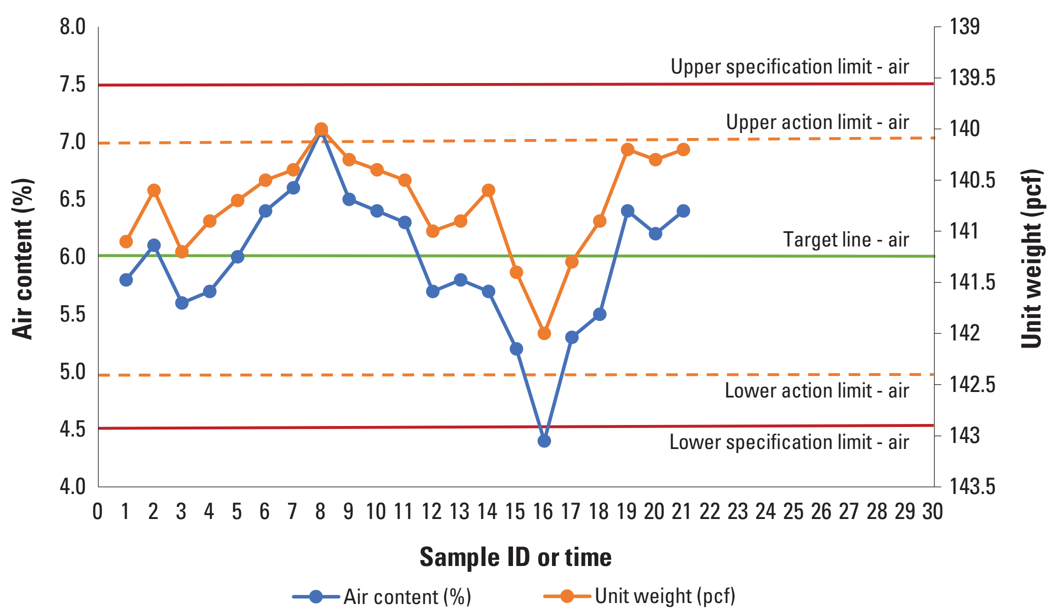

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Figure 6.19. Run chart for air content and unit weight, with secondary y-axis inverted

Different trends in the relationships 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.

In another approach to using the relationship between unit weight and air content to understand the performance of a mixture, a different type of plot than a run chart or control chart can be used to help identify undesirable variability. Using the mixture proportions and material properties of a given concrete mixture, the design unit weight of the concrete can be computed at a range of air contents, as shown in Table 6.2. Using this table, a graph can be prepared that shows the design (computed) unit weight at selected air contents (Figure 6.20).

Table 6.2. Design values of unit weight at selected design air contents

Design air content (%)	Design unit weight (pcf)
0.0%	153.7
2.0%	150.3
4.0%	147.0
6.0%	143.7
8.0%	140.4
10.0%	137.0

As the actual mixture is produced and QC measurements of air content and unit weight are obtained, the measured data can be tabulated and compared to the design values, as shown in Table 6.3, and plotted on the same graph as the design values, as demonstrated in Figure 6.20.

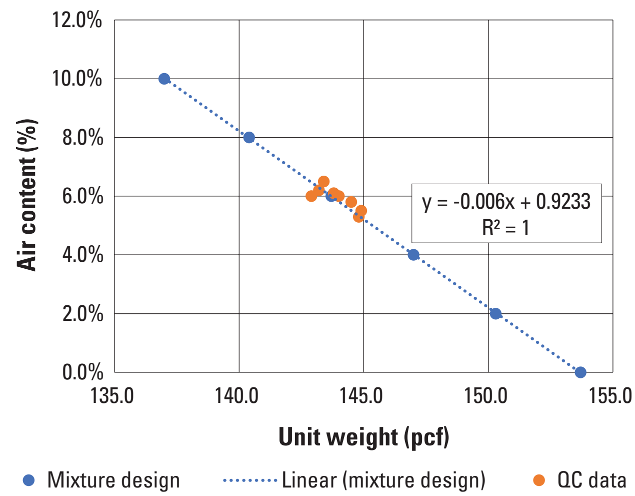

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Figure 6.20. Relationship between design air content and design unit weight and between design values and measured values

Table 6.3. Example comparison of measured and design values for unit weight and air content

Sample ID	Measured air content (%)	Measured unit weight (pcf)	Design unit weight (pcf)	Difference
1	5.5%	144.9	144.72	0.18
2	5.3%	144.8	145.05	-0.25
3	6.1%	143.8	143.72	0.08
4	6.2%	143.2	143.55	-0.35
5	5.8%	144.5	144.22	0.28
6	6.0%	142.9	143.88	-0.98
7	6.0%	144.0	143.88	0.12
8	6.5%	143.4	143.05	0.35

Measured values of air content and/or unit weight that fall unacceptably far from the computed relationship should raise concern. Values that fall below the relationship line in the graph are of particular concern because in those cases the measured unit weight is below what would be expected based upon the measured air content. If appropriate tolerances are considered, the absolute value of the difference between the measured and design values of air content and/or unit weight could be used to help establish action limits.

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 w/cm ratio and unit weight
- Compressive strength and surface resistivity (shown in the control chart in Figure 6.21)

As can be observed in Figure 6.21, the surface resistivity of the concrete mixture roughly follows the compressive strength, because as hydration occurs both strength gain and refinement of the microstructure occur, increasing electrical resistance.

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 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).

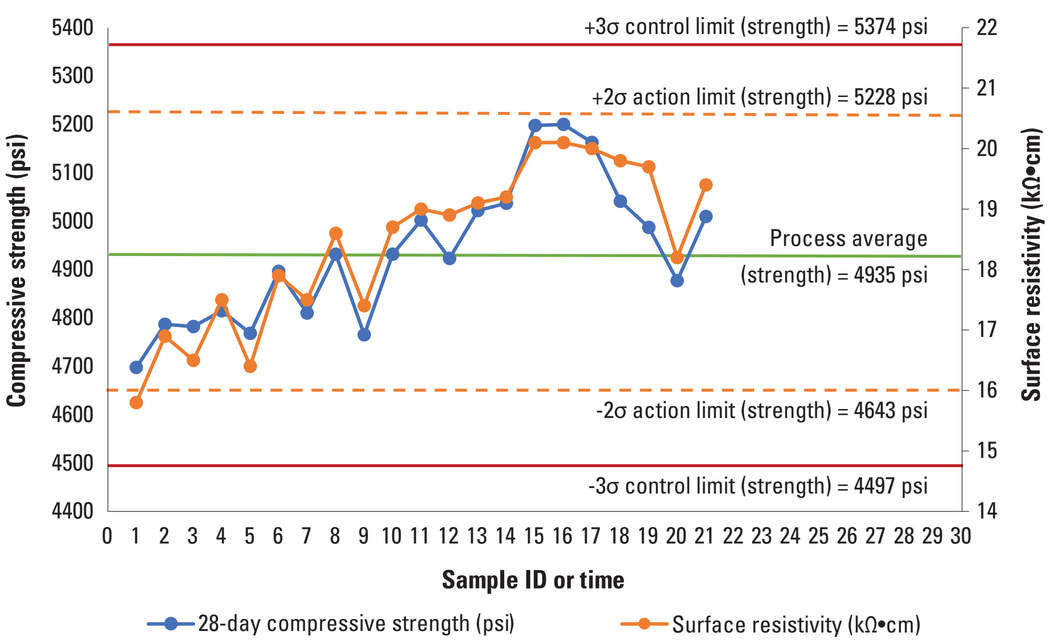

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Figure 6.21. Control chart for compressive strength and surface resistivity

Run charts and control charts also provide a clear, graphical means of displaying data and communicating issues to stakeholders other than QC personnel. Trends evident on these charts can easily 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.

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

Records Management

Almost all QC activities and processes produce records of some type, with each record having a certain useful service life. For records associated with a specific project, the useful service life may be for the duration of a project and perhaps for some period after the project is completed. Records associated with general quality management activities, such as calibration records or certifications, may have different useful service lives, perhaps until a certification expires or equipment is recalibrated. Once a record is no longer useful for an immediate or anticipated need, the record either retains enough importance to be archived or it is discarded.

The contractor should be aware of agency requirements for record retention, particularly for projects that have a warranty. The contractor should also be aware of agency requirements for record retention for materials suppliers, including those participating in an approved/prequalified supplier program.

Once agency requirements are known and contractor needs and preferences are considered, records management provisions should be developed and included in QC programs and plans. Provisions should include efficient means of creating, receiving, utilizing, and archiving records. Approaches to records management used by different entities differ greatly based upon the type of records managed, the recordkeeping infrastructure available, and contractor preferences. In general, the following should be considered when developing a records management policy:

1. Types of records obtained during typical operations and projects
2. Format of each type of record
3. Availability of physical and digital storage infrastructure for storing and archiving records during and after their useful service lives, respectively
4. Availability of manpower and time to support the use and storage of records
5. Schedule for retention of records
6. Means for adding useful information to databases or archives
7. Procedures for disposal of records
8. Processes for records management and the internal auditing of records

Records management policies, practices, and procedures should be supported by the manpower, technology, and time required to ensure that the necessary actions can be implemented regularly (Henshall 2019). Although allocating resources to records management may be viewed as burdensome, a well-functioning records management system pays dividends to a company in several ways. In addition to providing evidence that actions were performed, records can be used to answer questions such as "When was the last time this type of issue occurred?" or "How often has problem X been attributable to reason Y?" With records providing data-driven answers to these types of questions, opportunities for improvements can be identified, justified, and capitalized upon. In summary, appropriate records management practices allow a contractor to do the following:

- Retain an adequate archive of quality management initiatives and data
- Provide evidence to stakeholders that policies and procedures have been followed
- Utilize records to identify means for improvement

Chapter 7
Closing

Contractor QC is an integral part of an agency's QA program. A well-developed and implemented QC plan can assure an agency that a concrete paving project will meet specifications and provide a quality investment. From the contractor's standpoint, the implementation of a comprehensive QC program and the use of QC plans can improve profitability, lower risk, and ultimately support business growth.

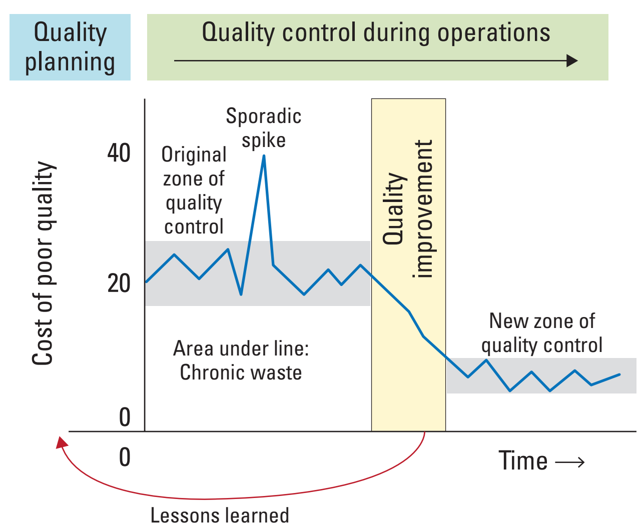
Agencies have various requirements for contractor QC during construction, but these requirements are only the minimum provisions that should be considered. Additional QC activities are almost always required to ensure that risk is mitigated and a quality pavement is constructed.

This document provides guidance on QC processes, measurements, and tools for various stages of concrete pavement construction. However, this guidance does not mandate that a contractor implement these activities in a certain way. The QC activities required to successfully complete each concrete paving project will differ, and each contractor approaches QC in a unique way.

A successful contractor QC program engages the appropriate personnel, manages the necessary processes, measures what matters, and uses the appropriate test methods. The types and sources of variability are understood, and the continuous improvement cycle is used to identify sources of variation and mitigate their impact on the expected quality of the product or work. Procedures are in place to investigate and address quality issues, and resources are directed toward improving process control. Accurate, adequate recordkeeping is performed, and the methods of documenting and presenting data allow various stakeholders to readily access and easily interpret information. Data are not just recorded but are used to monitor processes, inform changes in those processes, assist in agency acceptance activities, and provide insight into potential opportunities for process improvements. Communication is timely and used to support decision-making and action.

QC programs such as these achieve success over time through continuous improvement. The continuous improvement cycle relies upon identification of issues or potential improvements, actions to change a process, monitoring of the results, and assessment of the information gained. If performed continuously, this cycle can reduce the costs incurred by poor quality products or work (Figure 7.1) and enable contractors to allocate resources to other ventures and initiatives.

As agencies move towards performance specification provisions and PEMs in the coming decades, contractor QC plans will serve an increasingly valuable role in producing high-quality concrete. In any context, however, a QC plan with the appropriate provisions will support the construction of a quality product and benefit all stakeholders. The guidance presented in this document, along with the QC plan outline provided in Appendix C and the model QC plan provided in Appendix D, can help contractors develop or enhance their QC programs and establish effective QC plans.



