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Transportation Construction Quality Assurance

Reference Manual

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INTRODUCTION

Transportation Construction Quality Assurance

Introduction

Overview

In this introduction, the following course background and related information is presented:

0.1 - Background

0.1 - Background

Need for Construction Quality Assurance

The construction of all transportation facilities involves skilled labor, appropriate equipment, and proper materials and workmanship. After the labor and equipment have completed their work, the materials remain in place constituting embankments, pavements, runways, bridges, and related facilities. Construction Quality Assurance (QA) is intended to address three principal user needs:

1) Long-Lasting Facilities
2) Effective Use of Public Funds
3) Safe Facilities


Brooklyn Bridge circa 1900. Image from Library of Congress, LC-USZ62-4614

Long lasting transportation facilities can only be achieved if the materials in place meet their specified level of quality. Clearly defined construction Quality Assurance procedures provide the mechanism for contractors and agencies to attain the quality facilities expected by our customers.

Inadequate construction quality can be very costly to both contractors and the public. During a 2005 routine maintenance inspection of the I-94 Hudson Bridge over the St. Croix River, the Wisconsin DOT (WisDOT) discovered serious deficiencies, in spite of a recently completed $7.9 million bridge deck replacement. During subsequent repairs to the bridge, WisDOT identified additional evidence of poor workmanship by the contractor and insufficient oversight by a consultant inspection firm. WisDOT sought reimbursement of over $2.8 million in payments made to the contractor and the consultant. This incident damaged the public's faith in government's ability to effectively monitor construction projects and assure effective use of taxpayer funds.

Quality construction is also critical to providing safe transportation facilities. Project-specific Quality Assurance requirements need to be properly designed, implemented, and executed in order to ensure that the user needs are satisfied. Recent failures on some high profile projects have raised serious questions whether or not appropriate measures were implemented or executed to ensure the user needs. A highly publicized example of this is the July 2006 fatality of a motorist that resulted from the partial collapse of a tunnel ceiling on Interstate 90 in Boston, MA. Events such as this emphasize the important role that Quality Assurance must play throughout the design, development, and execution of transportation construction projects.

Need for Quality Assurance Training and Certification

The above examples, though extreme, illustrate the critical importance of solid construction Quality Assurance. As further discussed in this manual, a QA Program and QA Specifications are essential components of construction Quality Assurance implementation. One of the six core elements of a complete QA Program is ***Personnel Qualification/Certification***. Many states and regions have recognized the important role of training and qualification/certification of contractor and agency personnel to achieve quality. These personnel include those in responsible charge of construction projects, as well as staff performing inspection, sampling, and testing.

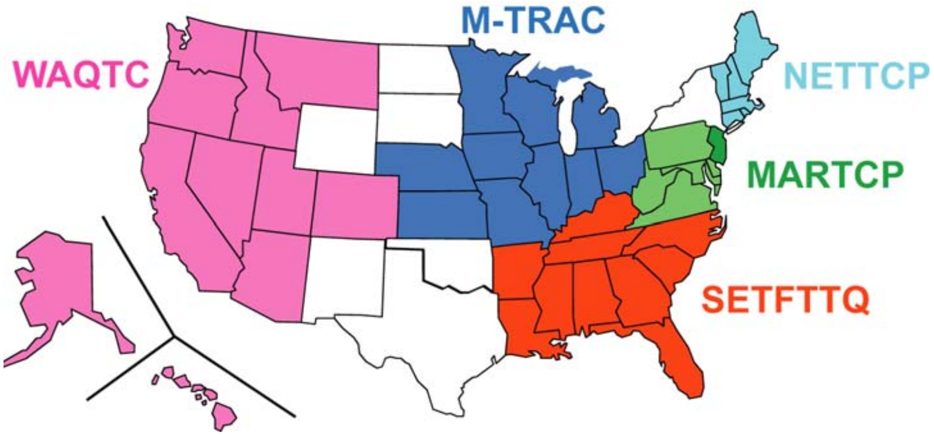
A lack of understanding by agency and industry personnel of their roles and responsibilities under Quality Assurance can, at the very least, lead to an unpleasant working experience and worse yet, can result in unnecessary disputes or unfair monetary loss to either party. Training and qualification/certification of all agency and contractor personnel responsible for interpreting and applying QA Specifications will facilitate more uniform implementation of Quality Assurance requirements and reduce or eliminate these undesirable situations.

Federal Quality Assurance Requirements

The federal regulation on ***Quality Assurance Procedures for Construction*** (23 CFR 637), issued in June 1995, requires that State Transportation Agencies have in place a QA Program to assure the quality of materials and workmanship on Federal-Aid highway construction projects. QA Program requirements identified in the regulation include: Agency Acceptance systems; Independent Assurance; Dispute Resolution; Laboratory Accreditation & Qualification; and Personnel Qualification. To address the requirements for qualified personnel, state agencies have developed (either individually or regionally) formal technician and inspector "qualification" or "certification" programs.

Regional Training & Qualification Organizations

Between 1994 and 2000, five (5) regional organizations formed within the Unites States to address training and qualifying personnel involved in highway construction and materials activities. These organizations include: New England Transportation Technician Certification Program (NETTCP); Mid-Atlantic Region Technician Certification Program (MARTCP); Southeast Task Force on Technician Training & Qualification (SETFTTQ); North Central Multi-Regional Training & Certification Program (M-TRAC); and Western Alliance for Quality Transportation Construction (WAQTC). Leadership for the regional organizations has been provided by the state agencies and Federal Highway Administration (FHWA), in partnership with industry and academia. Their initial focus was on training and qualification of testing and inspection personnel.



Evolution of the Transportation Construction Quality Assurance Course

In 1997, agency, industry, and academic representatives of the NETTCP identified the need for a Quality Assurance training/certification course for construction and materials personnel. In a concurrent effort, the FHWA outlined similar QA training needs in early 1998.

To help support the common training/qualification course needs of the states and regions, the ***Transportation Curriculum Coordination Council*** (TCCC) was formed in September 2000. FHWA provided leadership in establishing the TCCC and today this partnership includes representation from FHWA, AASHTO, the five regional training/qualification organizations, individual states, and industry.

In 2004, the TCCC members identified the need for a construction Quality Assurance course for training and certification purposes. After peer-reviewing the regionally-specific NETTCP QA course material, the FHWA and TCCC agreed to convert the material into a standard QA training course to be delivered through the ***National Highway Institute*** (NHI). This effort resulted in the final development of the NHI ***Transportation Construction Quality Assurance*** course.

NATIONAL HIGHWAY INSTITUTE

- END OF INTRODUCTION -

CHAPTER 1

Quality Assurance in Transportation Construction

Chapter 1

Quality Assurance in Transportation Construction

Chapter Overview

In this chapter, the following background, terms, and concepts pertaining to Quality Assurance are presented:

1.1 - Quality

1.2 - Total Quality Management (TQM)

1.3 - National Focus on TQM in Transportation Construction

1.4 - Quality Assurance (QA)

1.5 - Primary Components of Quality Assurance

1.6 - Implementing Quality Assurance

1.7 - Dispelling Some Quality Assurance Myths

1.1 - Quality

The term ***quality*** is not new to the transportation industry. Transportation agencies have always embraced quality and have strived to do the best job possible with the tools and resources available. However, to make cost-effective improvements in transportation construction, one must have a definition and a thorough understanding of the term quality.

Defining Quality

Unfortunately, there has been no clear consensus of the definition for quality within the transportation community. Although definitions or perceptions of quality exist, they vary from organization to organization and are dependent on the organization's role in producing the final product. Transportation Research Circular Number E-C037 (April 2002), *Glossary of Highway Quality Assurance Terms,* defines quality as follows:

> **Quality** - "(1) The degree of excellence of a product or service; (2) The degree to which a product or service satisfies the needs of a specific customer; or (3) The degree to which a product or service conforms with a given requirement."

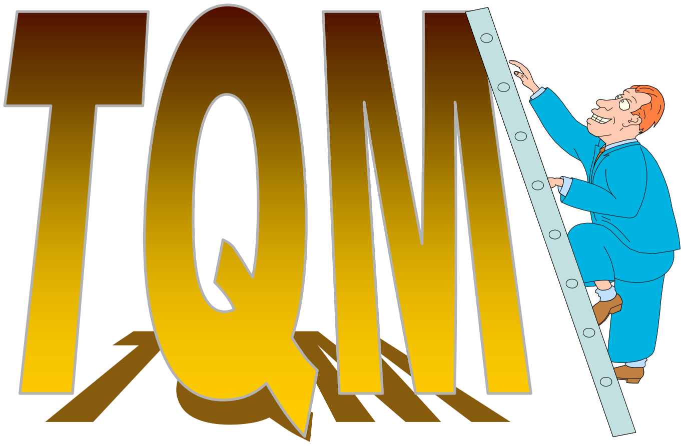
In his book, *Quality is Free*, noted quality management author Philip B. Crosby, provides the following simple definition of quality:

> **Quality** - "Conformance to requirements."

Quality is defined by our customers. As will be discussed further, the level of quality specified should be related to the product performance that is expected by our customers. The level of conformance to the customers' requirements is the measure of quality.

1.2 - Total Quality Management

Background of Total Quality Management



The term ***Total Quality Management*** (TQM) is probably familiar to most people. It is sometimes also referred to as "Continuous Quality Improvement" (CQI), Continuous Process Improvement (CPI), or simply "Quality Management." TQM provides a more comprehensive and effective approach to improve the overall quality of a product or service. The principles of TQM emerged in Japanese manufacturing beginning in the 1950s under the teachings of Dr. W. Edwards Deming and Dr. Joseph Juran. Deming and Juran, along with "quality experts" Dr. Armand Feigenbaum and Philip Crosby are generally recognized as the principal, and most influential, quality pioneers who introduced and advanced TQM in United States industry during the 1980s. While the term TQM has seemingly faded from use in recent years, its principles remain extremely relevant and continue to be applied in many sectors.

The perception has existed that TQM is intended only for the manufacturing industry. However, this is inaccurate. The principles of TQM have application to virtually any industry or organization, including construction. Unfortunately, the construction industry initially lagged behind other industries in implementing the principles of TQM. In 1992, the Construction Industry Institute (Austin, Texas) and the Associated General Contractors of America (AGC) published documents to address the application of TQM in construction.

Defining Total Quality Management

As applied to the transportation engineering and construction industry, TQM has been defined by the Associated General Contractors of America as follows:

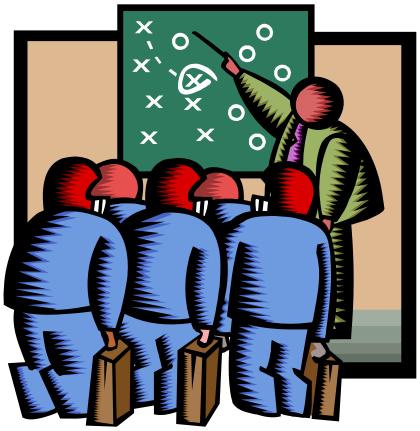
> **Total Quality Management** - "A continuous improvement process to meet customer requirements - a philosophy of doing the right thing the first time."

This definition may be used to represent all aspects of producing and accepting a quality product. The wider aim of TQM is to prevent mistakes before they happen. Accordingly, TQM in transportation construction requires a new approach to materials and construction programs and the corresponding responsibilities of transportation agencies and contractors.

Total Quality Management Objectives

The overall objectives of TQM in transportation construction are to build:

- Transportation facilities that have an actual life that is greater than or equal to the design life.
- Transportation facilities that have an actual serviceability that is greater than or equal to the anticipated performance.
- Transportation facilities that have an actual overall cost that approaches the minimum life cycle cost.

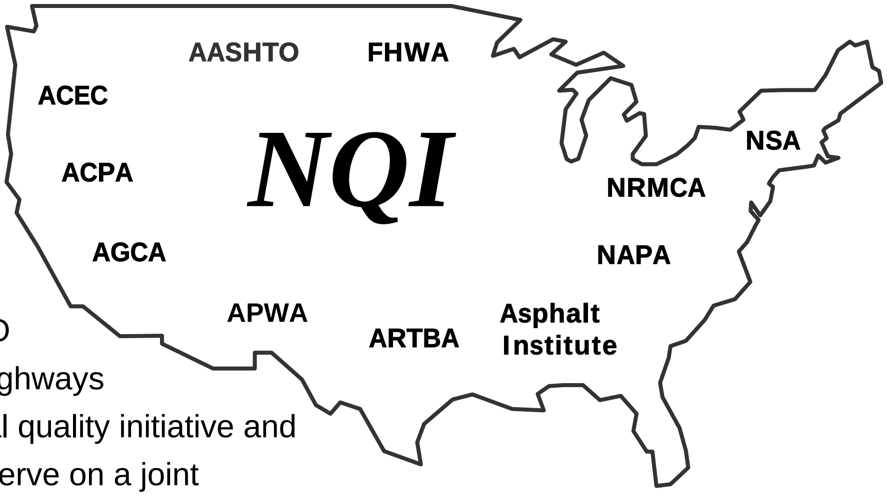


Our job is to provide the transportation user (customer) with the highest possible quality product at the lowest reasonable cost. To do this requires a two-fold effort by industry and agency working together in a partnership.

1.3 - National Focus on TQM in Transportation Construction

National Quality Initiative

The principles of Total Quality Management (TQM) were carried forward to the transportation construction sector thanks to the direction provided by the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA). The ***National Quality Initiative*** was an outgrowth of a December 1990 workshop sponsored under FHWA Demonstration Project No. 89 (DP-89), entitled "Quality Management." The representatives of State Transportation Agencies, academia, and industry who attended the DP-89 workshop recommended the development of a national initiative on quality.



In June 1991, the AASHTO Standing Committee on Highways voted to endorse a national quality initiative and appointed a task force to serve on a joint AASHTO/FHWA/Industry steering committee to guide the effort. Accordingly, in January 1992, the first National Quality Initiative (NQI) Steering Committee was formed with the mandate to focus national attention and to guide future efforts to promote the continuous improvement of highway construction quality. The initial NQI Steering Committee included AASHTO, FHWA and six industry organizations. They were joined later by other organizations.

National Policy on the Quality of Highways

On November 10, 1992, the first NQI "Partnerships for Quality" seminar was held in Dallas, Texas. The purpose of the seminar was to ensure that top managers from transportation agencies and industry agreed on the overall TQM concepts embraced by the NQI Steering Committee and to affirm these agency and industry leaders' commitment and support for future efforts to promote quality. To help articulate the specific quality principles of the NQI, the ***National Policy on the Quality of Highways*** was presented at the Partnerships for Quality seminar and signed by each of the NQI member organizations. Four of the six principles contained in the *National Policy*, which pertain directly to our work in transportation construction, are as follows:

"*National Policy on the Quality of Highways*"

1. Construction specifications related to performance, adherence to specifications, use of quality materials, and use of qualified personnel…;
2. Adequate assurances of quality achievement in…construction by owner agencies;
3. Incentives that reward achievements and innovations in providing a demonstrated level of value-added quality; and
4. Cooperative development of quality management systems and specifications between federal, state, and local agencies, academia and industry

National Partnership for Highway Quality

The ***National Partnership for Highway Quality*** (NPHQ) emerged as the successor name of the former National Quality Initiative at the final NQI workshop held on November 15, 2000.

The chief mission of the NPHQ is to advocate for the roadway customer's demands by promoting practices and programs that ensure our highways operate at peak performance now and into the future. The six goals of the NPHQ are to:

1) Establish an effective state highway quality program (SQP) (local, mini-version of NPHQ) in every state.
2) Use project partnering effectively at each stage of project delivery on all major projects in every state.
3) Attain national recognition as a leader in disseminating methods of advancing quality in project delivery, traffic and work zone safety, maintenance, and operation of highways and streets.
4) Maintain an effective communication program.
5) Ensure an adequate workforce with a strong quality orientation in the highway industry.
6) Implement objective measures of improved quality and customer satisfaction.

Additional information on the NPHQ can be accessed at http://www.nphq.org

1.4 - Quality Assurance

Defining Quality Assurance

The term ***Quality Assurance*** (QA) has been applied in transportation construction since at least the 1960s. "Quality Assurance" was practiced at varying levels by many transportation agencies in the United States prior to the emergence of TQM in the 1980s. What has evolved, however, through the NQI, the *National Policy on the Quality of Highways*, and now the NPHQ, is a clearer definition of quality and a better model of Quality Assurance for the transportation industry that is based on the principles of TQM.