Adapted from Juran 2017

Figure 7.1. Impact of continuous improvements in QC on costs

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Standards and Specifications

AASHTO

AASHTO M 6: Standard Specification for Fine Aggregate for Hydraulic Cement Concrete

AASHTO M 80: Standard Specification for Coarse Aggregate for Hydraulic Cement Concrete

AASHTO M 85: Standard Specification for Portland Cement

AASHTO M 145: Standard Specification for Classification of Soils and Soil–Aggregate Mixtures for Highway Construction Purposes

AASHTO M 157: Standard Specification for Ready-Mixed Concrete

AASHTO M 224: Standard Specification for Use of Protective Sealers for Portland Cement Concrete

AASHTO M 240: Standard Specification for Blended Hydraulic Cement

AASHTO M 295: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

AASHTO M 302: Standard Specification for Slag Cement for Use in Concrete and Mortars

AASHTO PP 84: Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures

AASHTO R 9: Acceptance Sampling Plans for Highway Construction

AASHTO R 10: Definition of Terms Related to Quality and Statistics as Used in Highway Construction

AASHTO R 80: Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction

AASHTO T 11: Standard Method of Test for Materials Finer Than 75 µm (No. 200) Sieve in Mineral Aggregates by Washing

AASHTO T 22: Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens

AASHTO T 27: Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates

AASHTO T 89: Standard Method of Test for Determining the Liquid Limit of Soils

AASHTO T 90: Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils

AASHTO T 96: Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

AASHTO T 97: Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

AASHTO T 99: Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5 kg (5.5 lb) Rammer and a 305 mm (12 in.) Drop

AASHTO T 119M/T 119: Standard Method of Test for Slump of Hydraulic Cement Concrete

AASHTO T 121M/T 121: Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

AASHTO T 152: Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method

AASHTO T 160: Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete

AASHTO T 161: Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing

AASHTO T 180: Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54 kg (10 lb) Rammer and a 457 mm (18 in.) Drop

AASHTO T 196M/T 196: Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method

AASHTO T 224: Standard Method of Test for Correction for Coarse Particles in the Soil Compaction Test

AASHTO T 255: Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying

AASHTO T 277: Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

AASHTO T 310: Standard Method of Test for In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)

AASHTO T 311: Standard Method of Test for Grain-Size Analysis of Granular Soil Materials

AASHTO T 318: Standard Method of Test for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying

AASHTO T 334: Standard Method of Test for Estimating the Cracking Tendency of Concrete

AASHTO T 336: Standard Method of Test for Coefficient of Thermal Expansion of Hydraulic Cement Concrete

AASHTO T 358: Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration

AASHTO T 363: Standard Method of Test for Evaluating Stress Development and Cracking Potential due to Restrained Volume Change Using a Dual Ring Test

AASHTO T 365: Standard Method of Test for Quantifying Calcium Oxychloride Formation Potential of Cementitious Pastes Exposed to Deicing Salts

AASHTO TP 118: Standard Method of Test for the Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method

AASHTO TP 119: Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test

AASHTO TP 129: Standard Method of Test for Vibrating Kelly Ball (VKelly) Penetration in Fresh Portland Cement Concrete

ASTM

ASTM C29: Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate

ASTM C33: Standard Specification for Concrete Aggregates

ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C78: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading

ASTM C94: Standard Specification for Ready Mixed-Concrete

ASTM C127: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate

ASTM C128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate

ASTM C136: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

ASTM C138: Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C143: Standard Test Method for Slump of Hydraulic-Cement Concrete

ASTM C150: Standard Specification for Portland Cement

ASTM C174: Standard Test Method for Measuring Thickness of Concrete Elements Using Drilled Concrete Cores

ASTM C183: Standard Practice for Sampling and the Amount of Testing of Hydraulic Cement

ASTM C231: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C311: Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete

ASTM C457: Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

ASTM C494: Standard Specification for Chemical Admixtures for Concrete

ASTM C566: Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying

ASTM C595: Standard Specification for Blended Hydraulic Cement

ASTM C618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM C917: Standard Test Method for Evaluation of Variability of Cement from a Single Source Based on Strength

ASTM C989: Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1064: Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete

ASTM C1074: Standard Practice for Estimating Concrete Strength by the Maturity Method

ASTM C1077: Standard Practice for Agencies Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Testing Agency Evaluation

ASTM C1157: Standard Performance Specification for Hydraulic Cement

ASTM C1202: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

ASTM C1585: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes

ASTM C1646: Standard Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete

ASTM C1753: Standard Practice for Evaluating Early Hydration of Hydraulic Cementitious Mixtures Using Thermal Measurements

ASTM C1810: Standard Guide for Comparing Performance of Concrete-Making Materials Using Mortar Mixtures

ASTM C1827: Standard Test Method for Determination of the Air-Entraining Admixture Demand of a Cementitious Mixture

ASTM D3665: Standard Practice for Random Sampling of Construction Materials

Appendix A

Review of Agency Quality Control Requirements

A review of agency specifications related to quality control (QC) was performed to support the development of this document. This appendix presents the typical QC plan requirements listed in agency specifications that were included in the review. Common requirements found in the reviewed materials are presented in standard, bold font, while less common requirements are shown in italics.

General Quality Control Requirements

- **Organizational relationships**
- **Personnel**
  - **Names and responsibilities (typically QC managers, QC technicians, batch plant operators, and others integral to implementing the QC plan)**
  - **Certification and training of personnel**
  - **Means of coordination between personnel**
- **Communication**
  - **Submittal procedures and required timeframes for submittal**
  - **Means for communicating QC information, including forms and check sheets**
  - **Processes for disseminating QC and corrective action information to appropriate parties, including personnel and timeframe requirements for actions**
  - **Processes for providing QC information to agency personnel**
- **Subcontractor evaluation and procurement control**
- **QC laboratory(ies)**
  - **Location(s)**
  - **Laboratory qualification(s) and/or accreditation information**
  - **Equipment calibration and condition inspection**
- **Concrete mixtures and component materials**
  - **Control of concrete mixture materials and QC testing**
  - **Concrete mixture design and QC testing**
- **Materials storage and batching/production of concrete**
  - **Location of handling, storage, and delivery of materials and equipment**
  - **Batch plants and material processing locations**
  - **Inspection and checks of equipment (initial and routine)**
  - **Process control testing and inspection activities, including test methods and inspection methods that the contractor intends to perform**
  - **Frequency of contractor testing and inspection**
- **Placement of concrete pavement**
  - **Preplacement checks**
  - **Control of placement equipment**
  - **Control of concrete placement**
  - **QC inspection and testing**
- **Documentation and documentation control**
  - **Information on recordkeeping and reporting (control charts, check sheets, spreadsheets/tables)**
  - *Means of ensuring availability of QC documentation to agency personnel*
  - *Requirements for contractor's daily report*
  - *Interim reports*
- *Corrective and/or preventative actions*
- *Procedures for nonconformance*
- *Dispute resolution and actions for testing discrepancies and nonconforming materials*
- *Internal quality audits*

Quality Control Requirements for Concrete Mixture Components

- **Material sources and information regarding their status in the agency's qualification program(s)**
- *Sampling techniques for components of concrete*
- **Aggregates**
  - **Specific gravity**
  - **Absorption**
  - **Gradation**
  - *Abrasion resistance*
  - *Percent passing No. 200 sieve*
  - *Fractured faces*
  - *Verification of non-alkali-reactive materials*
- **Cement and supplementary cementitious materials (SCMs)**
  - **Mill test reports**
  - **Material composition test results**
  - **Supplier material certification or other information to ensure material is an agency-approved product**
- **Admixtures and other materials used in concrete**
  - **Supplier material certification or other information to ensure material is an agency-approved product**
- *Water*
  - *Provisions for use of nonpotable water source*
- *Provisions for recycled concrete aggregates, including those produced on-site, produced near-site, or sourced from a local producer*
- *Other information relevant to QC testing of specific materials*
- *Disposition of unsatisfactory materials*

Quality Control Requirements for Concrete Mixtures

- **Concrete mixture design**
  - **Material sources and proportions**
  - **Prescriptive requirements, such as the following:**
    - **Minimum cement content**
    - **Water-to-cementitious materials (w/cm) ratio**
    - **SCM substitution rate(s)**
- **QC tests required for submittal and approval of mixture**
  - **Compressive strength**
  - **Flexural strength**
  - *Durability performance*

Quality Control Requirements for Batching and Testing of Concrete

- *Description of storage facilities for raw materials*
- *Stockpile management plan*
- **Production equipment**
  - **Description of production equipment**
  - **Control and inspection of concrete production equipment**
- **Batch plant requirements**
  - **Plant ID***, process control systems, loading control, loading and shipping controls*
  - *Measuring and weighing devices*
  - *Batching accuracy requirements*
- **QC testing laboratories**
  - **Description**
  - **QC laboratory qualification and accreditation**
- **Sampling techniques for fresh concrete**
- **Making and curing concrete test specimens**
  - *Handling, protection, initial curing, and transporting of strength test specimens*

- **QC tests for concrete mixture**
  - **Aggregate moisture contents**
  - **Verification of prescriptive requirements for mixture (w/cm ratio, cementitious materials contents)**
  - **Unit weight**
  - *Yield*
  - **Air content of fresh concrete**
  - *Air void system of fresh concrete*
  - **Temperature**
  - **Compressive strength**
  - **Flexural strength**
- **Allowable adjustments**
- *Control charts with action and suspension limits*
- *Corrective actions to address nonconformities (e.g., if moving average trendline approaches specification limits)*
- *Deficiency log and nonconformance reporting*
- *Disposition of nonconforming or failing material*
- *Contractor actions required to support agency QA testing and other verification activities*
- *Means to provide accessibility to allow inspections of locations and equipment supporting materials delivery, materials storage, sampling and testing, production*
- *Provisions for work in hot/cold/adverse weather*

Quality Control Requirements for Concrete Placement

- *Division of the pavement into lots, and division of lots into QC sublots*
- **Preplacement checks**
  - **Alignment and grade control (elevation, cross slope)**
  - **Stringline (if applicable)**
  - **Base (proof roll, moisture, trimming)**
  - **Reinforcement (placement, size)**
  - **Dowels (alignment, size, basket placement)**
  - *Provisions for anchoring dowel basket assemblies*
  - *Embedded items such as manholes, inlets, and other items*
- *Provisions for work in hot/cold/adverse weather*
- **Control and inspection of concrete equipment**
  - **Inspection of equipment**
    - **Paver**
    - **Paver vibrators (spacing, angle, vibration monitoring system)**
    - *Hand vibrators (condition and frequency)*
    - *Screeds*
    - *Finishing equipment*
    - *Hand finishing tools*
    - *Saws*
- **Control of concrete placement**
  - *Minimum rate of delivery*
  - **Depth checks**
  - **Finishing methods**
  - **Curing methods**
    - **Products used (brand/lot number)**
    - **Application rate**
  - *Protection of concrete in case of inclement weather*
  - *Provisions to stop placement for equipment breakdown, delay in operations, or nonconforming materials*
- **QC inspection and testing of pavement after placement**
  - **Texture**
  - **Smoothness**
  - **Ride quality**
- *Contractor actions required to support agency acceptance testing and other verification activities*
- *Means to provide accessibility to allow inspections of locations and equipment supporting materials delivery, materials storage, sampling and testing, production*
- *Methods to monitor construction equipment loading and strengths for opening to traffic*
  - *Maturity*
- *Use of HIPERPAV analysis for sawing time window*
- **Correction of nonconformances in constructed work**
  - *Provisions for crack repair*
  - *Joint filling*
    - *Products used (brand/lot number)*
  - *Requirements for coring for QC thickness measurement*

Appendix B
Example Quality Control Plan Provisions

This appendix presents example quality control (QC) plan provisions in a manner that demonstrates poor, fair, and good language and level of detail. This approach, which is adapted from a similar example presented in the *Federal Lands Highway Construction Manual* (FHWA 2009), illustrates the need for clear, concise language and an appropriate level of detail in specification provisions.

Aggregate Stockpile Management

- **Poor**: Aggregate stockpiles will be protected from runoff. Aggregates will be protected from the introduction of debris or other contaminants.
- **Fair**: Aggregate stockpiles will be protected from runoff using swales. Haul trucks will be unloaded adjacent to the stockpiles, and material will be placed on the stockpiles using other equipment. Contractor personnel will observe the stockpiles periodically to ensure contaminants have not been introduced to the material.
- **Good**: Aggregate stockpiles will be laid out in a manner that provides for adequate drainage away from the area. Swales and erosion control materials will be used to direct runoff as required. Prior to establishing stockpiles, the integrity of the subgrade soils will be verified and stabilized if necessary. Haul trucks used to bring aggregates to the site will be unloaded in a designated area adjacent to the stockpiles. Aggregates will then be transferred to the stockpile using a wheeled loader. Stockpiles will be maintained in a manner that minimizes segregation and prevents contaminant material from being introduced. Stockpiles will be visually inspected daily by the QC manager to ensure they are in good condition and to identify remedial actions, if necessary.

Testing of Concrete for Compressive Strength

- **Poor**: Compressive strength tests will be performed per the specification using a compression testing machine at the QC lab. Failing tests will be reported.
- **Fair**: Compressive strength tests will be performed per the project specification. The QC testing laboratory will use a calibrated testing machine. Failing tests will be reported to project management personnel and recorded in the daily log. Agency representatives will be notified if the moving average of five tests falls outside of specification limits.
- **Good**: Tests for concrete compressive strength will be performed per the agency sampling and testing guide and project specification. The testing machine will be calibrated within the previous 12 months, with the calibration certificate located on site at the QC laboratory. In the event of a failing test, QC technicians will notify the project manager or assistant project manager. Additional tests will be made to ensure that the result is valid. Failing tests will be recorded in the project testing log. If the moving average of three tests falls outside of the specification limits, a summary report will be emailed within two hours to the agency's regional testing laboratory as well as to the contractor QC director. Material producers will also be notified at the direction of the contractor QC director.

Preplaced Dowel Baskets

- **Poor**: Dowel bars will be placed prior to paving. The alignment will not deviate more than ⅛ in./ft.
- **Fair**: Dowel bars will be secured in place to ensure that they are in alignment per the project drawings and that the alignment error of the bars after paving does not exceed ⅛ in./ft in any direction.
- **Good**: Dowel bars will be placed across joints as shown on the project plan details. Dowels will be secured in place in a manner that will ensure that the error in alignment in both the vertical and horizontal directions does not exceed ⅛ in./ft after completion of the pavement placement.