AASHTO, the American National Standards Institute (ANSI), the American Society for Quality Control (ASQC), the National Cooperative Highway Research Program (NCHRP), and the Transportation Research Board (TRB) have worked to develop and adopt a formal definition of Quality Assurance. TRB Circular E-074 (May 2005) defines Quality Assurance as follows:

> **Quality Assurance** - "All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service."

More simply stated, Quality Assurance can be defined as follows:

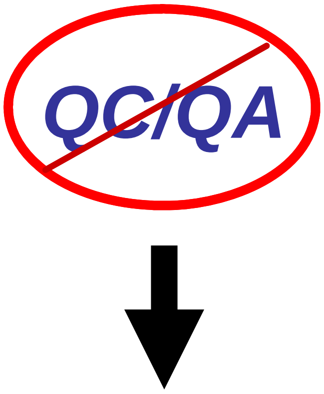
> **Quality Assurance** - "Making sure the quality of a product is what it should be."

Proper Use of the Term "Quality Assurance"

Today, Quality Assurance is an all-encompassing term that includes Quality Control (QC) by the contractor, Acceptance by the agency, Independent Assurance (IA), dispute resolution, and the use of qualified laboratories and qualified personnel by both parties. Additionally, Quality Assurance requires joint agency/industry support and the implementation of Quality Assurance specifications. This improved model of Quality Assurance is now accepted by AASHTO and the FHWA.

As stated in the *AASHTO Implementation Manual for Quality Assurance*, the term Quality Control/Quality Assurance or QC/QA has often been used in the past synonymously with Quality Assurance. The term QC/QA has been applied historically by some transportation agencies wherein Quality Control was viewed as the contractor's responsibility and Quality Assurance was seen as the agency's responsibility. However, as will be further explained, Quality Control is <u>not</u> a separate function from Quality Assurance, but rather is one of the core elements of a Quality Assurance Program.

Consistent with the above definition provided by AASHTO, ANSI, ASQ, and NCHRP, the term QC/QA is no longer used. Accordingly, <u>Quality Assurance</u> or simply <u>QA</u> is considered to be <u>the proper term</u> and is used throughout this course.



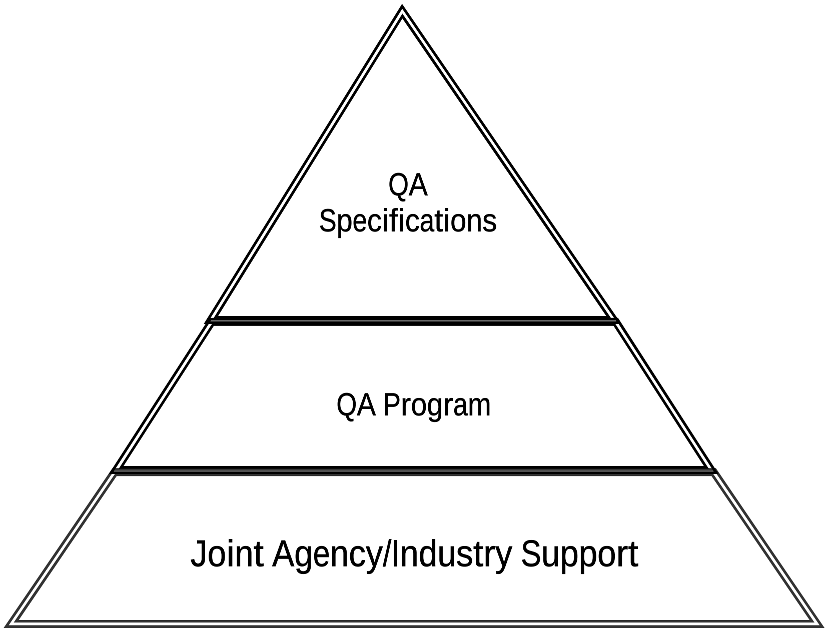
Quality Assurance (QA)

1.5 - Primary Components of Quality Assurance

Quality Assurance in transportation construction has not been replaced by TQM, but rather has been redefined and improved through its application. As presented previously, TQM in transportation construction seeks to attain quality through continuous process improvement. In applying the TQM approach to transportation construction, a new model of Quality Assurance has emerged. This new model recognizes that the successful implementation of Quality Assurance requires three essential components:

1. **Joint Agency/Industry Support**
2. **A Quality Assurance Program**
3. **Quality Assurance Specifications**

It is important to understand that each of these components is distinctly separate, yet interdependent. Although any one of the individual components can exist without the other two, the absence of any one component will result in an incomplete and ultimately unsuccessful implementation of Quality Assurance. In short, if an agency and their industry partners do not have all three primary components in place, they are not really practicing Quality Assurance. The role of each of these primary components of Quality Assurance is briefly explained below.



Joint Agency/Industry Support for Quality Assurance

The first component - ***Joint Agency/Industry Support*** - is essential to the successful implementation of Quality Assurance. As the graphic above indicates, Joint Agency/Industry Support serves as the foundation for the other two Quality Assurance components. Unfortunately this component is sometimes taken for granted or overlooked. Joint Agency/Industry Support includes:

- Commitment
- Training
- Communication
- Funding

At the heart of Joint Agency/Industry Support is commitment from personnel at all levels of each organization. Tangible support in the form of funding, training, and communication by both the agency and industry is also needed. The absence of any of these items will weaken the implementation and continued application of Quality Assurance. A more detailed discussion of Joint Agency/Industry Support is presented in **Appendix C**.

Quality Assurance Program

The second component - A construction ***Quality Assurance Program*** - establishes the core programmatic elements required to achieve quality materials and workmanship. The Quality Assurance Program (QA Program) serves as the skeleton or overall framework necessary for construction Quality Assurance implementation and clearly delineates the proper agency and industry roles and responsibilities in achieving quality. It also identifies specific requirements for qualifying both agency and industry laboratories and personnel.

Each agency should have an approved written Quality Assurance Program in place. The contents of the QA Program should be shared with all construction and materials personnel in the agency, as well as with contractor personnel.

The core elements of a Quality Assurance Program include:

- Contractor Quality Control
- Agency Acceptance
- Agency Independent Assurance
- Dispute Resolution
- Laboratory Accreditation and Qualification
- Personnel Qualification/Certification

Each of these Quality Assurance Program elements is presented in Chapter 2.

Quality Assurance Specifications

The third component - ***Quality Assurance Specifications*** - provides the project-specific instructions for applying Quality Assurance in the production and placement of individual construction materials. They should not be confused with the Quality Assurance Program, as they are two separate, but related, Quality Assurance components. Quality Assurance Specifications build upon the elements of an agency's QA Program and should reflect the specific requirements contained therein.

A Quality Assurance Specification states the specific contractor and agency activities to ensure quality materials and workmanship and typically determines payment based on the measured construction quality level rather than "reasonable conformance to specification criteria." Quality Assurance Specifications should identify:

- Minimum Quality Control (QC) activities to be performed by the contractor
- The Acceptance activities performed by the agency
- The specific Quality Characteristics to be measured for QC and Acceptance
- The targets and limits to be used for Acceptance of completed work
- Any pay adjustments related to quality level of the product

Joint development and review of Quality Assurance Specifications should include agency and industry personnel (engineers, inspectors, technicians) who are directly responsible for construction. Further explanation of Quality Assurance Specifications and the steps necessary to properly develop them are presented in Chapter 3.

1.6 - Implementing Quality Assurance

Scope of Quality Assurance Activities

A common misconception that exists with some agency and industry personnel is that Quality Assurance only applies to some construction materials (e.g., Hot-Mix Asphalt, Portland Cement Concrete). On the contrary, complete implementation of Quality Assurance in transportation construction necessitates that the three primary Quality Assurance components (i.e., Joint Agency/Industry Support, a Quality Assurance Program, and Quality Assurance Specifications) be developed to address all types of construction materials.

Materials used in transportation construction are broadly categorized according to their source and corresponding methods of production. The three principal material categories are as follows:

- Project Produced Materials
- Fabricated Structural Materials
- Standard Manufactured Materials

Although Quality Assurance is pertinent to and should be addressed for each of these material categories, the primary focus of this course manual is on the application of Quality Assurance to project produced materials.

In order to provide a basic understanding of the full scope of Quality Assurance, however, each of the three primary material categories is defined and briefly described below. The definitions presented are contained in AASHTO Materials Standard R 38 (*Standard Practice for Quality Assurance of Standard Manufactured Materials*).

Project Produced Materials

Project Produced Materials are defined as follows:

> "Major items produced directly for an individual construction project either by a contractor or by a material producer."

They are generally characterized by one or more of the following conditions:

- The production process for the material occurs either at the project site or at a producer plant located in close proximity to the project site.
- The material properties are subject to potential contamination or segregation during transportation from the plant to the project site.
- The materials arrive and are placed at the project site in a nonsolid or loose mixture state requiring subsequent mixing, compaction, finishing, or curing.

Fabricated Structural Materials

Fabricated Structural Materials are defined as follows:

> "Major structural items produced specifically for an individual construction project by a material fabricator."

They are generally characterized by one or more of the following conditions:

- The production process for the material occurs under controlled conditions at an established fabricator plant typically located within state or in another state.
- The material properties are stable and have no potential for alteration under proper transportation from the fabricator to the project site.
- The materials arrive at the project site in a solid state and require little or no additional work after installation.

Standard Manufactured Materials

Standard Manufactured Materials are defined as follows:

> "Standard items that are produced routinely (i.e., not for a specific project) by a manufacturer."

They are generally characterized by one or more of the following conditions:

- The materials are normally mass-produced under highly controlled and largely automated manufacturing conditions.
- The material properties are stable and have no potential for alteration under proper transportation from the manufacturer to the project site.
- The materials arrive at the project site in a solid, finished state* and require only installation (** Note: Exceptions to this condition include materials, such as PG binder, cements, and paints/coatings that are incorporated into either Project Produced Materials or Fabricated Structural Materials*).

Examples of Materials by Category

Some examples of project produced materials, fabricated structural materials, and standard manufactured materials used in transportation construction are presented in the table below. The list of items in the table is not all-inclusive, but is intended to show typical items within each of the three principal material categories.

Addressing QA for Each Material Category

Quality Assurance in transportation construction includes project produced materials, fabricated structural materials, and standard manufactured materials. Accordingly, agency Quality Assurance Programs normally identify the specific Quality Assurance procedures required for each category of materials.

The primary difference in how Quality Assurance is applied to each material category is in the level of Acceptance inspection and testing provided by the agency. The level of agency Acceptance activities is primarily a function of the potential for variation in the material properties during the production and placement processes. Typically, full-time Acceptance inspection and testing is provided by agencies (or their representative) for project produced materials and fabricated structural materials, whereas for standard manufactured materials, agency Acceptance inspection and testing is utilized on a less frequent or audit basis. However, adequate Quality Control procedures are required of all contractor parties (i.e., prime contractors, subcontractors, producers, fabricators, and manufacturers) for all materials, irrespective of materials category.

Materials Category	Example Items
Project Produced Materials	➢ Earthwork ➢ Subbase and Base Courses ➢ Geotechnical Items* ➢ Hot-Mix Asphalt (HMA)* ➢ Portland Cement Concrete (PCC)* ➢ Field Applied Structural Coatings* ➢ Pavement Markings*
Fabricated Structural Materials	➢ Fabricated Structural Steel and Coatings* ➢ Precast/Prestressed Concrete Structural Elements* (e.g., Precast Box Culverts, Prestressed Bridge Beams)
Standard Manufactured Materials	➢ Binders and Cements (e.g., PG Binder, Portland Cement) ➢ Drainage or Water Systems (e.g., Ductile Iron Pipe, Corrugated Metal Pipe, PVC Pipe, Hydrants, Gates and Valves, etc.) ➢ Geotextile Fabrics ➢ Landscaping items (e.g., Lime, Fertilizer, Seed, Mulch, Chain Link Fence, etc.) ➢ Paints and Coatings (e.g., Traffic Paints, Glass Beads, Preformed Markings, Epoxy, Zinc Galvanizing, etc.) ➢ Roadside Safety Devices (e.g., Impact Attenuators, Steel Beam Guardrail, Wood Posts, etc.) ➢ Standard Precast Concrete Items (e.g., Concrete Pipe, Concrete Manholes and Junction Boxes, Concrete Barrier, Concrete MSE Wall Panels, etc.) ➢ Standard Steel Shapes or Products (e.g., Anchor Bolts, Frames and Grates, Rebar, Stay-In-Place Forms, Sheeting and Piles, etc.) ➢ Traffic Control Devices (e.g., Electrical Conduit, Signal Heads, Signal Poles, Controllers, Signs, etc.)
* Note: Some constituent materials incorporated are evaluated as Standard Manufactured Materials.	

Agency Quality Assurance Programs and Quality Assurance Specifications should be developed to identify specific Quality Assurance requirements for all materials under each category. Again, the general difference in requirements for materials in each of the three categories lies in the specific Acceptance procedure and in the proper assignment of Quality Control to each contractor party.

AASHTO Standard Practice R 38 provides minimum requirements for manufacturer Quality Control and guidelines for agency Acceptance of standard manufactured materials.

However, as stated previously, the primary focus of this course manual is related to the application of Quality Assurance to project produced materials.

Quality Assurance Implementation Guidance

The following key documents were developed and issued between 1994 and 2004 by the NQI, FHWA, and AASHTO, respectively, to guide the implementation of transportation construction Quality Assurance. These documents include:

- NQI/FHWA Report No. SA-94-039 - *National Quality Improvement Task Force Report on Quality Assurance Procedures for Highway Construction* (June 1994)
- The Code of Federal Regulations (23 CFR 637B) - *Quality Assurance Procedures for Construction* (June 1995)
- FHWA Technical Advisory T6120.3 - *Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks* (August 2004)

- AASHTO Subcommittee on Construction - *Implementation Manual for Quality Assurance*
- AASHTO Subcommittee on Construction - *Quality Assurance Guide Specification*
- AASHTO Materials Standard R 9 - *Standard Recommended Practice for Acceptance Sampling Plans for Highway Construction*
- AASHTO Materials Standard R 38 - *Standard Practice for Quality Assurance of Standard Manufactured Materials*

These documents identify the key elements necessary for a successful Quality Assurance Program and related requirements for Quality Assurance specifications. Agencies and contractors may find the information contained in the above documents, as well as in this course manual, helpful in implementing Quality Assurance in transportation construction.

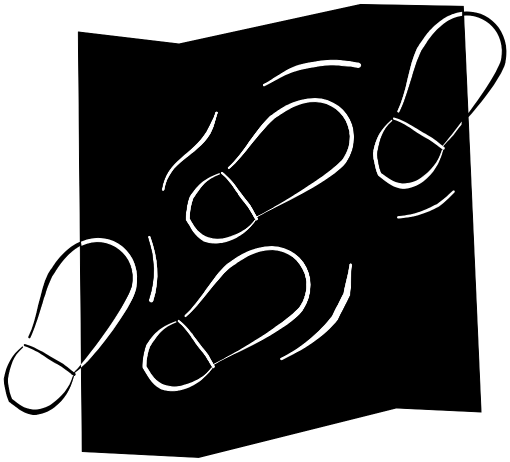
1.7 - Dispelling Some Quality Assurance Myths

Let's discuss some of the past myths that have been documented regarding Quality Assurance:

Myth #1 - There is a reduction in agency workforce

Many people think that Quality Assurance is being implemented for the purpose of reducing the number of agency personnel and that Quality Assurance is intended to reduce agency oversight and testing. This is not the case. Many agencies have lost personnel through the years and are now faced with a critical need to maximize the productivity of existing personnel. A well-organized Quality Assurance Program will help satisfy this need to more efficiently use existing personnel. Furthermore, a majority of agencies are finding no net reduction in needed technicians and inspectors, overall, during the first few years after the implementation of Quality Assurance Specifications. Initially, agencies do not reduce their amount or frequency of Acceptance inspection and testing. They just become smarter in when and where they inspect and test.

Myth #2 - The agency walks away from monitoring the project



Some personnel may interpret the Quality Assurance Program as a form of automation and believe that they are being stripped of responsibilities. They may feel that their only responsibilities are to "observe and record" test results and when the work is done, just apply the proper pay adjustment. This is not the case. Each Quality Assurance Specification includes a number of provisions that help to ensure that the agency is getting what it is paying for. Although the agency may be able to reduce the frequency of sampling and testing performed by its technicians, inspection of materials and workmanship during production and placement is essential in assuring the quality of the final in-place product.

Agency Inspectors and technicians must realize that their responsibility has not changed and that inspection is still a critical element of Acceptance. Quality Assurance Specifications still include provisions to reject material based on visual inspection. If the HMA material is obviously segregated or uncoated or if the PCC is visually honeycombed, or the soil structure is still weaving – only inspection, partnering tools, and agreed upon action by the agency and contractor are available to correct this. Make no mistake; visible, obvious deficiencies in the product still need to be addressed as was done in the past, only now it is the responsibility of both partners, the agency and the contractor.