Inspection of Underlying Materials before Paving

- **Poor**: Someone will verify that the base materials are in good condition prior to paving.
- **Fair**: The contractor will coordinate with the project manager from Alpha Testing Co. to ensure that a technician is scheduled to visit the site no more than 12 hours before paving to ensure that the underlying materials are in suitable condition for placement of concrete. The technician will verify that the underlying materials are the appropriate material, are free of contaminants, and are graded to meet project specifications.
- **Good**: The underlying materials will be checked for conformance with all specifications (materials, gradation, density, thickness, surface tolerances, etc.) and QC requirements (haul route stability, pad line stability and evenness, etc.) in sections as designated by the QC manager. Any deficiencies will be noted, corrected, and retested at least 36 hours before paving is scheduled. Once the underlying materials are approved by the QC manager, Alpha Testing Co. will be notified and asked to perform a final sign-off inspection at least 24 hours before paving is scheduled.

Concrete Placement and Consolidation

- **Poor**: Concrete will be deposited in front of the paver. It will be spread, vibrated, and finished.
- **Fair**: Concrete will be transported to the site using haul trucks that will place the concrete ahead of the paver. A belt placer in front of the paver will spread the concrete. The paver, which has an automated guidance system and computer-monitored vibrators, will finish the concrete.
- **Good**: Haul trucks will dump concrete onto a belt placer, which will convey the concrete to the approximate grade and strike it off at roughly the plan dimensions. A PaverCo 2500X paver will then finish the placed concrete using the pressure- and vibration-based extrusion process. Forward motion of the paver will be controlled automated guidance systems. Vibration will be accomplished using the series of hydraulic vibrators within the paver, which are controlled and monitored by an integrated computer monitoring system. Vibrators will not operate when the paver is not in motion.

Curing

- **Poor**: A curing compound will be applied to the pavement at the specified rate.
- **Fair**: A white-pigmented curing compound will be applied to the surface of the concrete at the appropriate time. The curing compound will be applied at the agency-specified rate using a texture/curing machine. The curing compound will be applied to smaller areas using hand-sprayers.
- **Good**: After finishing and texturing of the pavement, a white-pigmented curing compound approved by the agency will be applied to the concrete surface as soon as the surface water disappears and before any evaporation occurs. The curing compound will be applied by the PaverCo texture/cure machine at a rate that meets the agency's standards. As a quality control check, for mainline paving, containers of curing compound will be preplaced along the pavement spaced at a distance that supports use of a single container over a specified application surface. On shoulders and hand-placed areas of concrete, the curing compound will be applied using manual spray applicators or a tractor equipped with a spray bar at a rate that meets the agency's standards.

Appendix C

Quality Control Plan Outline

This appendix presents an outline of a quality control (QC) plan for concrete paving projects. The outline models the recommended structure for this type of document and provides a flexible framework that contractors can use to develop a new QC plan or enhance existing QC approaches.

Sections 1 and 2: General Quality Control Information and Applicable Specifications and Standards

Overview

Sections 1 and 2 are general in nature but should be tailored to each project in light of the applicable specifications and mixture design.

Outline for Sections 1 and 2

1. Quality Control Organization and Qualifications
    - 1.1. Narrative describing the contractor's approach to QC
    - 1.2. Organizational chart showing responsibility and authority
    - 1.3. Project-specific information
        - 1.3.1. Contact information for QC staff
        - 1.3.2. Plant location and contacts
    - 1.4. Subcontractor roles and responsibilities
    - 1.5. Communication protocols
        - 1.5.1. Submittal procedures
        - 1.5.2. Reporting QC data
        - 1.5.3. Recordkeeping protocols
    - 1.6. Summary of staff experience and certifications
    - 1.7. Listing of all QC resources
        - 1.7.1. Laboratories: Location, qualifications, and accreditations
        - 1.7.2. Laboratory equipment: Complete listing with serial numbers and latest calibrations and/or certifications
    - 1.8. Listing of all concrete paving equipment
        - 1.8.1. Plant
        - 1.8.2. Paving
2. Applicable Specifications and Standards
    - 2.1. Concrete material specifications
        - 2.1.1. Cementitious materials
        - 2.1.2. Aggregates
        - 2.1.3. Admixtures
        - 2.1.4. Mixing Water
        - 2.1.5. Other
    - 2.2. Concrete paving specifications
    - 2.3. Specified acceptance criteria
    - 2.4. Testing standards: AASHTO, ASTM, etc.
    - 2.5. Approved mixture design with supporting test data

Sections 3 through 6: Concrete Mixture Production and Concrete Paving Process

Overview

Sections 3 through 6, as outlined below, should provide detailed information for every step of the concrete mixture production and concrete paving process. These details should be developed based on the best practices documented in the appropriate chapters of *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019) and *Field Reference Manual for Quality Concrete Pavements* (Fick et al. 2012) or other appropriate and widely accepted industry standards.

Typical Content for Each Step

The typical content for each step outlined in Sections 3 through 6 should include the following:

- Narrative describing the construction process. In addition, photos and illustrations can be very effective at communicating and setting expectations of what the construction and QC processes will look like.
- QC measurements
    - Frequency
    - Locations
    - Action limits
    - Suspension limits

- Checklist items, including frequency and appropriate actions if deficiencies are noted
- Visual inspection items, including frequency and appropriate actions if deficiencies are noted
- Corrective actions for any item that is nonconforming to the QC plan

Example Content for Step 5.2.4

An example of the above approach for Finishing Concrete (5.2.4) is as follows.

5.2.4 Finishing Concrete

Narrative:
Immediately behind the slipform paver, a burlap drag will be attached to the paver to assist in filling surface voids in the pavement (Figure C.1). Before each day of paving begins, the burlap drag will be cleaned or replaced as needed. During paving, the burlap drag will be kept moist by spraying with a water hose from both sides of the paver. Crew members are trained and instructed to avoid spraying water on the pavement surface when rewetting the burlap drag.

Following the burlap drag will be hand finishers correcting bumps and dips in the fresh concrete surface. The hand finishing process will proceed as follows:

- A 16 ft float will be used to fill minor surface voids.
- A 20 ft straightedge will be advanced 10 to 16 ft between passes; at least 4 ft of the straightedge should be on either side of a doweled contraction joint.
- A 10 ft bump cutter will be used only when bumps and dips cannot be corrected with the 20 ft straightedge.

The Transtec Group, Inc., used with permission

Figure C.1. Burlap drag behind the paver

- Hand edging of the longitudinal joint will be performed where an adjacent lane or shoulder is to be placed.
- No additional water will be added to the surface of the pavement during the finishing process.

QC Measurements:
Inertial profiling of the finished pavement will be performed within 24 hours of paving. The resulting profiles will be analyzed using ProVAL, and a power spectral density (PSD) analysis will be performed to identify any dominant wavelengths that appear in the profiles. Finishing procedures and processes may be adjusted to correct any deficiencies identified by the profile analyses.

Checklist and Visual Inspection Items:
- Burlap is clean and making uniform contact across the width of the slab.
- Burlap is uniformly wet.
- Rewetting of the burlap is confined to the burlap and additional water is not being sprayed on the slab.
- Mechanical float is properly adjusted.
- Hand tools are true and clean.
- No additional water has been added during the finishing activities.

Corrective Actions:
- Areas found to be out of specification tolerance for smoothness will be diamond ground and retextured according to specifications.
- Any areas found to have had additional water added to the surface during the finishing process will be noted and subject to the following protocol:
  - The areas will be closely inspected for drying shrinkage cracking. Partial-depth cracks will be injected with an approved low-modulus epoxy per the manufacturer's recommendations
  - In situ surface resistivity will be compared to the surface resistivity of cylinder samples. If the surface resistivity in kohm•cm of the tested slab area is less than 80% of the average surface resistivity of cylinders from the same day's production, the affected area will be diamond ground to remove the affected surface up to ⅛ in., retextured per the applicable specification, and treated with an approved penetrating silane solution per the manufacturer's recommendations.

Outline for Sections 3 through 6

3. Prepaving Activities
    - 3.1. Subgrade: For each subitem, fully describe the approach for the construction of pavement foundation layers that conform to the specifications; **provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance.**
        - 3.1.1. Subgrade
            - 3.1.1.1. Support conditions
            - 3.1.1.2. Fine grading
        - 3.1.2. Subbase
            - 3.1.2.1. Support conditions
            - 3.1.2.2. Fine grading
4. Mixture Production: For each subitem, fully describe the approach for producing a uniform mixture that conforms to the specifications; **provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance.**
    - 4.1. Material sources
    - 4.2. QC plans from suppliers
    - 4.3. Aggregate stockpile management
        - 4.3.1. Stabilized foundation
        - 4.3.2. Segregation
        - 4.3.3. Moisture variability
    - 4.4. Plant calibration
    - 4.5. Mixture designs by phase and/or season
    - 4.6. Batching sequence
    - 4.7. Mixing time
    - 4.8. Verification of mixture proportions used by the batching control system
    - 4.9. Moisture compensation for free water in the aggregates
    - 4.10. Transportation of concrete
        - 4.10.1. Haul route maintenance
        - 4.10.2. Cleanout of hauling units
5. Concrete Paving: For each subitem, fully describe the approach for the construction of concrete pavement that conforms to the specifications; **provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance.**
    - 5.1. Paving schedule
    - 5.2. QC plans from subcontractors
    - 5.3. Fixed-form placement
        - 5.3.1. Form alignment and elevation
        - 5.3.2. Steel placement
        - 5.3.3. Spreading of concrete
        - 5.3.4. Consolidation
        - 5.3.5. Strike-off
        - 5.3.6. Finishing
        - 5.3.7. Texturing
        - 5.3.8. Curing
        - 5.3.9. Form removal
        - 5.3.10. Sawing of joints
            - 5.3.10.1. Timing
            - 5.3.10.2. Use of HIPERPAV to quantify risk of early-age cracking, if applicable
        - 5.3.11. Sealing of joints
        - 5.3.12. Backfilling of pavement edges
        - 5.3.13. Opening to construction traffic
        - 5.3.14. Opening to public traffic

5.4. Slipform placement

5.4.1. Steel placement

5.4.1.1. Preplaced dowel baskets and tie bars

5.4.1.2. Location
5.4.1.2.1. Spacing
5.4.1.2.2. Anchoring
5.4.1.2.3. Alignment

5.4.1.3. Preplaced continuous reinforcement
5.4.1.3.1. Spacing
5.4.1.3.2. Anchoring
5.4.1.3.3. Laps

5.4.2. Spreading of concrete

5.4.3. Strike-off and consolidation

5.4.3.1. Machine control method
5.4.3.1.1. Stringline
5.4.3.1.2. 3D

5.4.3.2. Controlling of the head of concrete in the grout box

5.4.3.3. Tamper bar, if used

5.4.3.4. Vibrators
5.4.3.4.1. Size
5.4.3.4.2. Rating
5.4.3.4.3. Spacing
5.4.3.4.4. Height and orientation
5.4.3.4.5. Real-time monitoring

5.4.3.5. Inserted steel
5.4.3.5.1. Contraction joint tie bars
5.4.3.5.2. Construction joint tie bars
5.4.3.5.3. Load transfer dowels

5.4.4. Finishing

5.4.4.1. Burlap or turf drag

5.4.4.2. Machine finishing

5.4.4.3. Hand finishing

5.4.5. Texturing

5.4.5.1. Drag texture

5.4.5.2. Tined texture

5.4.6. Curing

5.4.6.1. Timing

5.4.6.2. Application rate

5.4.7. Sawing of joints

5.4.7.1. Timing

5.4.7.2. Use of HIPERPAV to quantify risk of early-age cracking, if applicable

5.4.8. Smoothness measurements

5.4.8.1. Timing

5.4.8.2. Feedback loop to the paving crew

5.4.9. Sealing of joints

5.4.10. Backfilling of pavement edges

5.4.11. Opening to construction traffic

5.4.12. Opening to public traffic

6. Weather Adjustments: Fully describe all precautions and adjustments that will be made for daily and seasonal changes in weather.

6.1. Hot weather concreting

6.2. Cold weather concreting

6.3. Imminent rain

6.4. Evaporation rates above 0.2 lb/yd^2/hr

Appendix D
Model Quality Control Plan

The model quality control (QC) plan presented in this appendix is heavily based on the Typical Model Quality Control Plan prepared by the NorthEast Transportation Training and Certification Program (NETTCP) (NETTCP 2009). The model QC plan prepared by NETTCP is available at https://www.nettcp.com/ and is organized based on NETTCP's recommended standard format of 10 sections plus appendices. The NETTCP model QC plan provides an example of a complete earthwork QC plan for a fictitious transportation project.

The model QC plan presented in this appendix uses a section format similar to that recommended by NETTCP, though the content has been adapted for use in this guide. The body of the plan has been partially completed for a fictitious concrete paving project.

The information in this model QC plan is provided only as guidance and will need to be modified to suit the needs of a given project, the requirements of the agency, and the preferences of the contractor.

A section format similar to that recommended by NETTCP is shown below. Other formats may be recommended or required by agencies, and contractors should adapt their QC plans accordingly.

- Terms and Definitions (optional)
- Scope and Applicable Specifications
- Quality Control Organization
- Quality Control Laboratories
- Materials Control
- Quality Control Sampling and Testing
- Production Facilities
- Field Operations
- Appendices

In the model QC plan presented on the following pages, notes marked with an asterisk (*) and set in blue type indicate where information should be added or the existing information should be modified to meet agency requirements and to accommodate contractor preferences. Other text can also be modified as appropriate.

PCC Paving Company, Inc.

Construction Quality Control Plan

Division 2 – Earthwork
Division 7 – Concrete Pavements and Shoulders
Division 10 – Materials

Interstate 42
Cementitious City, USA

State Highway Agency Contract No. SHA 987-654-321

September 21, 2020

Submitted by:	PCC Construction Company, Inc.	Date
Approved by:	State Highway Agency	Date

Purpose

This Quality Control Plan (QC Plan) provides information on the resources, processes, and procedures that will be used by PCC Paving Company, Inc. (PCC Paving Company) to control the quality of the concrete materials produced and concrete pavement constructed as part of the Interstate 42 project in Cementitious City, USA, State Highway Contract No. SHA 987-654-321, and to ensure that the work is completed in accordance with the project plans, specifications, and project special provisions.