Myth #3 – The "fox is guarding the henhouse"

Some agency personnel may fear that the use of Quality Assurance Specifications will result in a loss of agency control and monitoring of the materials produced and placed. They may also be mistrustful of the producer's or contractor's sampling, testing, and inspection. As discussed previously, if each of the six required elements of a Quality Assurance Program is properly implemented, these concerns should be overcome. As part of their Acceptance responsibilities, agency technicians and inspectors must monitor the contractor's QC activities and still have a responsibility for Acceptance sampling, testing, and inspection that is independent of the contractor. Placing responsibility for Quality Control sampling, testing, and inspection in the hands of the producer and contractor is consistent with what is normally required in virtually all other business sectors that manufacture or produce products (e.g., electronics, appliances, automobiles, airplanes, food items).

The requirement for contractor personnel and laboratories to be qualified/certified in the same manner as agency personnel and laboratories is intended to provide confidence that all QC personnel are capable of performing their sampling, testing, and inspection duties properly. If the agency has not reached a complete level of comfort with including QC test results in their Acceptance determination, the agency may elect to use only their Acceptance test results. If the agency elects to utilize contractor QC test results in their Acceptance decision, these results must be mathematically validated against independently obtained agency Acceptance test results. The contractor's QC test data will only be included in the Acceptance determination if it is successfully validated by the agency.

Myth #4 - Quality Assurance should be implemented as soon as possible

Implementation of Quality Assurance should not be rushed, but rather stretched out over at least a 4- or 5-year period. State agencies have found that by moving too quickly, without adequate training and well thought out specifications, the overall implementation effort is hindered even to the point of failure. Time is needed to allow both the agency and the contractors to become adequately knowledgeable in the Quality Assurance Specification requirements and to understand their respective roles and responsibilities. Sufficient time and pilot projects are also needed to phase in pay factors and pay adjustments.

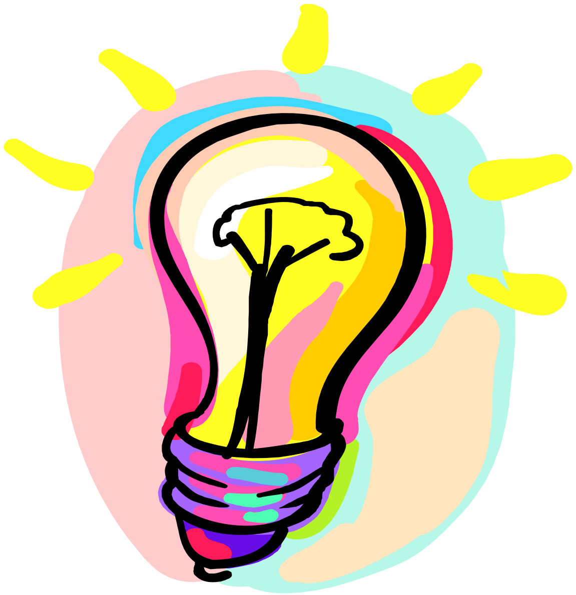
In summary, a sufficient amount of time is needed to:

- Educate everybody involved to truly understand the Quality Assurance concepts.
- Train and qualify frontline personnel involved in the process.
- Develop an overall QA Program and Quality Assurance Specifications that are fair to both partners.
- Implement pilot projects and begin to assess variability of the products (HMA, PCC, etc.) and validate the Quality Assurance Specification criteria.
- Phase in fair pay factors and pay adjustments.

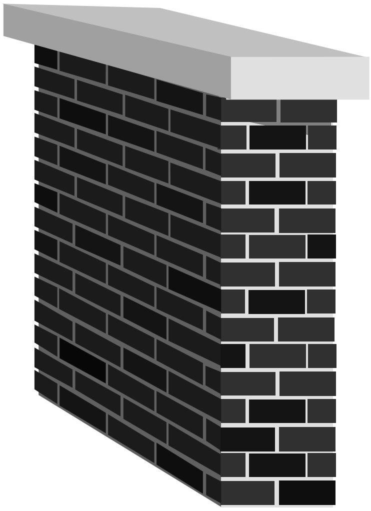
Myth #5 - The intent of Quality Assurance pilot projects is to evaluate whether Quality Assurance is a good idea or not

The intent of pilot projects is to provide a transition period for implementation and to refine and validate the Quality Assurance Specifications. However, pilot projects should not be used to evaluate whether Quality Assurance is a good idea or not. There should be a firm commitment from both agency and industry top management to the successful implementation of Quality Assurance, even if the first few pilot projects are less than successful.

Again, the bottom line is that a true understanding is required of the concepts behind Quality Assurance by both the agency and contractor. Jointly sponsored education through workshops, training sessions, industry association meetings, or partnering sessions are all needed to reach and communicate to all personnel that will be involved in Quality Assurance. Top administrators from both agency and industry must be trained and educated to then enable the managers, engineers and front line workers to follow their lead. Their prior knowledge of the program objectives and provisions will enable them to support the concept in instances where they are contacted by frustrated individuals who may view Quality Assurance as just "another fad."



Myth #6 - The biggest barrier to Quality Assurance implementation is resistance by contractors

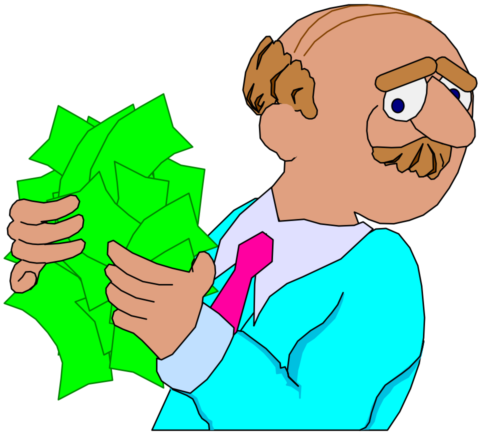


This has been found to be true in some states, but in others, where the contractors are involved in the process, training is provided, an implementation plan is developed, and the implementation is not rushed, the contractors have become the biggest proponents. In a number of cases the biggest barrier to implementation of Quality Assurance is not the contractors, but rather, the resistance within the state agencies. The key to address this resistance is training and communication and a well thought out and phased in implementation plan that is supported by top management.

Any change is difficult by human nature. Unless the potential benefits of Quality Assurance are recognized early on, caution may give way to a longer implementation process than necessary. It is highly recommended to provide training and awareness sessions as soon as possible to all parties involved in order to highlight the tangible benefits that are derived from early Quality Assurance projects.

Quality Assurance Myths Summary

Dispelling these myths will facilitate the acceptance and successful implementation of QA Programs and Quality Assurance Specifications. The result will be an increase in quality and performance of our transportation facilities that will begin to show up as a net savings to the overall cost of our transportation improvements.



- END OF CHAPTER 1 -

CHAPTER 2

Quality Assurance Program Elements

Chapter 2

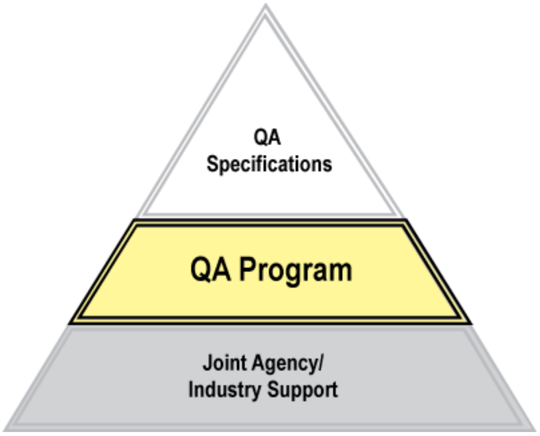
Quality Assurance Program Elements

Chapter Overview

In this chapter, the following six core elements of a Construction Quality Assurance Program will be defined and explained:

2.1 - Construction Quality Assurance Program Overview

The Second Quality Assurance Building Block



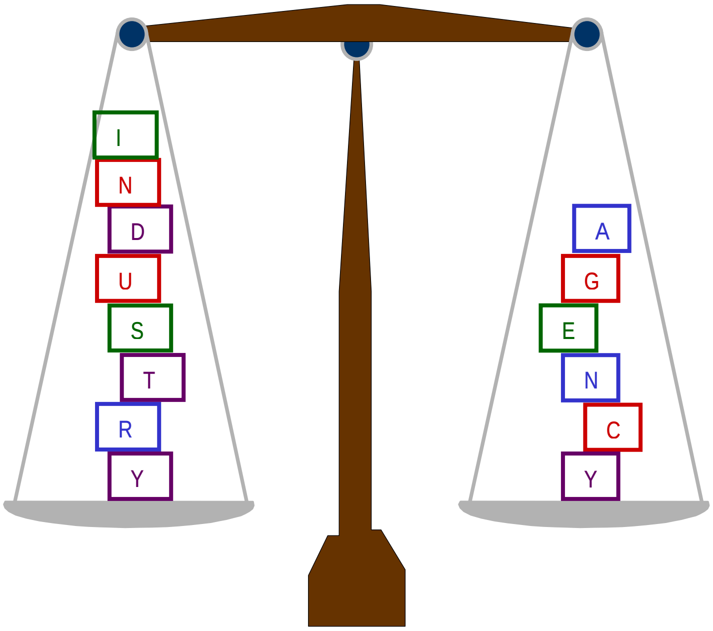
As briefly discussed in Chapter 1, the second primary component (middle of the pyramid) necessary for the implementation of Quality Assurance in transportation construction is a ***Construction Quality Assurance Program*** (QA Program). The QA Program provides the overall framework for implementing construction Quality Assurance.

A construction Quality Assurance Program is defined as follows:

> **Quality Assurance Program** - "The core programmatic elements required for construction Quality Assurance implementation."

The QA Program serves as the underlying skeleton that establishes the agency and contractor functions and requirements necessary to achieve quality construction. It must be founded upon a solid base provided by the first primary component of Quality Assurance (Joint Agency/Industry Support). Transportation agencies should have a construction QA Program in place before implementing Quality Assurance Specifications.

A successful construction QA Program requires a balanced effort of industry and agency personnel working together in a partnership. On the industry side it begins with each contractor party (i.e., prime contractor, subcontractors, producers, fabricators,



manufacturers) developing better Quality Control systems. On the agency side it begins with transportation agencies developing Acceptance systems that more appropriately assess the level of construction quality and include methods to compensate the contractor accordingly. Simply put, the contractor and agency are working together to ensure increased performance of a product through improved Quality Control and Acceptance systems.

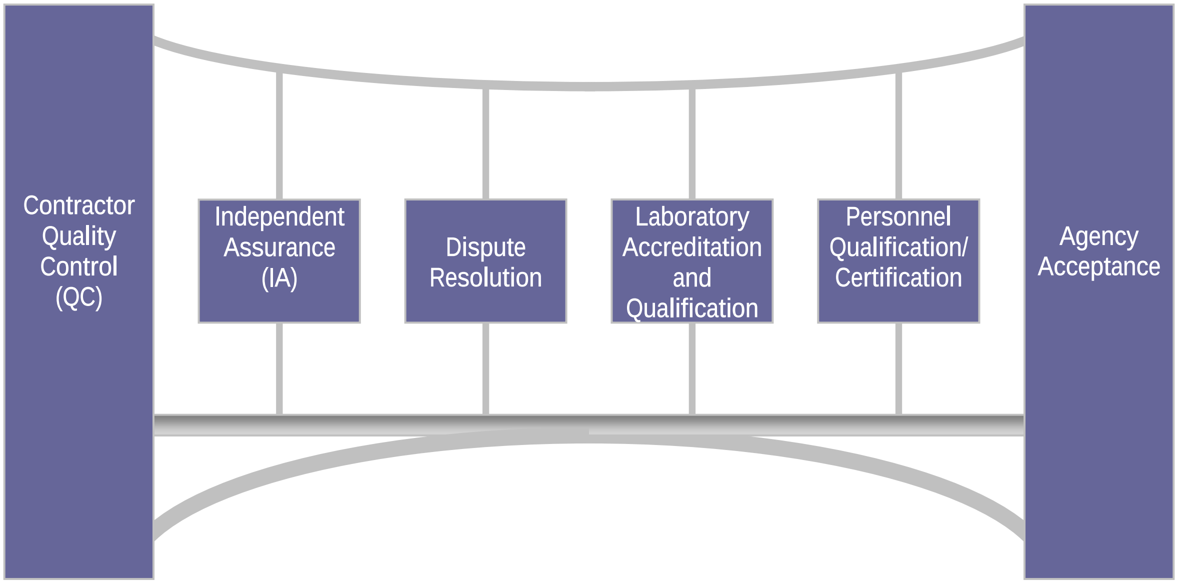
Core Elements of a Construction Quality Assurance Program

A successful Quality Assurance Program requires more than contractor Quality Control and agency Acceptance. A QA Program is comprised of six distinct elements that contribute to the achievement of quality. As presented in the *National Quality Improvement Task Force Report on QA Procedures for Highway Construction*, the *AASHTO Implementation Manual for Quality Assurance*, and *23 CFR 637*, the core elements of a construction Quality Assurance Program include:

1) Contractor Quality Control (QC)
2) Agency Acceptance
3) Agency Independent Assurance (IA)
4) Dispute Resolution
5) Laboratory Accreditation and Qualification
6) Personnel Qualification/Certification

All six elements are needed in order to have a complete and effective QA Program. A QA Program having only four or five out of the six program elements is not sufficient and should not be construed as being substantially compliant with the intent of the AASHTO guidelines or the federal regulation.

Each of these six elements may be compared to the major structural elements of a suspension bridge. The two primary “towers” of a construction QA Program are the Quality Control system by the contractor and the Acceptance system by the agency. As supporting elements of the Quality Assurance Program, laboratory and personnel qualification ensure that the principal facilities and personnel conducting sampling, testing, and inspection are capable of performing their corresponding QA activities. Additional support for the QA Program is provided by an Independent Assurance (IA) system, which provides an independent assessment of the QC and Acceptance sampling and testing. Added to the strength of these elements is a dispute resolution process, which is intended to reconcile differences between the QC and Acceptance systems. Each of these Quality Assurance Program elements is further discussed below.



2.2 - Quality Control

Quality Control Defined

The first core element of a QA Program is ***Quality Control*** (QC). Broadly stated, QC is the system(s) put into place by the contractor (i.e., prime contractor, subcontractors, producers, fabricators, manufacturers) to achieve quality. Quality Control is defined as follows:

> **Quality Control** - "The system used by a contractor party to monitor, assess, and adjust their production or placement processes to ensure that the final product will meet the specified level of quality."

Quality Control includes sampling, testing, inspection, evaluation, and corrective action (where required) to maintain continuous control of a production or placement process.

Contractor Responsibility for Quality Control

Quality Control activities are performed by the contractor. Technically, Quality Control has always been the contractor's responsibility. However, prior to the emergence of Quality Assurance many agencies assumed some of the responsibilities for QC, such as requiring an agency technician to control production facility operations through their sampling, testing, and inspection. Under a properly developed QA Program, the responsibility for the day-to-day Quality Control for production and field placement is assigned completely to the contractor.

The party producing or placing the product is in the best position to exercise Quality Control. It is ultimately the contractor who is responsible for completing the work in accordance with specification requirements through effective Quality Control.

Scope of Quality Control Activities

A contractor's Quality Control system should address all key activities during production and placement of construction materials. Within the context of transportation construction, QC includes materials production processes, materials transportation and handling, field placement or installation procedures, calibration and maintenance of equipment, and all sampling, testing, and inspection that is performed to maintain each process "in control." Quality Control involves making constant process measurements (i.e., sampling and testing) and observations (i.e., inspection). QC personnel are responsible for monitoring and evaluating these measurements and observations. An effective Quality Control system uses this information to make timely adjustments to production operations, placement techniques, personnel, and equipment.

Sampling and testing is only one part of contractor Quality Control. Inspection is an activity that is as important to contractor QC as sampling and testing. Inspection is necessary in order to minimize visually detectable problems at production facilities, such as stockpile or equipment maintenance practices or needs that may eventually affect the quality of the material produced. Likewise, visual inspection is essential to field placement operations to identify materials or workmanship that do not meet requirements for Quality. Appropriate Quality Control inspection practices and activities are presented in detail in Chapter 5.