Terms and Definitions

The following terms and definitions are utilized in this QC Plan.

* Provide terms and definitions that are useful in understanding and utilizing this QC plan, as appropriate.

1.0 Scope and Applicable Specifications

Specifications and other relevant documents for concrete paving are listed below.

1.1 Standard Specifications

* Add standard specifications, as appropriate.

This QC Plan applies to all work covered by the following sections of State Transportation Agency Standard Specifications for Highways and Bridges, 2018 edition:

- Division 2 – Earthwork
- Division 7 – Concrete Pavements and Shoulders
- Division 10 – Materials
  - Subsection 1000 – Portland Cement Concrete Production and Delivery
  - Subsection 1005 – Aggregates
  - Subsection 1006 – Aggregate QC and QA
  - Subsection 1024 – Materials for Portland Cement Concrete
  - Subsection 1026 – Curing Compound

1.2 Supplemental Specifications

* Add supplemental specifications, as appropriate.

State Transportation Agency Supplemental Specifications:

- Division 3, Section W (dated June 3, 2015)
- Division 7, Section X (dated April 13, 2017)
- Division 10, Section Y (dated May 17, 2019)
- Division 10, Section Z (dated October 3, 2018)

1.3 Project Special Provisions

* Add project special provisions, as appropriate.

Project Special Provisions applicable to this work include:

- PSP 8.1 – Removal of Existing Ramp (dated May 12, 2020)
- PSP 8.2 – Excavation of Unsuitable Fill (dated June 30, 2020)
- PSP 8.3 – Internally Cured Concrete Pavement Trial Section (dated August 19, 2020)

1.4 Project Drawings

* Modify description as appropriate and include project drawings in an appendix.

A current listing and set of project drawings for all applicable Work addressed by this QC Plan will be maintained by PCC Paving Company. The "Project Drawings List" will be updated and submitted monthly to the State Transportation Agency in electronic format. An example copy of the "Project Drawings List – Section 1: Concrete Pavement" is contained in Appendix A.

1.5 Standard Drawings

* Modify as appropriate to reference standard drawings applicable to the project.

All Standard Drawings related to Concrete Pavements and Shoulders contained in the Transportation Agency Construction Standard Details (2015) are applicable to Work addressed by this QC Plan.

2.0 Quality Control Organization

* Add narrative describing the contractor's approach to QC.

The personnel and their corresponding responsibilities for all Quality Control activities are as indicated above.

* Insert organizational chart (below) as appropriate.

2.1 QC Plan Manager

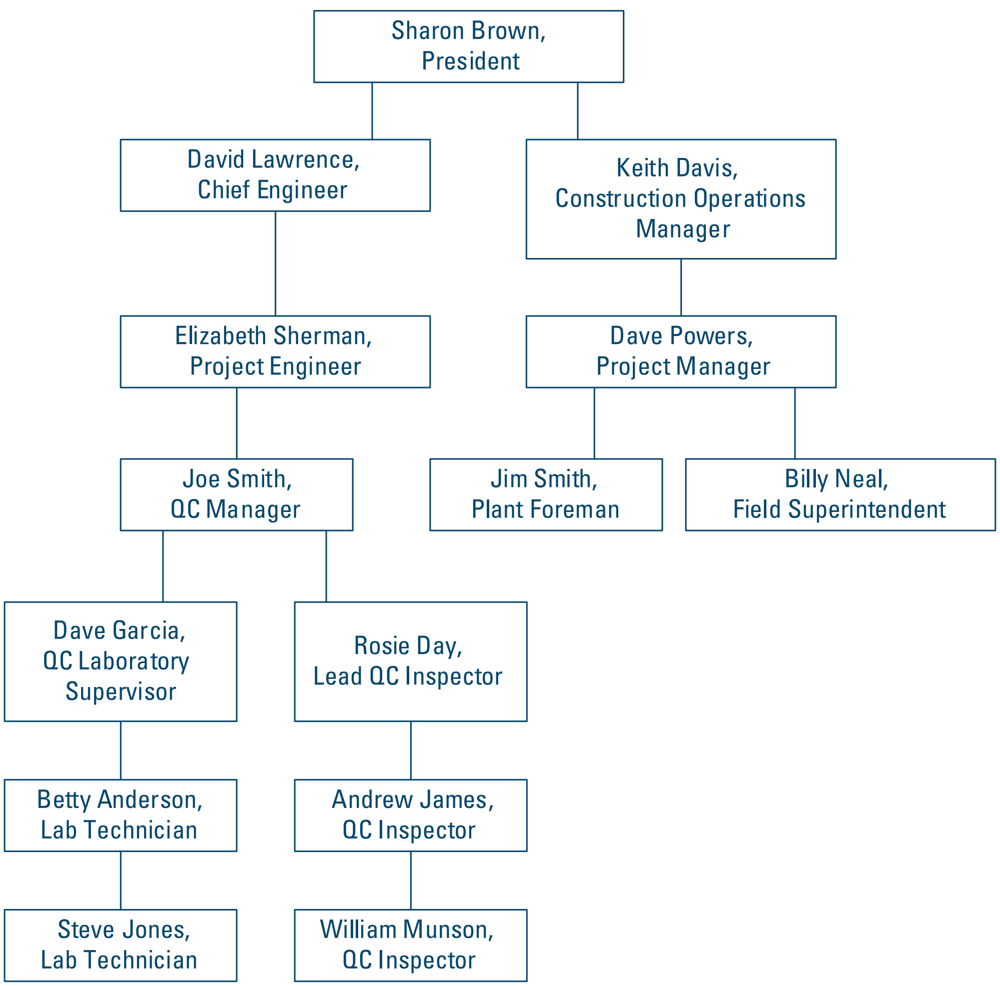
The QC Plan Manager is Mr. Joe Smith, P.E. He is employed by PCC Paving Company and is located at the PCC Paving Company Interstate 42 Project Office in Cementitious City, USA. Mr. Smith can be contacted through the following means:

- Office phone: 456-789-1234
- Cell phone: 456-123-6789
- Email: joe.smith@pccpaving.com

The QC Plan Manager has the responsibility and authority for the following items:

* Modify list and description of responsibilities as appropriate.

- Development and submission of this QC Plan for State Transportation Agency approval
- Overall coordination of personnel performing QC inspection, sampling, and testing at all off-site production facilities, QC laboratories, and on-site field operations.
- Approval of material sources prior to the start of any related work addressed by this QC Plan.
- Verification that producers have required certifications and qualified personnel and laboratories.
- Complete adherence to all QC requirements and activities contained in this QC Plan.



- Initiation of work suspension and determination of appropriate corrective action when testing or inspection identifies nonconforming materials or construction as outlined under Section 6.5 and Section 7.9 of this plan.
- Review and evaluation of all QC documentation for content and completeness.
- Maintenance of the "QC Record System – Concrete Pavement and Shoulders" in accordance with Section 5.5 of this plan.
- Preparation and submission of a "Weekly QC Summary Report" to State Transportation Agency within 7 calendar days following the reporting period.

2.2 Qualified Off-Site Production Facility QC Personnel

Personnel assigned to perform off-site production facility QC sampling, testing, and inspection of materials will be as indicated in the table below. A current listing of qualified off-site production facility QC personnel will be included in the "Weekly QC Summary Report."

* Modify table as appropriate.

Off-site production QC activities by PCC Paving Company will be scheduled as necessary. Where suppliers possess their own qualified QC personnel and laboratories, the results of the supplier's QC inspection and testing may be used by PCC Paving Company.

Project segment	QC position	Company	Qualifications
1, 2, 3	QC Manager	Rocky Aggregate Company	STA Certification, Grade 1
1, 2, 3	QC Manager	Ready-Mix Concrete Company	ACI Field Technician, Grade 1
1, 2, 3	QC Manager	Rock Solid Cement	ACI Field Technician, Grade 1
1, 2, 3	QC Manager	Mid-Central Fly Ash Supply	Not currently certified

2.3 Qualified QC Laboratory Personnel

Personnel assigned to perform QC laboratory sampling and testing of concrete pavement and shoulder materials are identified in the table below. A current listing of qualified QC laboratory personnel will be included in the "Weekly QC Summary Report."

* Modify table as appropriate.

QC laboratory personnel have responsibility and authority for the following items:

* Modify list and description of responsibilities as appropriate.

- Sampling of concrete and materials used to produce concrete.
- Laboratory testing of concrete and materials used to produce concrete.
- Preparation and signing of standard Test Report Forms (TRFs) for each test completed.
- Proper curing and storing of all concrete material samples and test specimens.
- Identification of concrete and concrete-making materials test results that do not conform with the requirements of the relevant specifications and this QC Plan and discussion of appropriate corrective action(s) with the QC Manager.

Project segment	QC position	Personnel, company	Qualifications
1, 2, 3	QC Laboratory Supervisor	Dave Garcia, PCC Paving Company	NRMCA Concrete Technologist, Level 3 ACI Lab Testing Technician, Level 1 ACI Field Technician, Grade 1
1, 2, 3	Laboratory Technician	Betty Anderson, PCC Paving Company	ACI Lab Testing Technician, Level 1 ACI Field Technician, Grade 1
1, 2, 3	Laboratory Technician	Steve Jones, PCC Paving Company	ACI Lab Testing Technician, Level 1 ACI Field Technician, Grade 1

2.4 Qualified On-Site Field QC Personnel

Personnel assigned to perform on-site field QC sampling, testing, and inspection of concrete pavement and shoulder materials are identified in the table below. A current listing of qualified on-site field QC personnel will be included in the "Weekly QC Summary Report."

* Modify table as appropriate.

On-site field QC personnel have responsibility and authority for the following items:

* Modify list and description of responsibilities as appropriate.

- Obtaining of random field samples of materials used for subgrade and base for laboratory testing.
- Performance of in-place sampling and testing of concrete pavement, subgrade, and base.
- Preparation and signing of Standard Test Report Forms (TRFs) for each test completed.
- Inspection of on-site paving work and related field construction items.
- Identification of on-site field placement practices or materials that do not conform with the requirements of the relevant specifications and this QC Plan and discussion of appropriate corrective action(s) with the Project Superintendent and the QC Manager.
- Suspension of the concrete paving operations when materials are not in conformance with the relevant specification requirements or when corrective actions have been determined necessary but have not been implemented.

2.5 Communication Protocols

* Add communication protocols for the following:

- Submittals
- Reporting QC data
- Recordkeeping

* Details should be provided for the distribution of each type of communication/report. The distribution list should typically include contractor personnel, agency personnel, suppliers, and others as appropriate.

Project segment	QC position	Personnel, company	Qualifications
1, 2, 3	Lead QC Inspector	Rosie Day, PCC Paving Company	STA Certification, Grade 1 ACI Field Technician, Grade 1
1, 2, 3	QC Inspector	Andrew James, PCC Paving Company	ACI Field Technician, Grade 1
1, 2, 3	QC Inspector	William Munson, PCC Paving Company	Not currently certified

3.0 Quality Control Laboratories

The QC laboratories to be used for all concrete paving materials and their corresponding testing responsibilities are as indicated below.

3.1 Qualified Primary QC Laboratory

The Primary QC Laboratory responsible for performing sampling and testing of concrete and concrete-making materials is identified in the table below.

* Modify table as appropriate.

The PCC Paving Company Interstate 42 Project Laboratory is responsible for performing testing of all concrete and concrete-making materials, as well as samples of the constructed pavement. The following tests will be performed on concrete and concrete-making materials by this laboratory:

* Modify list as appropriate.

- Aggregate gradation: ASTM C136 /AASHTO T 27, ASTM C566 / AASHTO T 255
- Combined gradation: Tarantula curve
- Aggregate moisture content: ASTM C29
- Slump: ASTM C143 / AASHTO T 119M/T 119
- Segregation: Visual observations
- SAM: AASHTO TP 118
- Unit weight: ASTM C138 / AASHTO T 121M/T 121
- Compressive or flexural strength: ASTM C39 / AASHTO T 22 and/or ASTM C78 / AASHTO T 97
- Resistivity/F-factor: AASHTO PP 84
- Hydration: Semi-adiabatic calorimetry
- Maturity: ASTM C1074

Equipment utilized for these tests is as follows:

* Add description of laboratory equipment, including a complete listing with serial numbers and latest calibrations and/or certifications.

* Describe equipment calibration process and recordkeeping.

Project segment	Laboratory	Location	Qualifications
1, 2, 3	PCC Paving Company Interstate 42 Project Laboratory	Cementitious City, USA	STA Certification Program

3.2 Qualified Subcontractor or Consultant Laboratories

Other qualified Subcontractor or Consultant laboratories that will perform QC sampling and testing of concrete and concrete-making materials are identified in the table below.

* Modify table as appropriate.

* Include information on subcontractor or consultant laboratories as appropriate.

The ABC Testing Company in Earthwork, USA, will serve as a backup to assist the Primary QC Laboratory in performing testing of all concrete and concrete-making materials, as well as any base and subgrade materials as required. The following tests may be performed by this laboratory:

* Modify list as appropriate.

- Soil classification: AASHTO M 145
- Gradation: AASHTO T 11 and T 27
- Liquid limit: AASHTO T 89
- Plastic limit/plasticity index: AASHTO T 90
- Maximum wear (LA Abrasion): AASHTO T 96
- Optimum moisture content: AASHTO T 99 and AASHTO T 180
- Maximum dry density: AASHTO T 99 and AASHTO T 180
- Coarse particles correction: AASHTO T 224
- Grain-size analysis: AASHTO T 311

Project segment	Laboratory	Location	Qualifications
1, 2, 3	ABC Testing Company	Earthwork, USA	AASHTO Accreditation Program: Soils (6/15/2020), Concrete (7/1/2020)

4.0 Materials Control

4.1 Materials Suppliers

The following materials suppliers will be providing materials for the concrete pavement. All materials suppliers will be responsible for testing and inspection to verify that materials meet the appropriate specifications prior to delivery to the project.

* Modify table below as appropriate.

4.2 Applicable Specifications and Standards

* Describe specifications and standards applicable to each material. Provide information detailing how materials will meet each specification and standard either at the producer/supplier or upon delivery to the project site.

4.3 Plant Layout and Materials Delivery/Storage

* Describe plant layout, including delivery/haul routes, drainage provisions, storage areas, and storage facilities.

4.3.1. Cementitious Materials

* Provide information on delivery and storage of cementitious materials.

4.3.2. Aggregates

* Provide information on delivery and storage of aggregates. Provide details on stockpile management and means to protect stockpiles from contamination. Describe the stabilized foundation used beneath stockpiles and how moisture variability will be controlled. Also describe plant loading procedures.

4.3.3. Admixtures

* Provide information on delivery and storage of admixtures.

4.3.4. Mixing Water

* Provide information on source of water used for mixing concrete. If ice is to be utilized, describe source and storage.

4.3.5. Other

* Provide information on delivery and storage of any other materials used for mixing concrete.

4.4 Specified Acceptance Criteria

* Provide information detailing how materials will be accepted upon delivery to the project site.

Material	Type/Brand	Supplier	Source
Cement	Type I/II	Rock Solid Cement	Limestone, USA
Fly ash	Class F	Mid-Central Fly Ash Supply	Bituminous, USA
Coarse/intermediate aggregate	No. 57/No. 89	Rocky Aggregate Company	Metamorphic, USA
Fine aggregate	C33 natural sand	Sandy Banks Company	Siliceous, USA
Admixtures	AEA/Bubbleair 9000, mid-range water reducer/Slumpy 750	Chemical Admixture Company	Synthetic, USA

4.5. Approved Mixture Designs with Supporting Data

* Describe approach to mixture design and proportioning. Provide information regarding specific requirements addressed during the mixture design and proportioning process (e.g., optimized aggregate gradations, use of supplementary cementitious materials).

Mixture designs for this project were developed using mixture designs previously utilized for State Transportation Agency projects. Each of these mixture designs meets or exceeds the requirements of the 2018 State Transportation Agency Standard Specifications.

* Modify mixture types and tables as appropriate.

* Provide a description of the process to be utilized for review and approval of new mixtures for the project.

Proposed mixture design for 100% cement mixture

Material	Batch weight (lb/yd^3)
Coarse aggregate	
Intermediate aggregate	
Fine aggregate	
Cement	
Water	

Proposed mixture design for mixture containing fly ash

Material	Batch weight (lb/yd^3)
Coarse aggregate	
Intermediate aggregate	
Fine aggregate	
Cement	
Fly ash	
Water	

5.0 Quality Control Sampling and Testing

The requirements and procedures to be used for QC sampling and testing of concrete, materials used to produce concrete, and concrete pavement are shown below.

5.1 Lot and Sublot Sizes

Each Lot of material will represent material from the same source, be produced or obtained under the same controlled process, and will possess normally distributed specification properties. Each Lot will be divided into Sublots of equal size in order to assess the quality characteristics of the Lot. The Lot size and corresponding Sublot size for each item is identified in the table below.

* Modify table to include items, materials, lot sizes, and sublot sizes as appropriate.

5.2 Random Sampling Plan

* Modify description of random sampling plan as appropriate. Provide documents related to random sampling in an appendix.

PCC Paving Company will establish a random sampling plan for QC sampling and testing for each Lot of material prior to placement of the Lot. All samples will be obtained randomly in accordance with ASTM D3665. The random sample location for each Sublot will be determined by station, offset, and depth within the Sublot.

All random sample locations will be documented on standard test report form D3665. A copy of the random sampling forms is located in Appendix B. PCC Paving Company will provide the State Transportation Agency a copy of the random sampling locations (a completed form D3665) for each placement during the start of the placement each day.

5.3 Sample Identification System

* Modify sample identification system as appropriate.

All material samples will be clearly identified as follows:

- Project segment (1, 2, 3)
- Material type
- Sample type (i.e., QC, informational test, etc.) and random/nonrandom
- Lot number and Sublot number
- Sample location (i.e., Exit 4A ramp, northbound shoulder, etc.)
- Station, offset, and depth
- Sample date
- Technician or inspector

Item	Material type(s)	Lot size	Sublot size
Aggregates	Coarse aggregate	300 yd^3	60 yd^3
	Intermediate aggregate	300 yd^3	60 yd^3
	Fine aggregate	300 yd^3	60 yd^3
Concrete	Fresh concrete	5,000 yd^2	1,000 yd^2
	Hardened concrete	300 yd^3	See testing table on page 128
	Concrete pavement	5,000 yd^2	1,000 yd^2

5.4 QC Sampling and Testing Requirements

The specific requirements (quality characteristics, frequency, location, methods) for QC sampling and testing of each item are outlined in the subsections and table below.

* Modify the subsections below to reflect the materials covered by the QC program and the sampling and testing requirements as appropriate.

5.4.1 Subgrade Soils

* Add information on quality characteristics, test methods, lot sizes, sublot sizes, test frequencies, points of sampling, and sampling methods as appropriate.

5.4.2 Stabilized Base

* Add information on quality characteristics, test methods, lot sizes, sublot sizes, test frequencies, points of sampling, and sampling methods as appropriate.

5.4.3 Aggregates

* Add information on quality characteristics, test methods, lot sizes, sublot sizes, test frequencies, points of sampling, and sampling methods as appropriate.

Material	Test/Test method	Lot size	No. of sublots	Testing frequency	Sampling location	Sampling method	Report type

5.4.4 Concrete

* Add information on quality characteristics, test methods, lot sizes, sublot sizes, test frequencies, points of sampling, and sampling methods as appropriate. **The table below is shown as an example only and should not be used for any other purpose than developing a project-specific schedule of testing to be incorporated into a QC plan.** Sampling and testing frequencies should be appropriate for the type of work being performed. In developing a QC plan for each project, the contractor should consider factors such as agency requirements, project size, project duration, and staging (among other factors) and adjust the QC plan accordingly.

* Add information on field curing, handling, protection, and testing facilities for QC and QA specimens. Describe storage, temperature control, moisture control, security provisions, and transport methods.

* Add information on curing conditions at the laboratory.

Material	Test/Test method	Lot size	No. of sublots	Testing frequency	Sampling location	Sampling method	Report type
Coarse and fine aggregates	• Gradation: ASTM C136	5,000 yd^2	5	1 per sublot and/or minimum 1 per day	Stockpile	Random, per agency specification	Tabular and graphical: percent retained, Tarantula curve
Fresh concrete	• Air content: ASTM C231	5,000 yd^2	5	First 3 loads per day and repeat for 3 loads whenever admixture dosages are adjusted	Plant, grade, and behind paver	Biased, start of day	Tabular and control chart
	• SAM: AASHTO T 152 • VKelly: AASHTO TP 129	N/A	5	First 3 loads per day and repeat for 3 loads whenever admixture dosages are adjusted	Plant	Biased, start of day	Tabular and control chart
Fresh concrete at grade	• Temperature: ASTM C1064 • Air content: ASTM C231 • Air void system: AASHTO T 152 • Unit weight: ASTM C138 • Water content: AASHTO T 318	5,000 yd^2	5	1 per sublot	Grade	Random	Tabular and control chart
Hardened concrete	• Compressive strength: ASTM C39 • Resistivity: AASHTO T 358	5,000 yd^2	5	One set of 3 replicates per lot and/or minimum set of 3 replicates per day	Plant	Random, per agency specification	Tabular and control chart
Concrete pavement	• Thickness probe: Per agency specification	5,000 yd^2	5	1 per sublot	Grade	Random	Tabular and control chart
	• Maturity: ASTM C1074	5,000 yd^2	5	1 per sublot	Grade	Random	Tabular and control chart
	• Thickness: ASTM C174 • Thickness: MIT SCAN-T3	5,000 yd^2	5	1 per sublot	Pavement cores	Random	Tabular and control chart
	• Dowels: MIT-DOWEL-SCAN	N/A	N/A	All dowelled joints	All dowelled joints	N/A	N/A

5.5 QC Test Result Reporting

All QC sampling and testing of materials used in construction of the concrete pavements will be documented on the following standard test report forms.

* Add information on forms and their titles as appropriate to the table below. Include examples of each form in an appendix.

A copy of the standard test report forms used for QC sampling and testing of concrete paving materials is located in Appendix C.

PCC Paving Company will retain a complete record of all completed testing and inspection in accessible files that will be labeled as the "QC Record System – Concrete Pavement and Shoulders". The QC Record System will contain the following QC documents:

* Add other records and documents as appropriate.

- The approved QC Plan
- Original copies of all completed QC standard test report forms, including random sampling forms
- Control charts
- Summaries of all test results
- Records of daily production quantity information

PCC Paving Company will also submit copies of all completed QC sampling and testing report forms to the State Transportation Agency with each "Weekly QC Summary Report."

5.6 QC Sample Storage and Retention Procedures

* Modify description of sample storage and retention procedures as appropriate. Include information on identification, storage location, storage condition, and retention time.

All physical QC samples of materials will be split prior to testing in accordance with relevant AASHTO and State Transportation Agency procedures.

The split sample portion of materials not used for testing will be retained in the original sample bag with proper identification. The split sample will be stored in the sample storage room at the laboratory that performed the test for a minimum of 60 days following testing.

Form no.	Form title

6.0 Production Facilities

6.1 Schedule of Production Operations

PCC Paving Company will provide the State Transportation Agency with a "Weekly Schedule of Production Operations" on each Friday prior to the week of production. A copy of the "Weekly Schedule of Production Operations" is located in Appendix D. The "Weekly Schedule of Production Operations" will identify the following:

- Material type
- Material source
- Production location
- Estimated production quantity

PCC Paving Company will track the actual production quantities on a daily basis and maintain a "Record of Material Production" for each week. Copies of the "Record of Material Production" will be made available to the State Transportation Agency in the "Weekly QC Summary Report."

6.2 Production Facilities and Equipment

Concrete produced as part of this project will be batched in a portable batch plant. The batch plant will be capable of producing the required quantities of concrete at sufficient rates of production and within the tolerances of the National Ready Mixed Concrete Association Plant Certification Checklist.

* Describe mixing equipment (manufacturer, model, mixing capacity, typical load produced).

* Describe location of batch plant.

6.3 Production Quality Control Activities

The activities and procedures to be followed for QC during production of concrete paving materials are as indicated below. Production QC personnel will perform the inspection, sampling, and testing activities at the frequencies indicated.

6.3.1 Preproduction QC Activities

* Describe preproduction QC activities.

* Describe plant calibration, providing details regarding QC measurements, checklists, and visual inspections.

* Describe certification process for scales and other equipment as appropriate.

* Describe how batch tickets or e-tickets will be utilized.

6.3.2 Production QC Activities

* Describe mixture production. For each item below, describe the approach for producing a uniform mixture that conforms to the specifications. Provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance.

- Batching sequence
- Mixing time
- Verification of mixture proportions used by the batching control system
- Moisture compensation for free water in the aggregates
- Transporting concrete
  - Haul route maintenance
  - Cleanout of hauling units

* Describe test strips. Whenever test strips are specified, the intent should be to evaluate all materials, construction, and QC processes. A test strip should be of sufficient length and volume to allow a thorough evaluation of all specification requirements. With the approval of the project engineer, the test strip may be placed as part of the planned area of paving.

6.4 Production Facility Control Charts

* Guidance for developing control charts is provided in Chapter 6 of *Quality Control for Concrete Paving: A Tool for Agency and Industry*.

Control charts will be used by PCC Paving Company and its materials suppliers to control production operations as described below.

6.4.1 Off-Site Production Control Charts

* Modify description of off-site production control charts as necessary.

Off-site material producers will use control charts as needed to provide adequate control of their production operations. Prior to production, PCC Paving Company will ask each material producer to identify and submit examples of any control charts to be used. PCC Paving Company will monitor and discuss the control charts with the producers during production.

6.4.2 On-Site Production Control Charts

PCC Paving Company will use control charts as follows to provide adequate control of its production operations:

* Modify list as appropriate.

- Aggregate moisture content (fine, coarse, and intermediate aggregates)
- Unit weight and air content
- SAM number
- Compressive strength
- Surface resistivity

6.5 Procedures for Corrective Action

* Modify procedures for nonconforming or nonspecification materials as appropriate.

The following procedures will be followed for corrective action of nonspecification materials encountered at the source or production facility:

- If contaminated or otherwise unacceptable materials are encountered, the limit of the contaminated material will be identified. The contaminated material will be clearly marked off by signs labeled "No Use on I-42".

The following corrective actions will be performed in the situations described below:

* Add/modify tables for control charts and modify situations/actions in the tables below as appropriate.

Aggregate control charts

Finding	Action
Single test result exceeds specification limit	• Test material again to verify result. • Increase testing frequency until results fall into desired range.
Moving average exceeds specification limit one time	• Notify project engineer immediately. • Notify aggregate supplier. • Identify and initiate process modifications.
Nine consecutive moving average points are on one side of target line	• Notify project engineer immediately. • Identify and initiate process modifications.
Three moving average points exceed specification limit	• Notify project engineer immediately. • Stop operations. • Investigate and modify process. • Resume operations only if preproduction sample tests indicate satisfactory results.