Principal Quality Control Documents

In order to guide Quality Control personnel in their day-to-day activities, it is important that all contractor QC procedures are clearly outlined. Normally this is achieved through the careful development of two principal types of Quality Control documents:

- Contractor Quality System Manual
- Quality Control Plans

The purpose of a Quality System Manual is to document the overall internal QC operating procedures for an individual contractor (i.e., prime contractor, subcontractor, producer, fabricator, manufacturer). It should define responsibility and accountability for Quality Control within the contractor organization. A Quality Control System Manual is intended to serve as a standard operating document that outlines QC operations that are applicable to all work produced or placed.

Quality Control Plans (QC Plans) are project-specific documents whose function is to address specific production facility and field placement processes for individual categories of work on a construction project (e.g., Hot-Mix Asphalt, Portland Cement Concrete, etc.). A contractor developed and documented QC Plan is a preferred and practical part of Quality Assurance Specifications. The QC Plan provides the agency and the contractor a forum to discuss the contractor's project-specific Quality Control provisions before work begins. It is also intended to be used throughout the work in conjunction with the project specifications. Overall, each Quality Control Plan serves as a tool to ensure that the contractor has adequate personnel, facilities, equipment, and QC procedures in place to achieve the specified product quality for each major work item.

The requirements for contractor Quality System Manuals and Quality Control Plans are more fully discussed in Chapter 5.

2.3 - Acceptance

Acceptance Defined

The second core element of a Quality Assurance Program is agency ***Acceptance***. In short, Acceptance is the system put into place by the agency to measure the quality of work provided by the contractor. Accordingly, Acceptance is defined as follows:

> **Acceptance** - "All factors used by the agency (i.e., sampling, testing, and inspection) to evaluate the degree of compliance with contract requirements and to determine the corresponding value for a given product."

Agency Responsibility for Acceptance

Acceptance is the responsibility of the transportation agency. All Acceptance activities must be carried out by the agency or their designated agent (i.e., consultant under direct contract with the agency) independent of the contractor. As is explained below, contractor QC data may be used by the agency as part of its final Acceptance determination. However, the responsibility for conducting Acceptance sampling and testing (also referred to as *Verification sampling and testing*), as well as determining the acceptability of all material produced and placed, remains with the agency.

Under all circumstances, the agency must independently obtain samples for Acceptance. As stated in the *AASHTO Implementation Manual for Quality Assurance*, "under the Quality Assurance concept, QC testing is the responsibility of the contractor and Acceptance testing is the responsibility of the agency." This fundamental Quality Assurance concept is also established by the FHWA in 23 CFR 637B - *Quality Assurance Procedures for Construction*.

Scope of Acceptance Activities

The agency Acceptance system includes the following primary activities:

- Monitoring the contractor's QC activity
- Acceptance sampling, testing, and inspection
- Evaluating product quality

Agency personnel should ensure that the contractor is performing all Quality Control activities in accordance with the approved QC Plan. This requires that agency technicians and inspectors be thoroughly familiar with the specific provisions contained in the QC Plan and that they monitor the contractor's QC sampling, testing, and inspection activity on a regular basis throughout production and placement of construction materials.

As discussed above, Acceptance sampling and testing must be performed by agency personnel. All Acceptance sampling and testing must be performed independent of the contractor's QC sampling and testing.

Agency <u>inspection</u> also remains as an essential part of the Acceptance process. Visual inspection must be used, in addition to sampling and testing, to determine conformance with specification requirements for acceptance. Sometimes, even when the contractor is following the QC Plan, visibly defective workmanship or material may be identified by the agency, which must be rejected or corrected.

Acceptance System Approaches

The Acceptance system defines a set of rational procedures to be used by the agency to determine the degree of compliance with contract requirements and the value of the product delivered by the contractor. To be mathematically ensured of the quality of the work produced, the agency needs sufficient information upon which to base its acceptance determination. Under Quality Assurance, there are two general Acceptance system approaches that an agency may apply to testing data:

- Use agency Acceptance test data only for the acceptance determination
- Include validated contractor QC test data in the acceptance determination

Both of these approaches are more fully described in Chapter 6.

Under the first approach, only the Acceptance sampling and testing performed by agency technicians or inspectors are used to evaluate product quality. The results of the agency's Acceptance tests and its on-going inspection activities form the basis of the Acceptance system. This approach requires a higher frequency of agency Acceptance sampling and testing than the second approach.

Under the second approach, contractor Quality Control test results may be used to augment the agency's Acceptance testing information provided that the QC results are from random samples that are validated by the agency. Validation is a mathematical procedure that compares contractor QC data to agency Acceptance data (from the same lot) and determines the probability that both sets of data came from the same lot. The agency may use one of the following three allowable options for its acceptance determination for a given lot under this approach:

Option A – Include all validated QC test results + agency Acceptance test results for the lot

Option B – Include all validated QC test results + correlated contractor splits of the agency Acceptance test results for the lot

Option C – Include all validated QC test results for the lot only

In order to obtain the best mathematical estimate for a material Quality Characteristic evaluated for acceptance, it is prudent to use all test results that are available. The source of these test results should not be of concern provided they are properly validated. Therefore, agencies are encouraged to use both the contractor's QC test results as well as their Acceptance test results in developing the mathematical estimate of the degree of compliance with contract requirements for each lot completed. Regardless of which approach is used, all agency Acceptance and contractor QC samples which are included in the acceptance decision should be randomly obtained.

Agency Acceptance Determination

The ultimate objective of the Acceptance system is to determine the degree of compliance with contract requirements and the value of work. Agency Acceptance personnel are responsible for making this determination in accordance with the specifications and other contract requirements.

The acceptance of completed work by the agency is based on both materials testing data and the results of inspection of workmanship. With Quality Assurance Specifications, the mathematical quality measure often used with testing data is Percent Within Limits (PWL). The computed PWL value is used by agency personnel to determine the acceptability of work completed and corresponding payment. An explanation of PWL and how it is calculated is presented in Chapter 8.

2.4 - Independent Assurance

Independent Assurance Defined

The third core element of a QA Program is ***Independent Assurance*** (IA). IA is a management tool intended to provide an assessment of the process, not the product. Independent Assurance is defined as follows:

> **Independent Assurance** - "Activities that are an unbiased and independent evaluation of all the sampling and testing (or inspection) procedures used in the Quality Assurance Program."

IA provides an independent verification of the reliability of the Acceptance data obtained by the agency and the QC data obtained by contractor. The results of IA testing or inspection are not to be used as a basis of material acceptance. IA procedures are designed to provide continuity to the Quality Assurance Program.

Responsibility for Independent Assurance

IA sampling, testing, and other procedures are required to be performed by agency personnel (or their designated agents) who do not normally have direct responsibility for project Acceptance sampling and testing or inspection. Likewise, equipment other than that used for project Acceptance activities should be used by IA personnel for IA sampling and testing. IA personnel and their equipment are either from the agency Central Laboratory or the district/regional laboratories. The agency may also elect to use a consultant's laboratory to perform IA under contract to the agency.

Regardless of whether agency personnel or consultant personnel are conducting IA, the agency should have an ethics policy restricting the IA personnel from performing IA on fellow personnel working in the same laboratory. IA personnel should make a strong effort to maintain good rapport with those responsible for the Acceptance and QC testing and should be knowledgeable in all sampling and testing procedures so that they can recommend corrective measures to be taken while on the project.

Scope of Independent Assurance Activities

Independent Assurance provides an assessment of agency Acceptance personnel proficiency and equipment and contractor QC personnel proficiency and equipment. Most IA systems have historically focused on sampling and testing personnel proficiency and equipment. However, it is important to note that IA may also be applied to inspection activities since inspection of materials and workmanship is an important part of each contractor QC system and each agency Acceptance system. Agencies should consider addressing inspection as part of a complete IA system.

IA provides a separate and distinct schedule of sampling, testing, and observation. These procedures are used to make independent checks on the reliability of the results obtained in both the agency's Acceptance system and the contractor's Quality Control system and are not used to make a determination of the quality and acceptability of the materials or workmanship. Acceptance testing that is performed in the agency's accredited Central Laboratory is not normally included in the IA process. Additional guidance on Independent Assurance activities is contained in AASHTO Materials Standard R 44 - *Standard Recommended Practice for Independent Assurance Programs*.

Independent Assurance Approaches

There are two principal approaches an agency may follow for Independent Assurance:

- The Project Approach
- The Systems Approach

A combination of these two approaches may also be applied.

Under the ***project approach***, IA personnel will ensure that both agency Acceptance personnel and contractor QC personnel working on an individual construction project are evaluated throughout the duration of the project. The frequency of IA sampling, testing, and observation is normally based on a minimum percentage (typically 10%) of the agency's Acceptance testing and the contractor's QC testing.

With the ***systems approach***, the Independent Assurance activity occurs without regard to the amount of testing activity on an individual project. Agency Acceptance technicians/inspectors and contractor QC technicians/inspectors are evaluated periodically across all active construction projects typically on the basis of time (e.g., minimum of once per year).

Use of Split Samples for Independent Assurance

Since the objective of the IA comparison is to identify discrepancies or variability in testing procedures or equipment, IA testing is performed on split samples. By using split samples, the inherent variability of the material or the construction process is eliminated from the analysis and only the variability due to the sampling procedures, test procedures, and the equipment is being evaluated.

To evaluate sampling and testing, Independent Assurance typically utilizes split samples and observations of the agency's Acceptance sampling and testing personnel and the contractor's QC sampling and testing personnel (if QC test results are included in the Acceptance determination). For Independent Assurance to be effective, IA inspectors or technicians who witness or obtain split samples for purposes of IA should take immediate possession of the IA portion of the split sample to ensure the validity of the split sample and the sample comparison.

If the IA samples indicate that a significant difference exists between the IA results and the Acceptance or QC tests, the reason for the difference must be determined. This is not always a simple task. There are many sources of error including laboratory, operator, testing equipment, sampling procedures, etc.

The comparison of split sample test results should be based on established tolerances that are representative of the testing procedures and materials used. AASHTO and ASTM have published precision statements for some test methods. However, not all test procedures have precision statements and historic split sample data are not always available. In such cases, it will be necessary for the agency to establish precision statements.

In some cases, the IA process may evaluate multiple split samples between the IA personnel and the agency Acceptance personnel (or the contractor QC personnel). This process typically utilizes a mathematical tool called the t-test for paired measurements (also referred to as a paired t-test). Since more data are employed with the paired t-test, it becomes more powerful at detecting differences when they exist.

2.5 - Dispute Resolution

Dispute Resolution Defined

The fourth core element of a Quality Assurance Program is ***Dispute Resolution***. The *AASHTO Quality Assurance Guide Specification* (February 1996) defines dispute resolution as follows:

> **Dispute Resolution** - "The procedure used to resolve conflicts resulting from discrepancies between the agency's and contractor's results of sufficient magnitude to impact payment."

Function of Dispute Resolution

Dispute resolution is a formal system designed to address significant differences between an agency's Acceptance test data and/or observations and a contractor's QC test data and/or observations. Formalizing this process provides a means to minimize adversarial relationships and claims. Dispute resolution is not intended to address day-to-day issues that are capable of being resolved by frontline personnel. It should only be invoked after every avenue has been exhausted to avoid and resolve conflicts at the lowest possible level.

If contractor QC test results are utilized in the acceptance decision, the Quality Assurance Program must have a dispute resolution system. Even if agency Acceptance test results are only being used in the Acceptance determination, it is recommended practice to have dispute resolution procedures.

Responsibility for Dispute Resolution

As part of the Quality Assurance Program, both the contractor and the agency will be performing testing and inspection independent of each other. Every effort should be made by the contractor and the agency personnel to avoid any potential conflicts in the program prior to and during a project by using partnering concepts, split sampling and testing, etc.

If a dispute between some aspect of the contractor's QC system and agency's Acceptance system does occur on a project, the dispute resolution system should be utilized to resolve the differences. As part of the dispute resolution process, the use of a third party (i.e., not part of the project) is recommended for resolving differences to avoid accusations of a bias.

Scope of Dispute Resolution

The dispute resolution needs to be timely, effective, and fair in achieving the main purpose, that is, resolution of major discrepancies between the contractor and the agency. As a minimum, dispute resolution procedures should address the following possible situations:

- Disputes involving different contractor and agency test methods to measure or establish the same material Quality Characteristic.
- Disputes where the contractor and agency test methods for the same Quality Characteristic are identical.
- Non-Test result related disputes on issues that cannot be easily quantified such as inspection-related disputes of materials quality or workmanship.

Specific guidance for developing dispute resolution procedures is contained in the *AASHTO Implementation Manual for Quality Assurance*.

2.6 - Laboratory Accreditation and Qualification

Definition of Accredited versus Qualified Laboratories

The fifth core element of a QA Program is ***Laboratory Accreditation and Qualification***. There is a difference between laboratory accreditation versus laboratory qualification. Accredited laboratories and qualified laboratories are defined, respectively, as follows:

> **Accredited Laboratories** - "Laboratories which are recognized by a formal accrediting body as meeting quality system requirements including demonstrated competence to perform standard test procedures."
>
> **Qualified Laboratories** - "Laboratories that are capable as defined by appropriate programs established or recognized by each agency."

Accredited laboratories are considered "qualified." However, a "qualified laboratory" need not be accredited.

Requirements for Laboratory Accreditation

All agency Central Laboratories are required under the federal regulations (23 CFR 637B) to be accredited through the AASHTO Accreditation Program (AAP). In addition, 23 CFR 637 requires any non-agency (consultant) laboratory that performs sampling and testing for either Independent Assurance or dispute resolution to be accredited through AAP.

The AAP is used to provide a mechanism for formally recognizing the competency of a testing laboratory to carry out specific tests on construction materials. This accreditation includes in-depth laboratory inspections by the AASHTO Materials Reference Laboratory (AMRL) and the Cement and Concrete Reference Laboratory (CCRL) of equipment and testing procedures to ensure conformance to the AASHTO standards. To maintain AAP accreditation, a laboratory must satisfy the quality system requirements specified in AASHTO Standard Practice R 18 and must also participate in proficiency sample programs of AMRL and CCRL.

Requirements for Laboratory Qualification

All <u>other agency, contractor or consultant laboratories</u>, which are involved in sampling and testing utilized in the agency's <u>Acceptance determination</u>, are required to be <u>qualified</u> through an agency approved Laboratory Qualification Program (LQP) or through the AAP. This is a requirement of 23 CFR 637. The FHWA and AASHTO have also issued guidance on the necessary elements of a Laboratory Qualification Program.

A Laboratory Qualification Program, referred to by some organizations as a "Laboratory Certification Program (LCP)," should meet the following minimum guidelines:

- Supervisors experienced (minimum 3 years) in sampling and testing
- Personnel qualified through an acceptable qualification/certification program
- Test equipment calibrated and verified in proper working order
- Current Reference Manuals with sampling and testing policies and procedures
- Periodic IA program evaluation of laboratory testing equipment and personnel
- A continuing program of proficiency testing

An example of a Laboratory Qualification Program is contained in **Appendix D**.

2.7 - Personnel Qualification/Certification

Definition of Qualified versus Certified Personnel

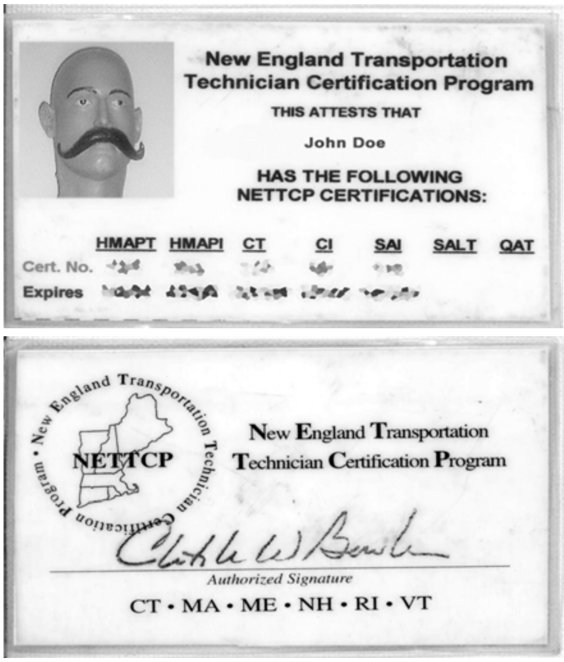
The sixth core element of a Quality Assurance Program is ***Personnel Qualification/Certification***. The terms qualification and certification are sometimes used interchangeably and are defined as follows:

> **Qualified Personnel** - "Personnel who are capable as defined by appropriate programs established or recognized by each agency."
>
> **Certified Personnel** - "Personnel who are recognized by a formal certifying body as qualified to perform sampling, testing, inspection, or related procedures."