Concrete control charts during production

Finding	Action
Single test result indicates notable change or approaches action limit	• Technician notifies batch plant operator, who will make adjustment. • Increase testing frequency until results fall into desired range.
Single test result exceeds specification limit	• Test material again to verify result. • Increase testing frequency.
Moving average exceeds specification limit one time	• Notify project engineer immediately. • Notify materials supplier(s) as appropriate. • Identify and initiate process modifications.
Seven consecutive moving average points are on one side of target line	• Notify project engineer immediately. • Identify and initiate process modifications.
Three moving average points exceed specifi-cation limit	• Notify project engineer immediately. • Stop operations. • Investigate and modify process. • Do not resume operations until appropriate adjustments have been made and approved by the project engineer. • Implement more frequent sampling, testing, and inspection until at least three consecutive data points are shown to be within the control limits.

6.6 Production QC Inspection Reporting

All QC inspection activities during production will be documented on the following standard QC inspection report forms.

* Modify form numbers and titles as appropriate. Include copies of these forms in an appendix.

Copies of the standard inspection report forms used for production QC are located in Appendix E.

Form no.	Form title
PQC-PPA	Production QC – Preproduction Audit Report
PQC-IDR	Production QC – Inspector's Daily Report

7.0 Field Operations

The activities and procedures to be followed for QC during placement of concrete paving materials are as indicated below.

7.1 Schedule of Field Placement Operations

* Modify description regarding schedule of field placement operations as appropriate.

PCC Paving Company will provide the State Transportation Agency with a "Weekly Schedule of Placement Operations" on each Friday prior to the week of placement. A copy of the "Weekly Schedule of Placement Operations" is located in Appendix F. The weekly schedule of placement operations will identify the following:

- Project segment
- Placement location
- Maximum placement depth
- Intended placement locations (roadway, station limits)
- Material type(s)
- Estimated placement quantities
- Material source(s)

PCC Paving Company will track the actual placement quantities on a daily basis and maintain a "Record of Placement" for each week. Copies of the "Record of Placement" will be made available to the State Transportation Agency.

7.2 Field Placement Facilities and Equipment

PCC Paving Company will utilize conventional facilities and equipment for the placement of all concrete pavement materials. The major types of facilities and equipment to be utilized for placement of concrete pavement materials are summarized in the table at right for each type of item.

* Add listing of all paving equipment and modify list of equipment and description as appropriate.

7.3 Construction/Preparation of Roadway Subgrade Material

* Fully describe the approach for construction/preparation of pavement subgrade layers that conform to the specifications; provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance. Provide information on the support conditions and fine grading.

7.4 Construction of Aggregate Base

* Fully describe the approach for construction of aggregate base layers that conform to the specifications; provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits and corrective actions for nonconformance. Provide information on the support conditions and fine grading.

7.5 Construction of Cement-Treated Base

* Fully describe the approach for construction of cement-treated base layers that conform to the specifications. Provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance. Provide information on the support conditions and the fine grading.

7.6 Construction of Portland Cement Concrete Pavement

* For each subitem on the following page, fully describe the approach for construction of concrete pavement that conforms to the specifications. Provide details regarding QC measurements, checklists, visual inspections, action limits, suspension limits, and corrective actions for nonconformance.

Item	Placement equipment
Roadway embankment material	• End dump trucks (multiple, various makes/models) • Tractor/dozers (multiple, various makes/models) • Vibratory rollers: 50 ton (multiple, various makes/models) • Sheepsfoot rollers (multiple, various makes/models) • Water trucks (multiple, various makes/models)
Trimmers	• Gomaco 9500 • Gomaco CMI TR225B
Roller screeds	• Terramite: 16 ft • Terramite: 16 ft
Pavers	• Gomaco GP 2600 • G&Z S-850
Cure Machine	• Gomaco TC 600 • G&Z TC1500

7.6.1 Fixed-Form Placement

- Form alignment and elevation
- Steel placement
- Spreading of concrete
- Consolidation
- Strike-off
- Finishing
- Texturing
- Curing
- Form removal
- Sawing of joints
  - Timing
  - Use of HIPERPAV to quantify risk of early-age cracking
  - Sealing of joints
  - Backfilling of pavement edges
  - Opening to construction traffic
  - Opening to public traffic

7.6.2 Slipform Placement

- Steel placement
  - Preplaced dowel baskets and tie bars
    - Location
    - Spacing
    - Anchoring
    - Alignment
  - Preplaced continuous reinforcement
    - Spacing
    - Anchoring
    - Laps

7.6.3 Spreading of Concrete

- Strike-off and consolidation
  - Machine control method
    - Stringline
    - 3D
  - Control of the head of concrete in the grout box
  - Tamper bar, if used
  - Vibrators
    - Size
    - Rating
    - Spacing
    - Height and orientation
    - Real-time monitoring
  - Inserted steel
    - Contraction joint tie bars
    - Construction joint tie bars
    - Load transfer dowels

7.6.4 Finishing

- Burlap or turf drag
- Machine finishing
- Hand finishing

7.6.5 Texturing

- Drag texture
- Tined texture

7.6.6 Curing

- Timing
- Application rate

7.6.7 Sawing of Joints

- Timing
- Use of HIPERPAV to quantify risk of early-age cracking

7.6.8 Smoothness Measurements

- Timing
- Feedback loop to the paving crew

7.6.9 Sealing of Joints

- Material
- Process description

7.6.10 Backfilling of Pavement Edges

- Material
- Process description

7.7 Placement Control Charts

Control charts will be used by PCC Paving Company to monitor field operations for each of the items listed below.

* Modify list as appropriate.

- Pavement thickness
- Average dowel alignment score
- Smoothness

7.8 Adjustments for Weather

* Fully describe all precautions and adjustments that will be made for daily and seasonal changes in weather. Provisions should be included for the following:

- Hot weather concreting
- Cold weather concreting
- Imminent rain
- Evaporation rates above 0.2 lb/yd²/hr

7.9 Procedures for Corrective Action of Nonconforming Materials

The following procedures will be followed for corrective action of nonspecification materials encountered during field operations.

* Add/modify tables for control charts and modify situations/actions in the tables as appropriate.

7.10 Field QC Inspection Reporting

All field QC inspection activities will be documented on the following standard QC inspection report forms.

* Add information regarding forms and titles as appropriate. Include examples of forms in an appendix.

Form no.	Form title
FQC-MRIR	Field QC – Material Receiving Inspection Report
FQC-IDR	Field QC – Inspector's Daily Quantity Surveillance Report
FQC-EBIR	Field QC – Embankment and Backfill Inspection Report

7.11 Opening Pavement to Construction Traffic

* Provide a description of the early-age strength requirements, and other requirements as necessary, to open a segment of pavement to construction traffic. Provide information on the use of maturity methods or laboratory testing to confirm that requirements have been met.

7.12 Opening Pavement to Public Traffic

* Provide a description of the early-age strength requirements, and other requirements as necessary, to open a segment of pavement to construction traffic. Provide information on the use of maturity methods or laboratory testing to confirm that requirements have been met.

Control charts for concrete pavement

Finding	Action
Single test result indicates notable change or approaches action limit	• Technician notifies field superintendent, who will make adjustment. • Increase testing frequency until results fall into desired range.
Single test result exceeds specification limit	• Perform testing again to verify result. • Increase testing frequency.
Moving average exceeds specification limit one time	• Notify project engineer immediately. • Notify materials supplier(s) as appropriate. • Identify and initiate process modifications.
Seven consecutive moving average points are on one side of target line	• Notify project engineer immediately. • Identify and initiate process modifications.
Three moving average points exceed specification limit	• Notify project engineer immediately. • Stop operations. • Investigate and modify process. • Resume operations only if preproduction sample tests indicate satisfactory results.

MODEL QC PLAN

APPENDIX A

Example of Project Drawings List
Division 2
Division 7
Division 10

MODEL QC PLAN

APPENDIX B

Random Sampling Report Forms

MODEL QC PLAN

APPENDIX C

Standard Test Report Forms for
Source Characterization and
QC Sampling and Testing of Materials

MODEL QC PLAN

APPENDIX D

Weekly Schedule of Materials Production Operations

MODEL QC PLAN

APPENDIX E

Standard Inspection Report Forms for Production Quality Control

MODEL QC PLAN

APPENDIX F

Weekly Schedule of Placement Operations

The Weekly Schedule of Placement Operations (Appendix F) will identify the following:

- Project segment
- Placement location
- Placement depth or thickness
- Intended placement locations
- Material types
- Estimated placement quantities
- Material source(s)

MODEL QC PLAN

APPENDIX G

Control Charts Used for Production

MODEL QC PLAN

APPENDIX H

Control Charts Used for Field Quality Control

Appendix E

Control Charts: Additional Statistical Example

Chapter 6 of this guide presents an overview of control charts and run charts, time-series charts plotted with and without statistically derived action and control limits, respectively, that can help users understand the performance of a process and make decisions on how to improve the process. Several examples of run charts and control charts are presented in Chapter 6, along with information on how limits can be established using statistical and nonstatistical methods.

In control charts, statistical derivation of limits allows users to identify data points that are likely to be influenced by an assignable cause and determine with some certainty whether a process is in control. Control charts thus provide advantages over nonstatistically based analyses. Statistically based methods for producing and using control charts are common in production applications, where a sufficiently large data set can be collected.

This appendix provides a detailed example of a statistical process that can be used to enhance the utility of a control chart. An explanation of this process provided by Besterfield (2009) has been adapted to develop an $\overline{X}$ (pronounced "X bar," or average) chart and an R-chart (range chart) for an example concrete paving application. Typically used with $\overline{X}$ charts, R-charts provide insight into the stability of a process by illustrating the range of values measured within subgroups.

Like the examples presented in Chapter 6, the goal of using the charts provided in this appendix is to identify assignable cause variation and, ultimately, to reduce natural variation through improved process control. The approach used in this example differs from the examples presented in Chapter 6 in that the central lines and limits are computed using statistical coefficients selected based upon the size of the subgroup of samples. In this example, the subgroup is represented on the control chart by the average of a set of three cylinders tested for compressive strength at an age of 7 days. Additional confidence is incorporated into the statistical analysis as the sample size becomes larger.

Guidance on sampling and sample size is presented in Chapter 6, and in all cases the subgroup used in the creation of a control chart should be selected in a manner that does not introduce bias into the analysis. The quality control (QC) personnel running tests and using the data in the control chart should develop a sampling and testing practice that can be practically implemented but provides confidence that the amount of testing performed adequately represents production. Lots and sublots used for the project may be selected based on agency requirements, the preferences of the QC team, or both.

Data Used in the Example

Table E.1 provides data collected from 7-day compressive strength tests of concrete used in a mainline paving project. Note that each subgroup (lot) is represented by three cylinders and the average and range have been computed for each subgroup. For ease of use, these data can be collected in a spreadsheet, where formulas can be used to calculate the average and range for each subgroup as new data are entered. The data sheet should also provide an area for comments regarding the production, sampling, and testing process to be entered.

To support the calculations presented for this example, the sum of the subgroup averages and the sum of the subgroup ranges have been computed and are provided at the bottom of the appropriate columns in Table E.1. These sums will change each time new data are entered. In this regard, a control chart is a "living" tool that, in order to be useful and effective, should be updated and reviewed periodically throughout a project.

Table E.1. Seven-day compressive strength test results used to support control chart development

Date	Time	Subgroup (lot) number	7-day compressive strength (psi) 1	2	3	Average	Range	Comments
6/2/2019	3:45 PM	1	3,486	3,574	3,278	3,446	296	
6/3/2019	2:27 PM	2	4,128	4,257	4,012	4,132	245	
6/4/2019	4:43 PM	3	4,157	4,487	4,352	4,332	330	Coarse aggregate delivery
6/5/2019	2:45 PM	4	4,125	3,948	4,012	4,028	177	
6/6/2019	3:30 PM	5	3,963	4,015	4,205	4,061	242	
6/9/2019	4:20 PM	6	3,942	3,578	3,745	3,755	364	Weigh issue—cement
6/10/2019	5:15 PM	7	4,187	4,287	4,402	4,292	215	
6/11/2019	2:29 PM	8	4,297	4,158	4,177	4,211	139	
6/12/2019	4:25 PM	9	4,055	3,987	4,288	4,110	301	
6/13/2019	2:45 PM	10	4,254	4,154	4,377	4,262	223	
6/14/2019	2:25 PM	11	4,003	4,425	4,256	4,228	422	
6/17/2019	4:15 PM	12	4,157	4,350	4,178	4,228	193	
6/18/2019	2:30 PM	13	3,965	4,005	4,154	4,041	189	Fly ash delivery
6/19/2019	2:50 PM	14	4,123	3,978	4,158	4,086	180	
6/20/2019	3:30 PM	15	3,951	3,963	4,152	4,022	201	
6/21/2019	4:50 PM	16	4,208	3,974	3,870	4,017	338	
6/24/2019	5:10 PM	17	3,894	4,125	4,078	4,032	231	Aggregate delivery
6/25/2019	2:20 PM	18	3,944	3,897	4,105	3,982	208	
6/26/2019	2:25 PM	19	3,984	3,784	4,057	3,942	273	
6/27/2019	4:30 PM	20	4,021	4,158	4,102	4,094	137	
			SUM			81,372	4,599	

Constructing the Control Charts

Using these data, a control chart is first produced that plots the average of the three compressive strength test results for the subgroup (lot) over time. This chart is called the $\bar{X}$ chart or average chart (Figure E.1).

A second chart can also be produced that plots the range of each subgroup. This chart is called an R-chart or range chart (Figure E.2).

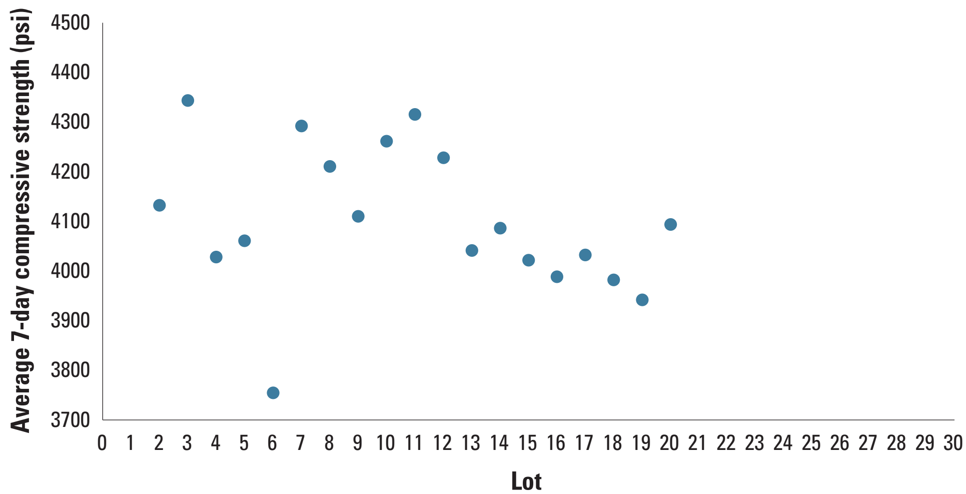


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Figure E.1. $\bar{X}$ chart of 7-day compressive strength test results, showing subgroup averages plotted over time

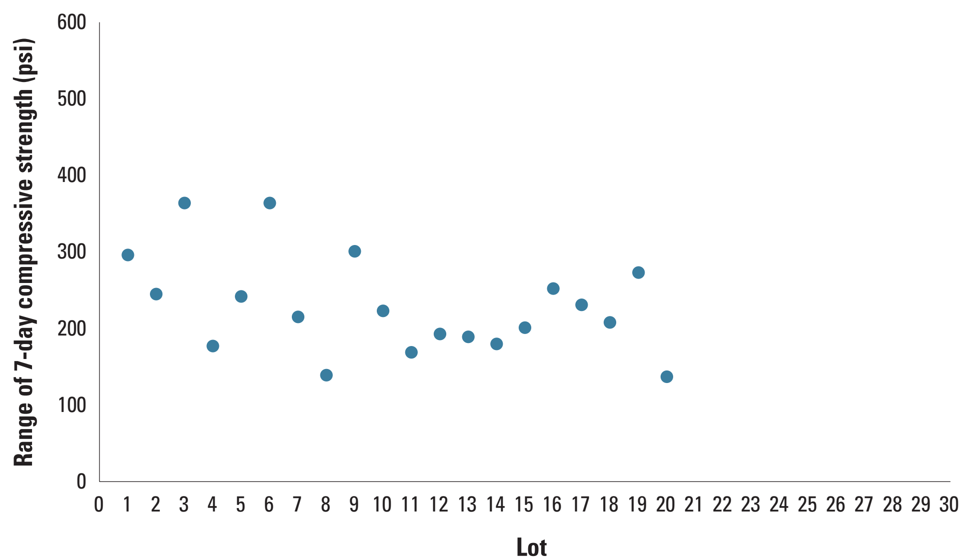

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Figure E.2. R-chart of 7-day compressive strength test results, showing subgroup ranges plotted over time

Next, the trial central line and control limits are established using statistical methods. The central line in an $\bar{X}$ chart is a measure of central tendency, called $\bar{\bar{X}}$ (pronounced "X double bar"). $\bar{\bar{X}}$ can be thought of as the "average of the averages" of a series of subgroups. The central line in an R-chart is the average of the ranges of a series of subgroups, called $\bar{R}$ (pronounced "R bar"). The central lines for the $\bar{X}$ chart and R-chart are computed using equations E.1 and E.2:

$$\bar{\bar{X}} = \frac{\sum_{i=1}^{g} \bar{X}_i}{g} \quad \textbf{[E.1]}$$

$$\bar{R} = \frac{\sum_{i=1}^{g} R_i}{g} \quad \textbf{[E.2]}$$

Where:

$\bar{\bar{X}}$= average of the subgroup averages

$\bar{X}_i$ = average of the i$^{\text{th}}$ subgroup

g = number of subgroups

$\bar{R}$ = average of subgroup ranges

R_i = range of the i$^{\text{th}}$ subgroup

The respective central lines for the $\bar{X}$ chart ($\bar{\bar{X}}$) and R-chart ($\bar{R}$) for this example are computed as follows:

$$\bar{\bar{X}} = \frac{\sum_{i=1}^{g} \bar{X}_i}{g} = \frac{81{,}372}{20} = 4{,}069$$

$$\bar{R} = \frac{\sum_{i=1}^{g} R_i}{g} = \frac{4{,}599}{20} = 230$$

As described in Chapter 6, upper control limits (UCL) and lower control limits (LCL) are typically established at ±3 standard deviations (σ) from the center line. Setting control limits at this distance from the center line provides a 99.73% chance that subgroup averages or ranges fall within the control limits if variation is from natural causes. Subgroup averages or ranges falling outside the control limits established at ±3σ may indicate that assignable cause variation is present and, importantly, that the process may not be in control.

Equations E.3 through E.6 provide formulas for computing trial control limits for $\bar{X}$ charts and R-charts established at ±3σ from the value of the central line:

$$UCL_{\bar{X}} = \bar{\bar{X}} + 3\sigma_{\bar{X}} \quad \textbf{[E.3]}$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - 3\sigma_{\bar{X}} \quad \textbf{[E.4]}$$

$$UCL_R = \bar{R} + 3\sigma_R \quad \textbf{[E.5]}$$

$$LCL_R = \bar{R} - 3\sigma_R \quad \textbf{[E.6]}$$

Where:

UCL = upper control limit

LCL = lower control limit

$\sigma_{\bar{X}}$ = population standard deviation of the subgroup averages

σ_R = population standard deviation of the range

Calculation of an accurate standard deviation relies upon a history of data. However, since control charts are often project or mixture specific and projects have a finite duration, a history of data is not necessarily available to support the calculation of a standard deviation using a large population. Therefore, a procedure for computing simplified estimates of the UCL and LCL based on the subgroup ranges has been developed using statistical factors that vary with the number of observations included in the sample (Besterfield 2009, ASTM 2018).

For control charts for small subgroups ($n \leq 10$) of equal size, trial LCL and UCL are calculated for both $\bar{X}$ charts and R-charts using Equations E.7 through E.10. Statistical factors A_2, D_3, and D_4 used in these equations are published by ASTM International. A portion of the tabulated statistical factors used for control charts is shown in Table E.2. Note that in Table E.2 the values of the coefficients for larger subgroup sizes allow for the computation of tighter control limits, which indicate more confidence in the ability of the chart to capture process variability. Additional detailed discussion and considerations for different sample sizes and standards are presented in ASTM publication MNL7-9TH, *Presentation of Data and Control Chart Analysis, 9th Edition* (ASTM 2018).

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2 \bar{R} \quad \textbf{[E.7]}$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2 \bar{R} \quad \textbf{[E.8]}$$

$$UCL_R = D_4 \bar{R} \quad \textbf{[E.9]}$$

$$LCL_R = D_3 \bar{R} \quad \textbf{[E.10]}$$

Where:

$UCL_{\bar{X}}$ = upper control limit for $\bar{X}$ chart

$LCL_{\bar{X}}$ = lower control limit for $\bar{X}$ chart

UCL_R = upper control limit for R chart

LCL_R = lower control limit for R chart

$\bar{R}$ = average of the subgroup ranges

A_2, D_3, D_4 = statistical factors obtained from Table E.2

In the example presented in this appendix, the subgroup size is 3, and therefore the coefficients A_2, D_3, and D_4 are 1.023, 0, and 2.575, respectively. The upper and lower control limits are computed for $\bar{X}$ and R as follows:

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2 \bar{R} = 4{,}069 + (1.023 \times 230) = 4{,}304$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2 \bar{R} = 4{,}069 - (1.023 \times 230) = 3{,}834$$

$$UCL_R = D_4 \bar{R} = 2.575 \times 230 = 593$$

$$LCL_R = D_3 \bar{R} = 0 \times 23 = 0$$

Using these data, trial UCL and LCL lines for $\bar{X}$ and R can be added to the $\bar{X}$ chart and R-chart shown in Figures E.1 and E.2, respectively. Figures E.3 and E.4 show these charts with trial central lines, UCLs, and LCLs added.

Table E.2. Factors for computing central lines and control limits for $\bar{X}$ charts, S charts, and R-charts

Number of observations in sample	Chart for averages ($\bar{X}$ charts)			Chart for standard deviations (S charts)					Chart for ranges (R-charts)					
	Factors for control limits			Factor for central line	Factors for control limits				Factor for central line	Factors for control limits				
n	A	A_2	A_3	c_4	B_3	B_4	B_5	B_6	d_2	d_3	D_1	D_2	D_3	D_4
2	2.121	1.880	2.659	0.7979	0.000	3.267	0.000	2.606	1.128	0.853	0.000	3.686	0.000	3.267
3	1.732	1.023	1.954	0.8862	0.000	2.568	0.000	2.276	1.693	0.888	0.000	4.358	0.000	2.575
4	1.500	0.729	1.628	0.9213	0.000	2.266	0.000	2.088	2.059	0.880	0.000	4.698	0.000	2.282
5	1.342	0.577	1.427	0.9400	0.000	2.089	0.000	1.964	2.326	0.864	0.000	4.918	0.000	2.114
6	1.225	0.483	1.287	0.9515	0.030	1.970	0.029	1.874	2.534	0.848	0.000	5.079	0.000	2.004
7	1.134	0.419	1.182	0.9594	0.118	1.882	0.113	1.806	2.704	0.833	0.205	5.204	0.076	1.924
8	1.061	0.373	1.099	0.9650	0.185	1.815	0.179	1.751	2.847	0.820	0.388	5.307	0.136	1.864
9	1.000	0.337	1.032	0.9693	0.239	1.761	0.232	1.707	2.970	0.808	0.547	5.394	0.184	1.816
10	0.949	0.308	0.975	0.9727	0.284	1.716	0.276	1.669	3.078	0.797	0.686	5.469	0.223	1.777
11	0.905	0.285	0.927	0.9754	0.321	1.679	0.313	1.637	3.173	0.787	0.811	5.535	0.256	1.744
12	0.866	0.266	0.886	0.9776	0.354	1.646	0.346	1.610	3.258	0.778	0.923	5.594	0.283	1.717
13	0.832	0.249	0.850	0.9794	0.382	1.618	0.374	1.585	3.336	0.770	1.025	5.647	0.307	1.693
14	0.802	0.235	0.817	0.9810	0.406	1.594	0.399	1.563	3.407	0.763	1.118	5.696	0.328	1.672
15	0.775	0.223	0.789	0.9823	0.428	1.572	0.421	1.544	3.472	0.756	1.203	5.740	0.347	1.653
16	0.750	0.212	0.763	0.9835	0.448	1.552	0.440	1.526	3.532	0.750	1.282	5.782	0.363	1.637
17	0.728	0.203	0.739	0.9845	0.466	1.534	0.458	1.511	3.588	0.744	1.356	5.820	0.378	1.622
18	0.707	0.194	0.718	0.9854	0.482	1.518	0.475	1.496	3.640	0.739	1.424	5.856	0.391	1.609
19	0.688	0.187	0.698	0.9862	0.497	1.503	0.490	1.483	3.689	0.733	1.489	5.889	0.404	1.596
20	0.671	0.180	0.680	0.9869	0.510	1.490	0.504	1.470	3.735	0.729	1.549	5.921	0.415	1.585

Adapted from Besterfield 2009 and ASTM 2018

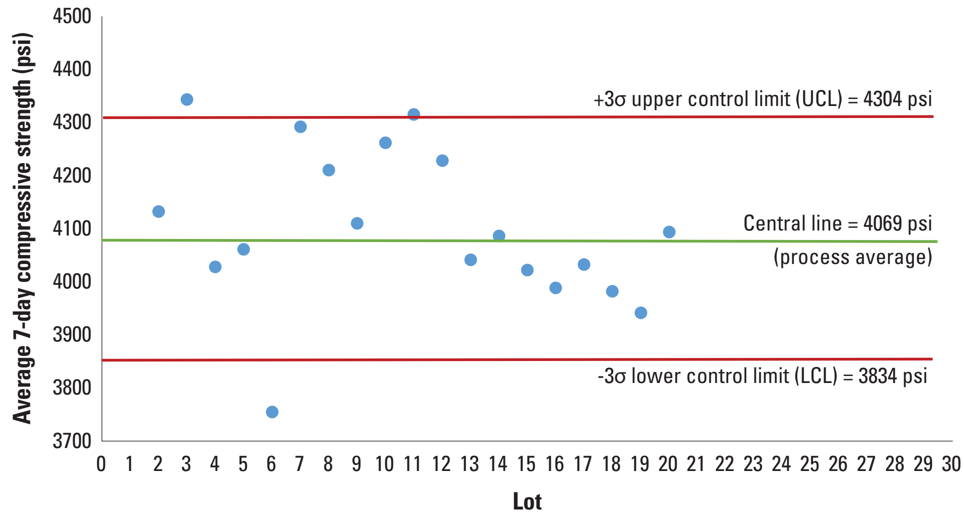

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Figure E.3. $\bar{X}$ chart with trial central line and control limits

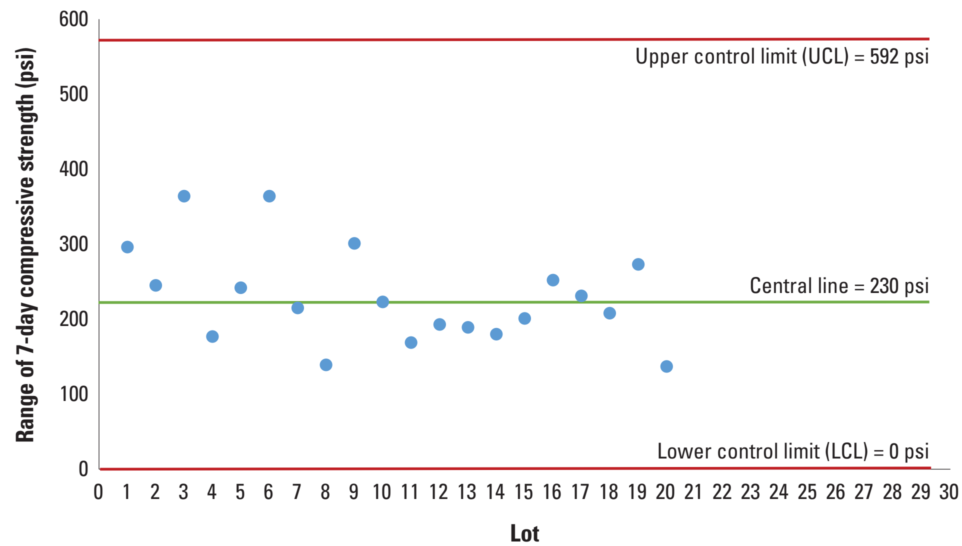

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Figure E.4. R-chart with trial central line and control limits

The LCL and UCL should be symmetrically offset from the central line. However, for small subgroup sizes ($n \leq 6$), a negative value could be computed for the LCL, which could either be confusing to the user or (often) not feasible. Therefore, for subgroup sizes less than 7, the statistical coefficient D_3 is assigned a value of zero, resulting in an LCL of zero for the R-chart.