Personnel who are determined to be "qualified" may not necessarily be "Certified." The principal reason why some agencies use the term "qualified" rather than "certified" is due to legal or administrative restrictions. In practice, there is typically no substantial difference between programs that qualify or certify personnel.

Function of Personnel Qualification/Certification

A QA Program requires that individuals who perform one or more of the actual sampling, testing, and inspection functions for the agency, contractor, or consultant laboratories be adequately trained and qualified/certified. In all cases, qualification/certification programs help ensure the qualifications of personnel and increase pride in the work performed.



New England Transportation Technician Certification Program
THIS ATTESTS THAT
John Doe
HAS THE FOLLOWING NETTCP CERTIFICATIONS:

	HMAPT	HMAPI	CT	CI	SAI	SALT	QAT
Cert. No.	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
Expires	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		

NETTCP
New England Transportation Technician Certification Program
Authorized Signature
CT • MA • ME • NH • RI • VT

Personnel qualification/certification programs are typically established and administered by individual transportation agencies, industry associations, or universities. Some regional programs have also been established including the New England Transportation Technician Certification Program (NETTCP), the Mid-Atlantic Region Technician Certification Program (MARTCP), and the Western Alliance for Quality Transportation Construction (WAQTC). National programs, such as those through the American Concrete Institute (ACI) and the Prestressed Concrete Institute (PCI), are also available.

An example of a qualification/certification card is shown above. These cards should include a photograph for positive identification and are typically laminated. Due to the potential for counterfeit cards or swapping of cards, agencies should periodically verify cards or certificates against the qualification/certification organization's official electronic database system.

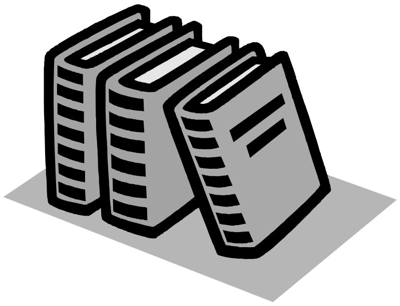
Requirements for Personnel Qualification/Certification

As a minimum, the following items are recommended for a complete personnel qualification/certification program:

- Formal training of personnel on all sampling and testing or inspection procedures (with instruction on the importance of adhering to proper procedures and the significance of testing and inspection results)
- Hands-on training to demonstrate proficiency of all sampling and testing or inspection to be performed
- A period of on-the-job training with a qualified individual to assure familiarity with transportation agency procedures
- A written examination and a performance examination for the various sampling and testing methods
- Re-qualification at 2 to 5 year intervals that demonstrates knowledge and/or skills currency (data from the agency Independent Assurance program can be used to satisfy the skills currency portion of the re-qualification process)
- The qualification program should have a documented process for removing personnel who perform sampling, testing, or inspection procedures incorrectly

Specific requirements and guidelines for personnel qualification/certification programs are contained in the following documents:

- 23 CFR 637B - *Quality Assurance Procedures for Construction*
- Non-regulatory Supplement to 23 CFR 637 (http://www.fhwa.dot.gov/legsregs/directives/fapg/0637bsup.htm)
- NQI - *Guidelines for Establishing a Technician Training and Certification Program*
- AASHTO Materials Standard R 25 - *Standard Recommended Practice for Technician Training and Qualification Programs*



2.8 - Quality Assurance Program Documentation

Requirements for Construction QA Program Document

It is necessary for each State Transportation Agency to prepare a written QA Program document that addresses the six (6) core elements required for complete construction Quality Assurance implementation. Each agency Construction QA Program must meet the requirements of 23 CFR 637B (*Quality Assurance Procedures for Construction*) and is required to be approved by the FHWA. Once an agency's QA Program document is approved by the FHWA Division Office, it becomes the guiding instrument for construction quality on all federally funded National Highway System (NHS) projects.

QA Program Document Contents and Format

It is important to keep in mind that the QA Program is intended to establish the core programmatic elements necessary to achieve quality materials and quality workmanship. Construction Quality Assurance and a QA Program, therefore, are not focused solely on materials sampling and testing. Inspection of workmanship is a critical part of Quality Assurance and must be reflected in the QA Program document.

While there is no prescribed format for a QA Program document, it is recommended that the general outline follow the six core elements (i.e., Quality Control, Acceptance, Independent Assurance, dispute resolution, laboratory accreditation and qualification, personnel qualification/certification). The document should address the above core elements for all three of the principal materials categories (i.e., project produced materials, fabricated structural materials, standard manufactured materials).

The QA Program document may be a stand-alone document or may reference some information contained in other agency documents (e.g. Construction Manual, Materials Manual).

Development of QA Program Document

Transportation agency Construction QA Program documents should be jointly developed and implemented by the agency's Construction Section and Materials Section in consultation with FHWA. It is recommended (per Joint Agency/Industry Support) that input from industry partners be obtained when developing the QA Program. Once developed and approved, the QA Program should be shared with all agency construction and materials personnel, as well as with contractor personnel, through training or workshops.

- END OF CHAPTER 2 -

CHAPTER 3

The Evolution of Quality Assurance Specifications

Chapter 3

The Evolution of Quality Assurance Specifications

Chapter Overview

In this chapter, the following major types of transportation construction specifications will be defined and explained:

3.1 - Achieving Quality with Specifications

Specifications Defined

Construction ***specifications*** are an important part of the contract documents for transportation projects. Specifications complement the plans for each construction project and enumerate the particular project requirements. The AASHTO *Guide Specifications for Highway Construction* defines Specifications as follows:

> **Specifications** - "The compilation of provisions and requirements to perform prescribed work."

This definition (or a slightly modified version) is found in the standard construction specifications of most transportation agencies.

Scope of Specifications

Transportation construction specifications provide the agency with a standard set of procedures for management and execution of a project. They provide written terms and standards to be met by the contractor in completing all work items included in a project. Construction specifications include requirements for three principal functions:

1. Contractual and legal responsibilities
2. Controlling and measuring quality of work
3. Measurement and payment of work

The specific approach to each of these functions is dependent upon the type of specification utilized by the agency.

Specification Requirements for Quality

As an outgrowth of an agency's documented QA Program, construction specifications should include appropriate requirements for the second principal specification function noted above (i.e., **controlling and measuring quality of work**). As presented earlier in Chapter 1, a simple definition of quality is "*conformance to requirements.*" With a Quality Assurance Program in place, the specification requirements to which conformance is sought should reflect the long-term performance of the completed work.

Agency construction specifications should, therefore, identify specific materials and workmanship requirements that directly relate to the desired performance of each work item. They should also include quantitative activities of the contractor and the agency to measure these materials and workmanship requirements (i.e., testing and inspection).

Major Types of Transportation Construction Specifications

Transportation construction specifications have evolved through the years, and continue to evolve, in how they specify quality of work. The major types of transportation construction specifications include:

- Method Specifications
- End-Result Specifications
- Quality Assurance Specifications
- Performance-Related Specifications
- Performance-Based Specifications

Past specifications focused primarily on prescribed methods and procedures for completion of work with the expectation that these requirements would achieve the quality sought. In recent decades, specifications have moved to defining performance-related criteria and corresponding measurement activities. Each of the above major types of specifications and their respective approach to controlling and measuring quality of work are presented in this chapter.

Warranties are not included in the above list of construction specifications as they are not a complete stand-alone type of specification. Warranties are a type of contract provision to address performance after completion of construction. When warranty provisions are used, it should be in conjunction with a Quality Assurance Specification or Performance Specification.

3.2 - Method Specifications

Definition of Method Specifications

Most transportation agencies historically have used what are referred to as ***Method Specifications*** (also called Materials and Methods Specifications, Recipe Specifications, or Prescriptive Specifications). Method Specifications are defined as follows:

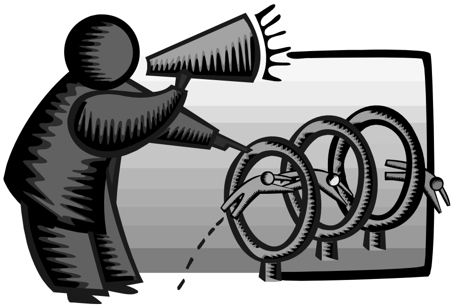
> **Method Specifications** - “Specifications that require the contractor to produce and place a product using specified materials in definite proportions and specific types of equipment and methods under the direction of the agency.”

Overview of Method Specifications

Method Specifications, which have been commonly used since the 1940s, place maximum control and responsibility in the hands of the specifying agency. Typically, these types of specifications:

- Provide a “cookbook” with specific “recipes” for the contractor to follow
- Utilize agency inspection, sampling, and testing to control the work
- Base acceptance on “reasonable conformance” or “substantial compliance”
- Evaluate individual test results from material samples
- Pay 100% across a range of quality

Agency Control of Materials and Work



A Method Specification spells out exactly the equipment, methods, materials, and techniques a contractor will be required to use. The contractor or producer is directed to combine specified materials in definite proportions and use specific types of equipment and methods in order to place the materials or product in a prescribed way. Each step is controlled—and in many cases directed—by a transportation agency representative. In effect, the agency rents the contractor's personnel and equipment. This type of specification does not allow the contractor to be innovative.

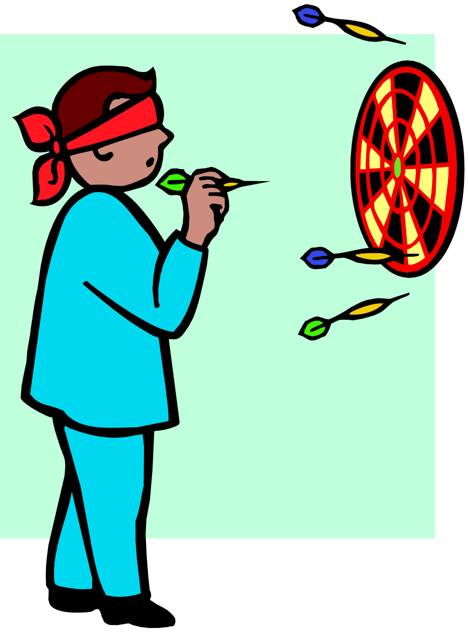
Acceptance Based on Reasonable Conformance

Some version of Method Specifications is still used today by many agencies, but it usually includes a greater degree of materials testing than in the 1950s. In the early use of Method Specifications, little or no material testing was performed. The specifying agency based acceptance primarily on inspection. In many cases, the agency did not have any defensible means to shut down facilities producing non-compliant materials, require correction or removal of deficient materials, or have payment adjusted. Acceptance was determined based upon "substantial compliance" with the specification requirements.

Acceptance decisions under Method Specifications are rather arbitrary since there is no established quality level defined by the specification. Typically Method Specifications require only that the work be in "reasonable conformance", "substantial compliance", or be "completed to the satisfaction of the Engineer." A specification under these terms is difficult to uniformly enforce and has questionable legality if the contractor has met the materials and methods requirements, but is told that the work is not acceptable.

Materials Assessed by Individual Test Results

Even though today's Method Specifications may make greater use of test results for Acceptance, they usually focus on test results for individual material samples. Each test result for a particular Quality Characteristic (e.g., air voids, compressive strength) is usually checked against the prescribed Quality Limits (typically a maximum and/or minimum value is specified). As will be discussed in Chapter 4, focusing only on individual test results ignores the inherent variability in construction materials and relies on that single test result to determine the acceptability of large quantities of material.



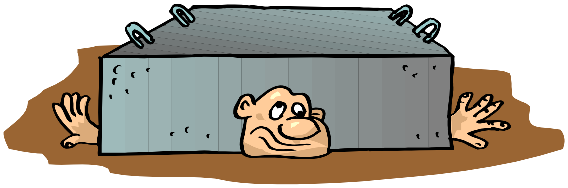
When an individual test result "fails" under Method Specifications, it is difficult to determine whether to correct the process, shut down production, or reject/remove material placed. Many agencies have been faced with the dilemma of having to render acceptance or rejection of a product based upon one material sample. In short, this is like playing Russian Roulette! The test result for one sample could, just by chance, represent an acceptable product or, just by chance, represent an inferior product.

Payment Not Linked to Quality

The inherent problems posed by acceptance based upon "substantial compliance" and/or individual test results make it difficult to establish any objective procedures for pay adjustment. Method Specifications do not usually indicate whether or specifically how contract payment should be adjusted for non-specification materials or workmanship. Likewise, Method Specifications do not allow the contractor to be rewarded for providing a higher quality product than called for in the specification. Under a Method Specification, contractors typically receive 100% payment for the work completed, regardless of the level of quality.

Disadvantages of Method Specifications

In summary, the principal disadvantages of Method Specifications include:



- The agency controls each step of the contractor's operation.
- The contractor may not be allowed to use the most economical or innovative procedures and equipment to produce the product sought.
- Acceptance of work is based on inspection for "substantial conformance."
- Decisions based on test results of individual samples can increase disputes and confrontation between the contractor and agency.
- Contractor payment is not linked to product quality or long-term performance.

3.3 - End-Result Specifications

Definition of End-Result Specifications

The construction of the AASHO (*Predecessor to AASHTO*) Road Test in 1958 provided the first step toward ***End-Result Specifications***. End-Result Specifications are defined as follows:

> **End-Result Specifications** - "Specifications that require the contractor to take the entire responsibility for producing and placing a product. The agency's responsibility is to either accept or reject the final product or to apply a pay adjustment commensurate with the degree of compliance with the specifications."

Overview of End-Result Specifications

End-Result Specifications typically:

- Assign the contractor complete responsibility and latitude in determining the materials, procedures, and equipment used to produce the product.
- Leave Quality Control sampling, testing, and inspection entirely at the discretion of the contractor or producer.
- Base agency acceptance on sampling and testing of the final in-place product.
- Determine a pay adjustment based upon the degree of compliance with the specification criteria.

Contractor Flexibility for Materials and Procedures

Under End-Result Specifications, the contractor or producer takes the entire responsibility for supplying a product or an item of construction. This type of specification does have the advantage of affording the contractor the greatest amount of flexibility in exercising options for developing new techniques and procedures to perform the work and improve the quality of the end product. True End-Result Specifications place no restrictions on the materials used or the methods and equipment used to incorporate them into the completed product. This is a well-meaning consideration, but is definitely outweighed by the inherent disadvantages.

Acceptance of Final In-Place Product

End-Result Specifications stress sampling and testing, as opposed to inspection, as the main measure of agency acceptance. “End-Result” is a term that defines the desired quality of the finished product. The specification either accepts or rejects the final product, or applies a penalty system that accounts for the degree of non-compliance. One of the principal objections to this type of a specification in the transportation construction industry is that a large quantity of material may be found to be defective after it is already in place, when there is very little opportunity for correction. This is very risky from the standpoint of the specifying agency accepting undesirable product. It also discourages accumulating testing results throughout construction to obtain a more representative estimate of the product quality. Practically speaking, it is difficult to enforce such a specification and the implications are involved with legal procedures and concepts rather than sound engineering considerations.

Quality Limits Based on Judgment

Another problem with this type of specification is determining reasonable levels of acceptance and determining relationships between the materials properties and final product performance. The limits used for Acceptance on the AASHO Road Test were developed by a panel of engineers who used their expertise to determine limits that they thought could be met by the contractor and which would lead to the desired performance of the product. The testing from the AASHO Road Test, however, proved that the limits could not be met consistently. Specifications that have Quality Limits based solely on subjective judgment are often difficult to meet due to a lack of definition of the capabilities of the production process and the desired product. An estimate of the desired target value and the variability that can be tolerated are necessary to establish realistic Quality Limits. However, a valid agency Acceptance Plan must be based on a scientific and engineering analysis of historical production test data to establish practical target values and to identify inherent variability. Only when this is done can the specification be considered truly attainable and defensible.

Disadvantages of End-Result Specifications

The primary disadvantages of End-Result Specifications include:

- The responsibility for Quality Control is often not clearly defined.
- Acceptance decisions based on the results of limited testing of the in-place product do not provide for timely identification and correction of non-compliant material and may unfairly reject acceptable material.
- The specification target values and Quality Limits are often based on subjective "experience" rather than an analysis of historical data.

3.4 - Quality Assurance Specifications

The Third Quality Assurance Building Block

As briefly discussed in Chapter 1, ***Quality Assurance Specifications*** are the third primary component (top of the pyramid) necessary for the implementation of Quality Assurance in transportation construction. Before implementing Quality Assurance Specifications, agencies should have a documented Construction QA Program in place. Quality Assurance Specifications should build directly upon the six core elements of an agency's QA Program. They provide the project level requirements to be followed by the contractor and the agency in delivering and measuring construction quality.