After the trial central lines, UCLs, and LCLs are plotted, the user can review the $\overline{X}$ chart and R-chart to identify trends and to determine whether the process is in control. If all points fall between the UCLs and LCLs of the $\overline{X}$ chart and R-chart, there is strong likelihood that the process is in control. However, if one or more points fall outside of the UCL or LCL on the $\overline{X}$ chart, the R-chart, or both charts, there is a high probability that assignable cause variation is present and the process is not in control.

Refining the Control Charts

During the next steps in the process, the user reviews each data point falling outside of the UCL or LCL. When these points are identified, the user reviews any notes (such as those shown in Table E.1 in this example) or other evidence that may help identify whether the observed variation exceeds that which could be attributed to natural causes.

It should be noted that most processes are not in control when first plotted on control charts and analyzed. The initial trial central lines and control limits are used to facilitate an initial review of the process. Once data associated with assignable cause variation are identified, actions to address the causes of variation are implemented, and these data points are removed from the data set. Revised central lines and control limits are then computed, with the revised lines more likely to reflect only natural variation in the process.

In the example presented in this appendix, two subgroup averages fall outside of the UCL on the $\overline{X}$ chart (Lots 3 and 11) and one subgroup average falls below the LCL (Lot 6). No data points on the R-chart fall outside of the control limits. By reviewing the notes recorded in Table E.1, the QC team learns that a coarse aggregate delivery was made during the production of Lot 3. No notes were made regarding the production of Lot 11 that would indicate a potential issue.

If a review of the available data or information provides no indication of the potential cause for a value falling outside of the control limits, it can reasonably be assumed that this value is part of natural variation in the data. If no likely assignable cause for the variability is identified, the data for the subgroup should be allowed to remain in the data set as the analysis proceeds. In the judgement of the QC team for this example, the change in coarse aggregate during the production of Lot 3 does not seem to be reasonably linked to the relatively high compressive strength value, and no evidence of an assignable cause for the variability was noted during the production of Lot 11. Therefore, the team does not have reason to suspect that the average compressive strength values of Lots 3 and 11 are the result of assignable cause variation.

But of more concern to the QC team than compressive strength values that are slightly higher than the UCL is the average compressive strength result for Lot 6, which is lower than the LCL. Table E.1 indicates that an issue with the weigh system for cement was noted during the production of Lot 6. This issue could reasonably be assumed to be an assignable cause of variation that negatively influenced the strength of this lot, resulting in a data point lower than the LCL. Corrective actions were taken by the QC team to address this issue after the event, and the data for the subsequently produced lots fall within the control limits, indicating that only natural cause variability is likely present in the data set after Lot 6.

If the compressive strength value for Lot 6 were allowed to remain in the data set, it would adversely influence the central line and control limits. To be useful, the central line and control limits should reflect an in-control process with only natural cause variability present. Therefore, in the next step of the control chart development process, the data point for Lot 6 is removed from the data set and the central line and control limits are recomputed so that the data set reflects only natural cause variability.

A review of the R-chart shows that the range of all subgroups falls within the control limits. This indicates that there is no reason at this time to suspect the presence of assignable cause variation in the process based upon the ranges of results for the lots produced to date. Although there is some disagreement on whether excluding a data point from one chart (either the $\overline{X}$ chart or the R-chart) warrants exclusion from both the $\overline{X}$ chart and the R-chart, most guidance indicates that removal is at the discretion of the user (Besterfield 2009). In this example, it will be assumed for the sake of convenience that the user chooses to remove the Lot 6 data point associated with assignable cause variability from both the $\overline{X}$ chart and the R-chart.

After removing the data point for Lot 6 from the data set, the revised centerlines and control limits for both the $\bar{X}$ chart and the R-chart can be computed. Using the updated data set, the revised centerlines for the $\bar{X}$ chart ($\bar{\bar{X}}$) and R-chart ($\bar{R}$) are computed using equations E.11 and E.12 (modified from equations E.1 and E.2):

$$\bar{\bar{X}} = \frac{\sum_{i=1}^{g} \bar{X} - \bar{X}_d}{g - g_d} \quad \textbf{[E.11]}$$

$$\bar{R} = \frac{\sum_{i=1}^{g} R - R_d}{g - g_d} \quad \textbf{[E.12]}$$

Where:

$\bar{X}_d$ = discarded subgroup averages

g_d = number of discarded subgroups

R_d = discarded subgroup ranges

For the example presented in this appendix, the central line for the $\bar{X}$ chart ($\bar{\bar{X}}$) and R-chart ($\bar{R}$) are recomputed as follows:

$$\bar{\bar{X}}_{new} = \frac{\sum_{i=1}^{g} \bar{X} - \bar{X}_d}{g - g_d} = \frac{81{,}372 - 3{,}755}{20 - 1} = 4{,}085$$

$$\bar{R}_{new} = \frac{\sum_{i=1}^{g} R - R_d}{g - g_d} = \frac{4{,}599 - 364}{20 - 1} = 223$$

Once the central lines are recomputed without the data point(s) associated with assignable cause variability, they should be used as standard values, as shown in equations E.13 and E.14. To compute revised control limits, Equation E.15 is used, which includes another statistical factor, d_2, from Table E.2, to estimate the standard deviation σ_0 from the range R_0.

$$\bar{X}_0 = \bar{\bar{X}}_{new} \quad \textbf{[E.13]}$$

$$R_0 = \bar{R}_{new} \quad \textbf{[E.14]}$$

$$\sigma_0 = \frac{R_0}{d_2} \quad \textbf{[E.15]}$$

Where:

$\bar{X}_0$ = standard in-control central line for averages

$\bar{\bar{X}}_{new}$ = new trial central line for $\bar{X}$ chart

R_0 = standard in-control central line for ranges

$\bar{R}_{new}$ = new trial central line for R-chart

σ_0 = lower control limit

R_{new} = new average of the subgroup ranges

d_2 = statistical factor obtained from Table E.2

Using the statistical factor d_2 = 1.693 from Table E.2, the new estimate of standard deviation can be computed for this example as follows:

$$\sigma_0 = \frac{R_0}{d_2} = \frac{223}{1.693} = 132$$

Using this estimate of the standard deviation, computed without the Lot 6 data point associated with assignable cause variability, the revised control limits for the $\bar{X}$ chart ($\bar{\bar{X}}$) and R-chart ($\bar{R}$) can be computed using equations E.16 through E.19 (modified from equations E.7 through E.10):

$$UCL_{\bar{X}} = \bar{X}_0 + A\sigma_0 \quad \textbf{[E.16]}$$

$$LCL_{\bar{X}} = \bar{X}_0 - A\sigma_0 \quad \textbf{[E.17]}$$

$$UCL_R = D_2\sigma_0 \quad \textbf{[E.18]}$$

$$LCL_R = D_1\sigma_0 \quad \textbf{[E.19]}$$

Where:

A, D_1, D_2 = statistical factors obtained from Table E.2

As obtained from Table E.2 for a subgroup size of 3, the statistical factors A, D_1, and D_2 are 1.732, 0, and 4.358, respectively. Using these statistical coefficients, the revised UCLs and LCLs can be computed using equations E.16 through E.19 as follows:

$$UCL_{\bar{X}} = \bar{X}_0 + A\sigma_0 = 4{,}085 + (1.732 \times 132) = 4{,}314$$

$$LCL_{\bar{X}} = \bar{X}_0 - A\sigma_0 = 4{,}085 - (1.732 \times 132) = 3{,}856$$

$$UCL_R = D_2\sigma_0 = 4.358 \times 132 = 575$$

$$LCL_R = D_1\sigma_0 = 0 \times 132 = 0$$

The revised central lines, UCLs, and LCLs can then be added to the $\bar{X}$ chart and R-chart. The revised charts for the example presented in this appendix are shown in Figures E.5 and E.6. Note that the revised central lines and control limits reflect the fact that the influence of the assignable cause variation from Lot 6 has been removed. The central lines in both charts have shifted slightly because only the data assumed to be exhibiting natural variation are included. It can also be observed that the control limits are slightly tighter, reflecting the variation expected from an in-control process.

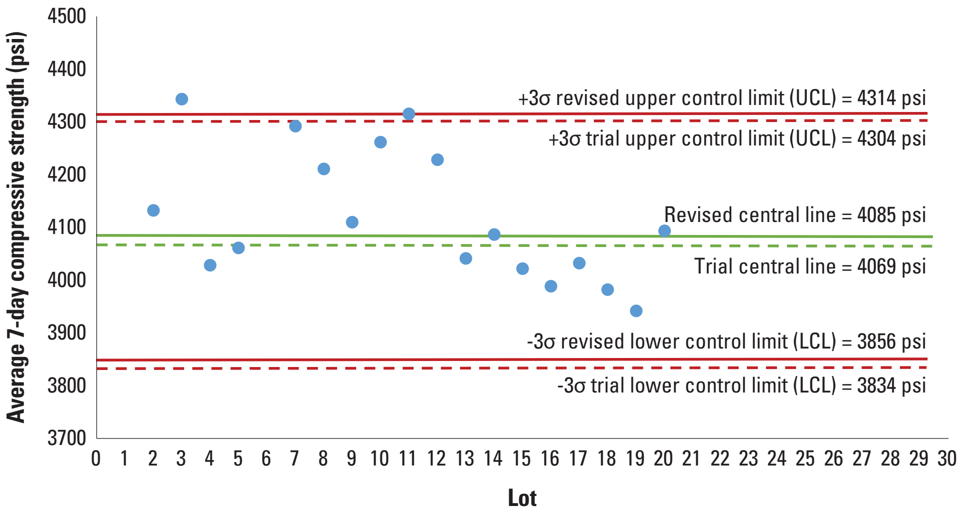

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Figure E.5. $\bar{X}$ chart with trial and revised central lines and control limits

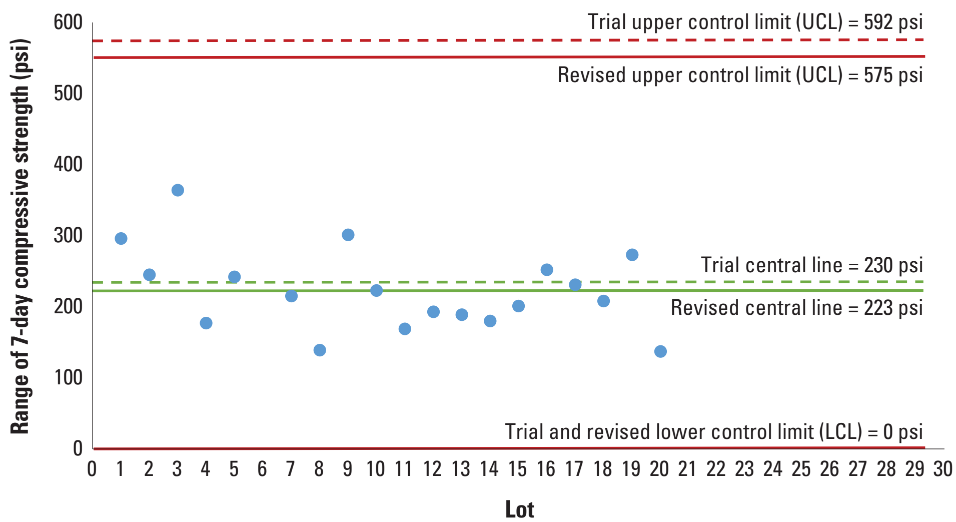

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Figure E.6. R-chart with trial and revised central lines and control limits

Over time, as process improvements are made and quality issues are addressed, the control charts should be revisited. The user should identify and remove data associated with assignable cause variability and subsequently recompute the central line and control limits. With each iteration, the control limits will tend to move closer to the central lines as the process becomes more stable and very much in control. Over the long term, the values resulting from the control chart analysis will tend to approach the best estimates of population standard values as the data set increasingly reflects only natural process variability.

Using Control Charts Effectively

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 natural cause variability in addition to reducing assignable cause variability. 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 Resources

For additional information on control chart analysis, including the construction of control charts for different types of data (attributes, nonconformities) and the use of control charts with respect to standards, the reader is referred to ASTM publication MNL7-9TH, *Presentation of Data and Control Chart Analysis, 9th Edition* (ASTM 2018). Additional guidance on control charts is available through training courses offered by the National Highway Institute (NHI) and other groups such as the NorthEast Transportation Technician Certification Program (NETTCP).

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