Definition of Quality Assurance Specifications

The use of ***Quality Assurance Specifications*** (or QA Specifications), which were initially called "Statistically-Based Specifications," began in the 1960s. Quality Assurance Specifications are defined as follows:

> **Quality Assurance Specifications** - "Specifications that require contractor Quality Control and agency Acceptance activities throughout production and placement of a product. Final acceptance of the product is usually based on a statistical sampling of the measured quality level for key Quality Characteristics."

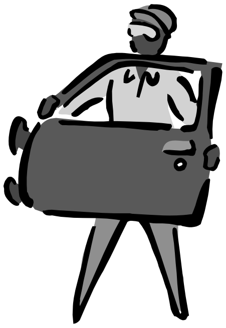
Overview of Quality Assurance Specifications

The Quality Assurance Specification is a more rational form of specification that clearly delineates contractor and agency responsibilities and determines payment on the measured construction quality level. QA Specifications:

- Assign Quality Control (QC) responsibility to the contractor.
- Base Acceptance on both inspection and testing by the agency.
- Use Acceptance Plans that recognize the inherent variability of materials.
- Provide pay adjustments related to the quality level of the product.

Quality Control Responsibility and Requirements

Under a Quality Assurance Specification, the contractor is completely responsible for Quality Control (QC). Placing responsibility for all QC activities in the hands of the contractor is consistent with what is normally required in virtually all other business sectors that manufacture or produce products (e.g., electronics, appliances, automobiles, airplanes, food items).



QA Specifications will identify the <u>minimum</u> Quality Control requirements and activities to be provided by the contractor. This includes performing QC inspection as well as QC sampling and testing throughout production and placement of work items.

Acceptance System Requirements

With a QA Specification, the transportation agency is still responsible for Acceptance of all work items. The specifications should reflect the Acceptance System outlined in the agency's documented QA Program. This includes both Acceptance inspection and Acceptance testing by agency personnel as items of work progress (not just at the end of the project).

QA Specifications will identify specific items to be inspected related to the quality of materials and workmanship. The specific *Quality Characteristics* to be tested and corresponding *Quality Measure(s)* used for Acceptance are also identified in the specification. A complete QA Specification typically indicates that, as part of its Acceptance responsibilities, the agency will also monitor the adequacy of the contractor's QC activities.

Acceptance Plans that Recognize Inherent Variability

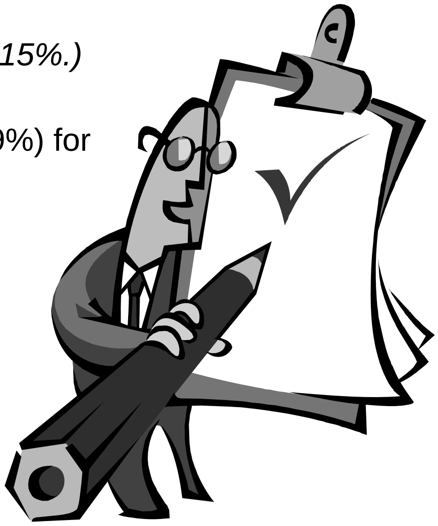
Complete Quality Assurance specifications provide a rational means for achieving a high level of quality while recognizing that variability exists in all processes and finished products. The Statistical Acceptance Plans typically used in QA Specifications for transportation construction were originally derived from U.S. Department of Defense specifications (Military Standard 414 – *Sampling Procedures and Tables for Inspection by Variables for Percent Defective*). This type of Acceptance Plan is based on proven mathematical probability (statistical) principles that take into account the sources of inherent variability contained in all test data. QA Specifications provide a more realistic assessment of the degree of conformance to the level of quality specified. This is accomplished by evaluating test data against properly developed Quality Limits using a statistical Quality Measure (e.g., Standard Deviation, PWL) to quantify the degree of variability.

Pay Adjustment Linked to Quality

Quality Assurance Specifications typically determine pay adjustment based upon a mathematical assessment of the measured quality of the product. Usually, Quality Assurance Specifications provide:

- Increased payment or “incentives” (typically 101-105%) for superior quality work.
  (Note: Some agencies may pay as much as 110-115%.)

- Reduced payment or “disincentives” (typically 0-99%) for lesser quality work.



Work that is determined to be below a minimum quality level (referred to as the *Acceptance Limit*) is normally rejected by the agency. QA Specifications typically indicate that such “rejectable-level” work is subject to corrective action (if possible), removal and replacement, or further pay reduction (if the work is to remain in place).

Rationale for Positive Pay Adjustments

Although positive pay factors have sometimes been included in QA Specifications due to the concerns of contractors, it cannot be overemphasized that pay adjustment linked to quality level is intended to provide both the contractor and the agency with a more equitable measure of value received. Positive pay factors may be viewed by some primarily as a bonus for the contractor. However, the real reason why payments greater than 100% are included in QA Specifications (along with disincentives) is really a matter of fairness.

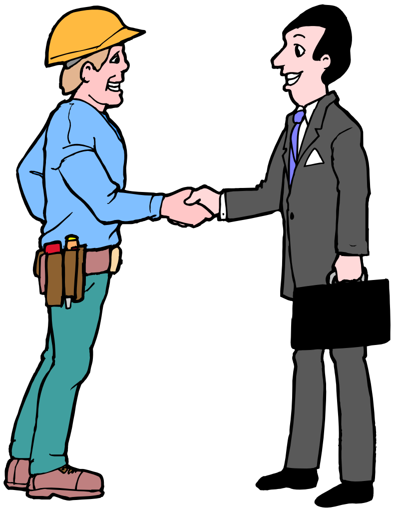
QA Specifications establish for each Quality Characteristic an Acceptable Quality Level (AQL) that warrants 100% pay. When using “Percent Within Limits” (PWL) as the

Quality Measure, the AQL value is typically established around 90 or 95 PWL. For example, assume the AQL for concrete strength is specified as AQL = 90 PWL. When the calculated PWL value for 3 or more test results evaluated together is exactly 90 PWL, the lot represented warrants 100% pay. Without providing a lengthy discussion here, PWL is calculated using a statistical procedure (that contains some degree of variability) to arrive at an “estimate” of the PWL for an entire lot of material. The procedures for estimating PWL are presented in detail in Chapter 8.

The estimated PWL value for a given set of test results will either be exactly at the established AQL (e.g., 90 PWL) or will be above it or below it to varying degrees. When the estimated PWL value is below the AQL (i.e., < 90 PWL), a reduced payment (i.e., disincentive) is received. If the specifications allow only full payment or a disincentive, whenever the estimated PWL calculation yields a value above the AQL (i.e., between 90 and 100 PWL), payment will always be limited to a maximum of 100%. In this scenario where the pay adjustment schedule includes only disincentives, the pay schedule will always be biased downward. As a result, the average pay adjustment will also be biased downward and will result in unwarranted pay reductions. The appropriate way to correct this is by providing increased payment (i.e., incentives) when the PWL value is greater than the AQL.

Advantages of Quality Assurance Specifications

As briefly discussed above, some of the key features and corresponding advantages of Quality Assurance Specifications include the following:



- Requirements for Quality Control make the contractor responsible for monitoring his/her operations and producing a quality product on a real-time basis.

- Agency personnel perform Acceptance activities (<u>both</u> inspection and testing) as the work progresses. (If properly implemented, this eliminates situations of finding “unacceptable” quality with the final in-place product.)

- A Statistical Acceptance Plan for test data is normally included that utilizes a Quality Measure and appropriate Quality Limits that reflect inherent variability.

- Pay adjustment provisions are typically included. (They provide a rational mechanism to award increased payment for higher quality work and to apply reduced payment or corrective action for lesser quality work.)

3.5 - Performance-Related Specifications

Definition of Performance-Related Specifications

Since the late 1980s, the evolution of transportation construction specifications has focused on the development of ***Performance-Related Specifications***. At a May 2000 workshop conducted by the Florida DOT, FHWA, and the NQI, the following technical definition of Performance-Related Specifications (P-R Specifications) emerged:

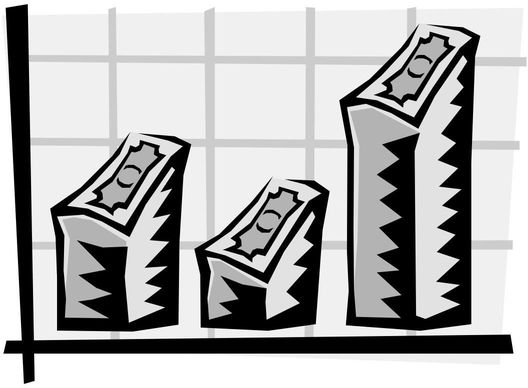
> **Performance-Related Specifications** - "Specifications that use quantified Quality Characteristics and Life Cycle Cost (LCC) relationships that are correlated to product performance."

Simply put, Performance-Related Specifications are <u>improved Quality Assurance Specifications</u>. From a management standpoint, P-R Specifications are seen as the bridge between construction quality and long-term product performance.

Overview of Performance-Related Specifications

The major distinguishing features of Performance-Related Specifications include:

- Acceptance based on key <u>Quality Characteristics</u> that have been found to <u>correlate</u> with fundamental engineering properties that predict performance.
- Mathematical models used to quantify the relationship between key Quality Characteristics and product performance.
- Pay adjustments related to the expected Life-Cycle Cost (LCC) of the constructed work item(s).



Using Quality Characteristics Linked to Performance

Performance-Related Specifications attempt to relate the Quality Characteristics being measured to the likely performance of the in-place product. Like Quality Assurance Specifications, however, they specify only the product Quality Characteristics measured at the time of construction, and do not specify the desired long-term product performance after construction completion. The tests used to determine Acceptance with P-R Specifications are selected because the Quality Characteristics being measured relate in some way to the performance of the product.

Some examples of Quality Characteristics that relate to the long-term performance of transportation facilities include:

- The total in-place <u>air voids</u> or <u>ride smoothness</u> of Hot Mix Asphalt pavements.
- The <u>permeability</u> or the <u>strength</u> of Portland Cement Concrete.

These Quality Characteristics lend themselves to Acceptance sampling and testing at the time of construction.

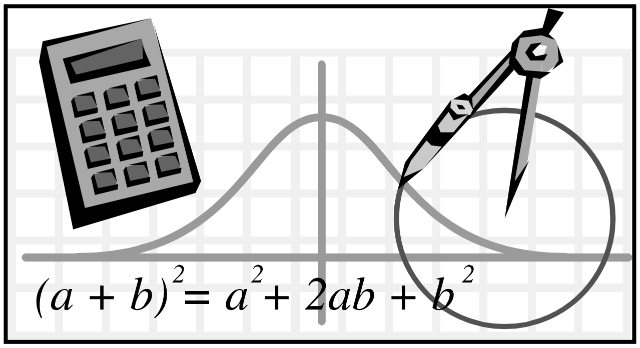
Mathematical Models That Predict Performance

True P-R Specifications not only describe the desired levels of these Quality Characteristics, but also employ the quantified relationships (i.e., mathematical models) containing the characteristics to predict subsequent product performance. The use of quantifiable models is a feature that distinguishes Performance-Related Specifications from other transportation construction specifications. The models are based on actual performance data and present a much clearer picture of what influences a constructed product's performance than can be visualized through engineering judgment and intuition alone. With recent research conducted under the Strategic Highway Research Program (SHRP), and by the FHWA and the National Cooperative Highway Research Program (NCHRP), it is now possible to relate the specification requirements to the predicted performance of the product.

Performance-Related Specifications contain two types of models:

1. Performance-Prediction Models
2. Maintenance-Cost Models

Performance-prediction models predict when and to what extent a construction product (such as a pavement) will exhibit a given type of distress, such as fatigue cracking or joint spalling. Maintenance-cost models estimate the post-construction *Life-Cycle Cost* (LCC), which is the cost of maintenance and rehabilitation necessary throughout the projected life of the product. Inputs for these models include design variables (such as traffic loading, climatic factors, drainage, soil factors) and Quality Characteristics (such as asphalt binder content and air voids, concrete permeability and strength, and ride smoothness).



Pay Adjustment Linked to Life-Cycle Cost

These models provide the basis for rational acceptance and/or pay adjustment decisions. Pay adjustments are determined using two different Life-Cycle Costs:

- The As-Designed LCC
- The As-Constructed LCC

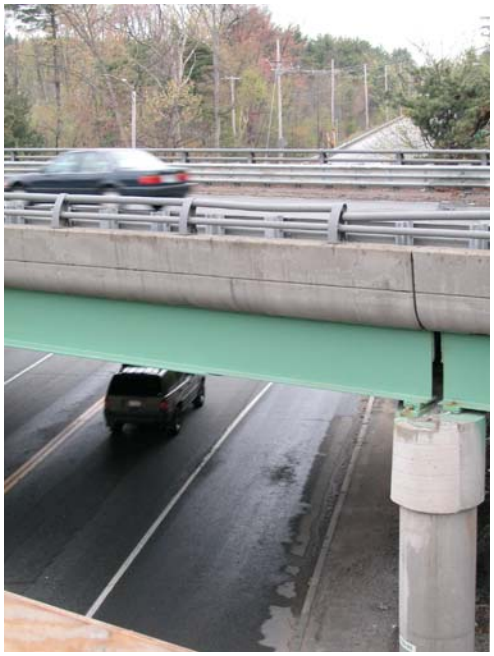
The As-Designed LCC is determined by using the target values of the specified Quality Characteristics as inputs to the models. The As-Constructed LCC is determined by using the actual measured values of the Quality Characteristics as input. The difference between the As-Designed LCC and the As-Constructed LCC is the basis for any pay adjustment.

As-Designed LCC
- As-Constructed LCC
= Pay Adjustment

Data Needed to Develop Performance Models

The ability to develop and utilize valid Performance-Related Specifications is dependent upon having reasonable performance-prediction models and maintenance-cost models. These models can only be developed and validated through good quality data, including:

- Pavement and bridge performance data
- Construction quality data
- Construction cost data
- Maintenance cost data



Transportation agencies should utilize their Management Systems (Pavement, Bridge and Maintenance) to collect this data and generate the required performance-prediction models and maintenance-cost models. Unfortunately, many Management Systems do not include all of the above data files and the related LCC data. Many Management Systems cannot relate loss in performance (as measured by condition deterioration, ride, and structural value) to a particular construction specification family or to the measured as-built material/construction Quality Characteristics. In the absence of agency specific data, recent and ongoing research by the FHWA and NCHRP has generated some models for the development of Performance-Related Specifications.

Implementation of Performance-Related Specifications

To date, only a handful of transportation agencies have developed true Performance-Related Specifications. The implementation of P-R Specifications to date has focused only on pavements. At a November 2006 FHWA-hosted workshop, it was reported that from 2000 to 2006 only five states (CA, FL, IN, TN, WI) have piloted Performance-Related Specifications for Portland Cement Concrete (PCC) pavement. These states used FHWA's Pave*Spec* 3.0 software for data analysis. It was also reported at the workshop that, while much research has occurred with P-R Specifications for HMA pavements—including WesTrack (NCHRP Study No. 455) and NCHRP Study No. 9-22—there are currently no states that have implemented complete Performance-Related Specifications for HMA pavements.

Some of the “obstacles to implementation” of P-R Specifications (for PCC & HMA pavements) cited include:

- Each P-R Specification requires project-specific development.
- Too many data inputs are required by construction project staff.
- Questions remain about accurately relating structural designs, materials mix designs, and project testing.
- Transportation agencies fear that P-R Specifications can be manipulated by contractors.

As a result of these major issues, it does not appear likely that P-R Specifications will be broadly adopted in the near future. Even if the issues identified above can be sufficiently resolved, the application of P-R Specifications will most likely be limited to only large or major transportation projects.

3.6 - Performance-Based Specifications

Definition of Performance-Based Specifications

Sitting much further on the horizon in the evolution of transportation construction specifications are ***Performance-Based Specifications***. Transportation Research Circular Number E-074 formally defines Performance-Based Specifications (P-B Specifications) as follows:

> **Performance-Based Specifications** - "Quality Assurance Specifications that describe the desired levels of fundamental engineering properties (e.g., resilient modulus, creep properties, and fatigue) that are predictors of performance and appear in primary prediction relationships."

The "primary prediction relationships" contained in P-B Specifications are models that can be used to predict stress, distress, or performance from combinations of predictors that represent traffic, environment, supporting materials, and structural conditions.

Overview of Performance-Based Specifications

The primary features of Performance-Based Specifications include:

- Acceptance based on measurement of the finished product's fundamental engineering properties that predict performance.
- Quality Limits that are established using a statistically valid basis.
- Mathematical models used to quantify the relationship between the fundamental engineering properties measured and product performance.
- Pay adjustments based on the expected Life-Cycle Cost (LCC) of the constructed transportation facility.

Performance-Based Specifications are different from Performance-Related Specifications in that they specify the desired levels of the actual fundamental ***engineering properties*** (not the key Quality Characteristics) that are predictors of performance. The fundamental engineering properties specified (e.g., resilient modulus, creep properties, and fatigue properties) are used in performance prediction relationships (i.e., mathematical models) that can be used to predict stress, distress, or performance from combinations of predictors that represent traffic, environmental, and structural conditions. In the true sense, P-B Specifications are concerned with the performance of the final in-place product and not how it was built.

Status of Performance-Based Specifications

Complete P-B Specifications do not yet exist. The Superpave Performance Graded Asphalt Binder (PGAB) specifications, which were developed through the SHRP research program, are an example of a partial Performance-Based Specification. However, PGAB is only one component of the final product. All of a product's constituent materials and their related fundamental engineering properties must be included in order to have complete models to predict performance of that product. Other performance-based test methods have not been fully developed. Performance-based test methods that have been developed are not yet user-friendly enough to permit timely Acceptance testing during construction. Further development and validation of performance-based tests is currently underway through FHWA, NCHRP, and TRB research programs.

In addition, true P-B Specifications will require good Management System data to generate and validate the models required to determine pay adjustments based on expected Life-Cycle Costs. As discussed previously, most agency Management Systems do not presently collect and evaluate all of the data necessary to develop the required performance and cost models. Accordingly, Performance-Based Specifications have not yet emerged as a viable tool for transportation agencies.

3.7 - Development of Quality Assurance Specifications

Overview of QA Specification Development Process

Quality Assurance Specifications require more engineering knowledge of each product than do Method Specifications or End-Result Specifications. Before a valid QA Specification can be fully implemented with incentive/disincentive provisions, a considerable amount of engineering is necessary. A well-defined and documented agency QA Program should also be in place before developing QA Specifications. This is to ensure that contractor QC requirements and agency Acceptance system requirements are clearly outlined and can be further fleshed out in the construction specifications. The development and implementation process for a Quality Assurance Specification requires the following four phases:

- Phase I - QA Specification Initiation and Planning.
- Phase II - Develop Pilot Quality Assurance Specifications.
- Phase III - Implement Pilot QA Specifications.
- Phase IV - Evaluate and Refine QA Specifications.

Each of these four phases is briefly described below.

Phase I - QA Specification Initiation and Planning

The first phase of QA Specification development involves the following three startup activities:

- Form an agency and industry QA Specification Task Force.
- Select the specific work item(s) and material(s) for QA Specification application.
- Prepare an outline of QA Specification provisions.

The transportation agency developing the QA Specification should form a task force. The task force should include both agency personnel (state, federal, local) and industry personnel (contractor associations, producer organizations) to ensure that all of the relevant partners provide their input and available technical expertise. Agency representation on the task force should include personnel from the agency “Construction Section,” “Materials Section,” and possibly Design personnel. The specific construction work item(s) and material(s) that the specification will address must be selected. As a general rule, it is recommended that the agency select one or two items involving major project-produced materials (e.g., HMA pavement, concrete pavement, structural concrete, earthwork) for initial QA Specification development. Once the work item is selected, a draft outline of the specification should be prepared. The general outline should follow the major parts of a QA Specification listed below (i.e., contractor QC requirements, agency Acceptance requirements, dispute resolution provisions, and a Statistical Acceptance Plan).

Phase II - Develop Pilot Quality Assurance Specifications

In the second phase, a “pilot” Quality Assurance Specification must be drafted. Regardless of the work item or material selected, a complete QA Specification should include specific requirements for each of the following four (4) major parts:

- Part 1 - Establish Contractor Quality Control (QC) requirements
- Part 2 - Establish agency Acceptance requirements
- Part 3 - Develop dispute resolution provisions
- Part 4 - Develop Statistical Acceptance Plan

Each of these parts of a QA Specification is briefly described below.

Part 1 - Establish Contractor QC Requirements

The first part of a QA Specification should clearly state the requirements for each of the following contractor Quality Control functions:

- Minimum QC Plan/Quality System Manual requirements
- QC personnel requirements
- QC laboratory requirements
- Minimum QC inspection requirements
- Minimum QC sampling and testing requirements
- QC data analysis and documentation

The specific Quality Control requirements in a pilot QA Specification must build upon the contractor QC system criteria and guidelines outlined in the agency QA Program document. The specification should require a project-specific QC Plan for each major work item involving project-produced materials. The QA Specification should include an outline of the minimum contents required in each QC Plan as well as requirements for submittal. The specification may also identify requirements for Quality System Manuals to be in place for fabricated structural materials and standard manufactured materials. Qualification requirements for QC personnel and laboratories should be specified. The minimum items to be inspected and Quality Characteristics to be tested for Quality Control must also be identified. Lastly, requirements for contractor documentation and analysis of QC data need to be specified, including: inspection and testing report forms, QC record books, control charts, and running quality level. Contractor Quality Control requirements typically found in QA Specifications are presented in Chapter 5.

Part 2 - Establish Agency Acceptance Requirements

The agency Acceptance system requirements comprise the second part of a QA Specification and should address the following:

- Agency Acceptance system approach
- Items to be inspected by the agency for Acceptance
- Quality Characteristics subject to agency Acceptance (Verification) testing
- Requirements for correlation of contractor and agency split samples
- Procedures for validation of contractor QC data
- Procedures for identifying outliers
- Procedures for re-sampling and re-testing
- Provisions for determination of quality and payment (Acceptance Plan)

The agency Acceptance requirements in a pilot QA Specification must follow the Acceptance system criteria established in the agency QA Program document. First, the specifications should specify the Acceptance system approach to be used for inspection and testing data (i.e., use agency data only or include validated QC data in the Acceptance determination). Key items that will be inspected by the agency for quality of workmanship should be identified. The key Quality Characteristics subject to agency Acceptance testing must also be identified. Requirements for correlation of split samples and validation of QC data (if included in the Acceptance determination) should be specified. It is important that procedures for identification of test data outliers along with procedures for appropriate re-sampling or re-testing also be included. A Statistical Acceptance Plan, used to evaluate product quality based on testing data, is typically the last piece of the agency Acceptance requirements (See Part 4 below). Typical QA Specification requirements for Acceptance are discussed in Chapter 6.

Part 3 - Develop Dispute Resolution Provisions

The third part of a QA Specification should provide the project-specific instructions for resolving disputes between the contractor and the agency. Dispute resolution provisions in a pilot QA Specification must build upon the dispute resolution system requirements outlined in the agency QA Program document. Dispute resolution provisions should address each of the following:

- Dispute resolution approach
    - Use of third party
    - Use of agency laboratory
- Dispute resolution personnel requirements
- Dispute resolution laboratory requirements
- Procedures for dispute resolution

The Dispute resolution approach should be specified, that is, whether a third party or another agency laboratory (other than the laboratory performing Acceptance testing for the project) will be used in the dispute resolution process. Requirements for qualifications of personnel and laboratories that perform dispute resolution activities should also be indicated. The specific procedures to be followed in the dispute resolution process must be clearly stated, including, but not limited to: identification of the location and limits of materials or workmanship in dispute; the use of split samples; additional sampling and testing that may be performed; and procedures for additional inspection activity.

Part 4 - Develop Statistical Acceptance Plan

The Acceptance Plan is a set of provisions within a specification that details how completed work will be accepted and paid based on testing data only. The fourth part of a complete QA Specification is typically a ***Statistical Acceptance Plan***. A Statistical Acceptance Plan applies mathematical probability-based criteria to evaluate test data and determine quality and corresponding payment.

Development of a Statistical Acceptance Plan involves the following six steps:

Step 1 - Confirm lot size, sublot size, and sample size.
Step 2 - Select Quality Measure.
Step 3 - Analyze available historic quality data.
Step 4 - Establish Quality Targets and Limits.
Step 5 - Develop pay adjustment provisions.
Step 6 - Assign and evaluate risks.

In Step 1, the lot and sublot size(s) established for Acceptance testing in the agency QA Program document must be confirmed. At a November 2006 FHWA hosted workshop, it was reported that in order to have a meaningful amount of test data, the recommended sample size (i.e., number of samples per lot) is a minimum of 20 to 30 material samples per lot. If contractor QC data is allowed in the acceptance decision, the minimum ratio of contractor QC samples to agency acceptance samples is 4:1 and, preferably, 2:1.

Step 2 requires selection of the mathematical Quality Measure that will be used to evaluate the test data and determine the quality of each lot. Quality Measures are further explained in Chapter 4.

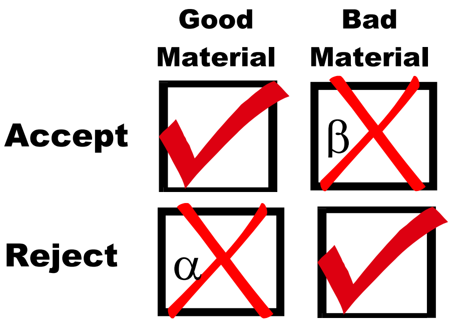
Step 3 involves analyzing historic random agency and contractor test data for the specific material(s) and Quality Characteristics that will be tested for Acceptance. The analysis is intended to identify the average (mean) quality level and amount of variability historically achieved.

In Step 4, the results of the historic data analysis should be used to assist in establishing targets and Quality Limits for each Quality Characteristic tested for Acceptance.

The 5th Step is to develop provisions for adjustment of contractor pay (i.e., incentives and disincentives) linked to the computed quality (using test data only) of each lot. Typical provisions for pay adjustment found in QA Specifications are presented in Chapters 6 and 10.

Step 6 of the Statistical Acceptance Plan development is to analyze and set the risks involved in performing work under the Acceptance Plan selected in the above five steps. The agency (buyer) can evaluate their risk of accepting what is actually bad material against the contractor (seller) who stands a risk of having good material rejected. These risks are generally defined by the following terms:

- Seller's (Contractor's) Risk = Alpha (α)
- Buyer's (Agency's) Risk = Beta (β)



The alpha and beta risks must be analyzed and in a well-written Acceptance Plan are, ideally, balanced. These risks are typically set in the 5% plus or minus range for both the agency and the contractor. Suggested alpha and beta risk levels are provided in the *AASHTO Standard Recommended Practice for Acceptance Sampling Plans for Highway Construction* (AASHTO R 9).

Operating Characteristic (OC) Curves and Expected Pay (EP) Curves can assist in establishing a balanced sharing of risk. An OC Curve provides a graphical presentation of the relationship between the quality level (e.g., PWL) of a lot *versus* the probability of acceptance. An EP Curve provides a graphical presentation of the quality level (e.g., PWL) *versus* the expected Pay Factor.

Phase III - Implement Pilot QA Specifications

The third phase for development of a sound QA Specification is the staged implementation of the pilot specifications prepared in Phase II described above. The implementation process for pilot QA Specifications includes the following activities:

- Develop and implement a Quality Assurance database.
- Ensure personnel training and qualification programs are in place.
- Ensure laboratory qualification program is in place.
- Implement pilot projects.
- Collect pilot project data and feedback.

The importance of developing a comprehensive ***Quality Assurance database*** system cannot be overstated. A construction QA database is needed by the agency to collect and evaluate data during the pilot implementation phase and beyond. A properly designed agency QA database system serves several key functions including: project-level data entry and analysis; program-wide review of data from multiple projects; and further evaluation of the Statistical Acceptance Plan used in the specifications. Before the pilot QA Specification implementation begins, it is also important to ensure that the applicable qualification programs for both contractor and agency personnel and laboratories are fully in place in accordance with the agency QA Program document.

With the pilot QA Specification prepared, a QA database up and running, and personnel and laboratory qualification programs in place, ***pilot projects*** can proceed. Pilot projects should be implemented over a minimum period of 3 to 5 years. This implementation period is needed to simulate all aspects of the QA Specifications and to collect meaningful data from the pilot projects and feedback from project personnel.

Phase IV - Evaluate and Refine QA Specifications

The last phase of QA Specification development is to evaluate and refine all aspects of the specifications. This includes the following activities:

- Analyze pilot project data and feedback.
- Address contractor and agency feedback.
- Validate Statistical Acceptance Plan.
- Revise and reissue QA Specifications.
- Reevaluate QA Specifications periodically.

Each of the four parts of a QA Specification (contractor QC requirements, agency Acceptance requirements, dispute resolution provisions, and Statistical Acceptance Plan) must be evaluated based on test data and other feedback obtained from the pilot projects implemented in Phase III. Analysis of QC test data and Acceptance test data will assist in better quantifying the inherent variability of materials produced and placed.

Feedback collected on inspection criteria and other requirements and procedures in the pilot QA Specifications should be used to refine the specifications. Data must be used to validate all aspects of the Statistical Acceptance Plan, including targets, quality limits, pay adjustment provisions, and the assignment of agency and contractor risks.

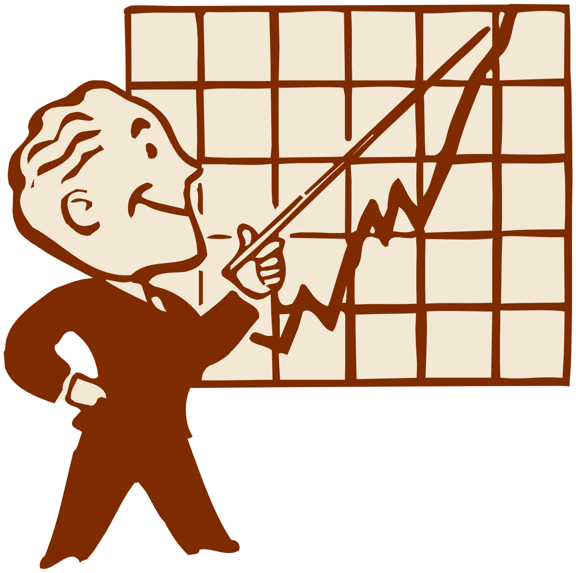
After the pilot project data and feedback have been fully evaluated, appropriate revisions should be incorporated into the QA Specifications. The QA Specifications should be ready for issuance as either a “Standard Specification” or an approved “Special Provision” for use in all agency projects. The agency, in consultation with the organizations involved in the initial QA Specification Task Force, should periodically reevaluate the specifications based on continually accumulated data and feedback.

3.8 - Transportation Construction Specifications Summary

The evolution of transportation construction specifications began with prescriptive and inspection-intensive Method Specifications. Some agencies considered but eventually dismissed End-Result Specifications. Due to a shortcoming of End-Result Specifications in relating quality to known variability and expected product performance, Quality Assurance Specifications have evolved. The future will see Performance-Related Specifications and perhaps Performance-Based Specifications.

With Quality Assurance Specifications, transportation products can be evaluated using material Quality Characteristics that are related to long-term product performance. As transportation agencies collect and evaluate actual performance data against as-constructed quality levels, QA Specifications can be continually improved.

Agencies should establish an ultimate goal of implementing Performance-Related Specifications, eventually followed by true Performance-Based Specifications. Before this can be achieved, however, it is necessary to first implement a properly developed Quality Assurance Specification.



- END OF CHAPTER 3 -

CHAPTER 4

Quality Measurement Fundamentals

Chapter 4

Quality Measurement Fundamentals

Chapter Overview

In this chapter, the following principles and related practices applied to measure construction quality are presented:

4.1 - Overview of Quality Measurement

Quality Measurement Tools

As presented in Chapter 1, a simple definition for quality is "conformance to requirements." How is the quality of a transportation construction product or work item determined? With QA, this is accomplished through ***Quality Measurement***. Quantitative tools are needed to measure the quality of construction work items. The two principal tools used to measure conformance with the requirements specified for each work item are:

- Inspection
- Testing

Webster's dictionary defines a tool as "anything which serves as a means to an end." Inspection and testing are the means used to accomplish the end of "quantified quality." A properly developed construction QA Program and complete QA Specifications require that data obtained through both inspection and testing be utilized to quantify product quality.

An understanding of what constitutes inspection *versus* testing has varied across transportation construction organizations. This chapter defines both of these quality measurement tools and explains the role of each tool in assessing construction quality.

Inspection

The first tool for quality measurement is ***inspection***. Inspection is defined as follows:

> **Inspection** - "The process of visual examination or physical measurement of an item for comparison against applicable requirements."

Inspection activities are primarily visual in nature. The characteristics (i.e., attributes) of a product or item are assessed using both visual observations (i.e., examination) and check measurements (i.e., physical measurement).

Examination involves visual observation or scrutiny of a product or material. Examples of items that are typically inspected through examination include segregation of HMA or honeycombing of PCC.

The information obtained from inspection by *examination* is primarily *subjective* and *qualitative*. An interpretation of whether examination findings show conformance with requirements can vary between persons, leading to "varying degrees of conformance." For example, in the absence of a clear standard reference, what is considered extensive segregation of HMA by one inspector may be considered only moderate by another inspector. However, inspection results through examination can be transformed into a quantitative format through the application of measures such as quantified checklists or scoring systems. One such approach is presented in Transportation Research Record 1712.

Inspection through physical measurement typically involves confirmation of product dimensions, material application rates, or atmospheric conditions (e.g., temperature, humidity). The equipment and corresponding procedures used to obtain physical measurements are typically simple (e.g., tape measures, thermometers), requiring only minimal training or experience to operate. Examples of items inspected through physical measurement include the tack application rate for an HMA pavement course or the temperature (e.g., ambient, surface, internal) of curing concrete.

The information collected from inspection by *physical measurement* is normally *objective* and *quantitative*. Inspection results from physical measurement can be quantified numerically.

Specific criteria required to measure quality with inspection data (whether from examination or physical measurement) are presented in Section 4.2 below.

Testing

Testing is the second tool for quality measurement. Testing is defined as follows:

> **Testing** - “The application of prescribed apparatus and procedures to characterize a specified property of a material or product.”

Testing is used to determine whether the physical or chemical characteristics of either a finished product or its constituent materials meet the established requirements. Testing differs from inspection (by examination) as it provides an *objective* and *quantitative* measurement tool. It provides numerical magnitude for a specified property (i.e., Quality Characteristic).

Testing requires equipment and standard protocols (i.e., test methods) that are generally more sophisticated than those utilized for inspection. This typically necessitates more in-depth training and higher levels of experience of personnel performing the testing.

Key characteristics and engineering properties related to the performance of a material or product can be uniformly and accurately measured with testing. For example, the percent air voids in an HMA pavement is an important product characteristic that relates to pavement performance. The strength of concrete is an example of an important engineering property necessary for structures or pavements to perform as designed. These characteristics can be objectively quantified through testing.

The criteria necessary for quality measurement with testing data are presented in Section 4.3 below.

4.2 - Measuring Quality with Inspection

Three quality measurement criteria must be established for a comprehensive inspection system. These criteria include:

- Inspection Components
- Inspection Attributes
- Conformance Measures

Each of these quality measurement criteria is explained below.

Inspection Components

A complete construction QA Program and QA Specifications should include inspection activities associated with each of the following four major ***Inspection Components***:

- Equipment
- Environmental conditions
- Materials
- Product workmanship

Inspection procedures for contractor Quality Control should address each of the four inspection components. The first two inspection components (i.e., equipment, environmental conditions) pertain only to the <u>quality of the process</u> for production or placement of an item. As will be further explained in Chapter 5, contractors need to use all four inspection components as feedback and information to control their processes.

The second two inspection components (i.e., materials, product workmanship) are intended to assess the quality of a product or completed work item. As is further discussed in Chapter 6, the inspection activities in an agency's Acceptance system should be focused on these two inspection components. The agency should use the information from these two inspection components to determine Acceptance of work items as they are completed.

Inspection Attributes

The way in which the four inspection components are applied becomes clearer when we identify specific ***attributes*** to be measured. An attribute is defined as follows:

> **Attribute** - "A characteristic that, by its presence or absence, classifies an item as conforming or nonconforming."

Inspection attributes should be selected that directly relate to one of the four inspection components. Unfortunately, many construction specifications (including QA Specifications) have not clearly identified the specific attributes to be inspected. FHWA requirements for Agency Construction QA Programs (23 CFR 637) necessitate the "identification of the specific attributes to be inspected which reflect the quality of the finished product" (23CFR637.207). New AASHTO guidelines for Construction QA Programs being developed by the AASHTO Subcommittee on Construction likewise include recommended minimum requirements that address inspection attributes.

In addition to providing requirements for inspection attributes in an agency's QA Program document, agencies should include the attributes to be measured in their Quality Assurance Specifications and should distinguish those attributes required for Quality Control from those required for Acceptance. As discussed below, a comprehensive Construction QA Program and complete Quality Assurance Specifications will normally identify a greater number of inspection attributes for contractor QC than for agency Acceptance.

Inspection Attributes for QC

Inspection attributes used for QC should be directly related to maintaining control of production and placement processes to ensure conformance with the requirements for each item of work. Additionally, attributes selected for QC inspection will contribute either directly or indirectly to the long-term performance of the product.

The minimum number and type of attributes which require QC inspection should be specified by the agency. However, contractors should look beyond the minimum agency requirements and include in their Quality Control system all attributes necessary to ensure proper control of their processes.

Inspection attributes for contractor QC should address each of the four major inspection components (i.e., equipment, environmental conditions, materials, product workmanship).

Examples of typical inspection attributes for QC of Hot-Mix Asphalt (HMA) and Portland Cement Concrete (PCC) are presented in the following table:

Examples of Inspection Attributes for Quality Control (QC)

Inspection Component	Hot-Mix Asphalt (HMA)	Portland Cement Concrete (PCC)
Equipment	• Haul Unit Bed Covers	• Mixer Drum Blade Condition
	• Paver Screed Settings	• Vibrator Frequency
	• Vibratory Roller Settings	• Finishing Machine Settings
Environmental Conditions	• Underlying Surface Cleanliness & Moisture	• Form Cleanliness
	• Temperature of Air & Underlying Surface	• Temperature of Air & Contact Surfaces
Materials	• Aggregates & PG Binder (Correct Type)	• Aggregates & Cementitious Material (Correct Type)
	• Asphalt Emulsion Tack (Correct Type)	• Admixtures (Correct Type & Dosage)
	• Temperature of Delivered HMA Mix	• Temperature of Delivered PCC Mix
Workmanship	• Tack Application Rate	• Form Dimensions
	• Joint Location & Alignment	• Reinforcement Bar Layout
	• Physical Segregation	• Finished Dimensions
	• Joint Tightness	• Surface Defects (Honeycombing, Cracking)

The inspection attributes identified in the table above are examples for only two predominantly used project produced materials (HMA and PCC). Specific inspection attributes for Quality Control of other transportation construction materials should be consistent with the requirements contained in the agency QA Program and applicable QA Specifications.

Inspection Attributes for Acceptance

The agency Acceptance function is focused on the quality of completed work items (and their constituent materials), rather than the process quality. Inspection attributes for Acceptance should relate directly to long-term product performance. Accordingly, attributes inspected for Acceptance should be associated only with the inspection components of materials and product workmanship. The number of attributes selected for Acceptance inspection will vary depending upon the work item.

Examples of typical inspection attributes for Acceptance of HMA and PCC are presented in the table below:

Examples of Inspection Attributes for Acceptance		
Inspection Component	**Hot-Mix Asphalt (HMA)**	**Portland Cement Concrete (PCC)**
Materials	• Aggregates & PG Binder (Correct Type)	• Aggregates & Cementitious Material (Correct Type)
	• Asphalt Emulsion Tack (Correct Type)	• Admixtures (Correct Type & Dosage)
Workmanship	• Tack Application Rate	• Finished Dimensions
	• Joint Location & Alignment	• Surface Defects (Honeycombing, Cracking)
	• Physical Segregation	
	• Joint Tightness	

Again, the inspection attributes shown in the table above are only examples for HMA and PCC. Specific inspection attributes utilized for Acceptance of all transportation construction work items should be established in the agency QA Program document and QA Specifications.

Conformance Measures

The observations and measurements made through inspection are compared to the required attributes for the item being inspected. The comparison of the inspection result for each attribute to the corresponding requirement yields a determination of ***conformance*** (or non-conformance) for each attribute. Conformance is defined as follows:

> **Conformance** - "An affirmative indication or judgment that a product or process meets specified requirements."

The level or degree of conformance can be expressed in different ways, depending upon the particular ***conformance measure*** applied to the inspection attributes. The definition of conformance measure is as follows:

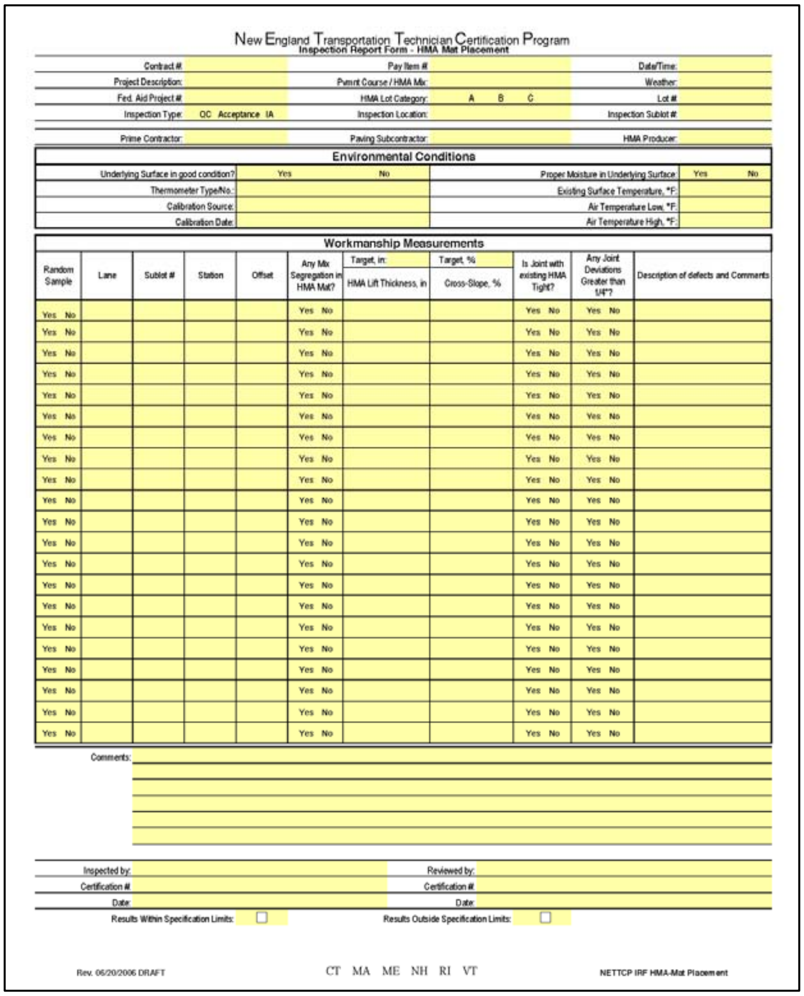
> **Conformance Measure** - "The method used to evaluate inspection findings to determine the degree of product conformance with quality requirements."

The conformance measure used can be very simple and qualitative or can utilize a numeric or quantitative approach. The typical conformance measures applied include the following:

- Pass/Fail
- Percent Conforming
- Numeric Score

The determination of conformance for all attributes inspected (whether for QC or Acceptance) should be made using at least one of these conformance measures. An agency may elect to apply one conformance measure (e.g., pass/fail) on some attributes and another (e.g., numeric score) on other attributes. Each of these conformance measures is briefly described below.

The ***Pass/Fail*** approach is the simplest conformance measure to apply. The inspection results for a particular attribute are determined to meet one of two possible outcomes (i.e., pass or fail). Examples of the descriptors typically used for the two outcomes include the following: conforming or non-conforming; yes or no; meets or does not meet; present or missing. Standard Inspection Report Forms (IRFs) or checklists are needed that list all of the inspection attributes for a particular work item. The pass/fail approach can be applied to attributes inspected through both visual examination and physical measurement. At a minimum, agencies should implement this conformance measure to document and evaluate conformance with quality requirements for both contractor QC and agency Acceptance. An example of an IRF using the pass/fail method as the inspection conformance measure is shown below.



New England Transportation Technician Certification Program
Inspection Report Form - HMA Mat Placement

Contract #:
Pay Item #:
Date/Time:
Project Description:
Pvmnt Course / HMA Mix:
Weather:
Fed. Aid Project #:
HMA Lot Category: A B C
Lot #:
Inspection Type: QC Acceptance IA
Inspection Location:
Inspection Sublot #:
Prime Contractor:
Paving Subcontractor:
HMA Producer:

Environmental Conditions

Underlying Surface in good condition? Yes No
Proper Moisture in Underlying Surface: Yes No
Thermometer Type/No.:
Existing Surface Temperature, °F:
Calibration Source:
Air Temperature Low, °F:
Calibration Date:
Air Temperature High, °F:

Workmanship Measurements

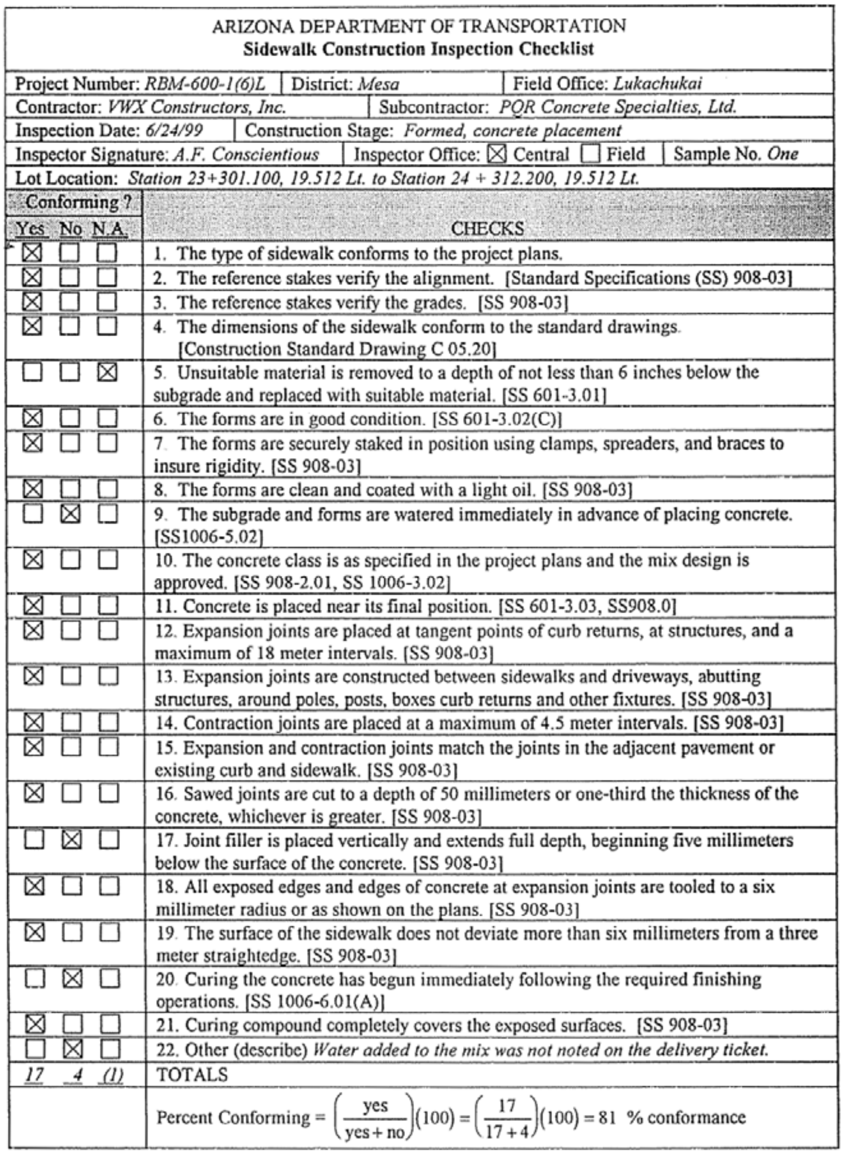
Random Sample	Lane	Sublot #	Station	Offset	Any Mix Segregation in HMA Mat?	Target, in:	Target, %:	Is Joint with existing HMA Tight?	Any Joint Deviations Greater than 1/4"?	Description of defects and Comments
						HMA Lift Thickness, in	Cross-Slope, %			
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	
Yes No					Yes No			Yes No	Yes No	

Comments:

Inspected by:
Reviewed by:
Certification #:
Certification #:
Date:
Date:
Results Within Specification Limits: ☐
Results Outside Specification Limits: ☐

Rev. 06/20/2006 DRAFT
CT MA ME NH RI VT
NETTCP IRF HMA-Mat Placement

The ***Percent Conforming*** approach uses the inspection results from the pass/fail method and provides an aggregate measure of quality for a process or product. This conformance measure has been utilized by Arizona DOT since the mid 1990s and is outlined in Transportation Research Record 1712. Quantified Checklists are used that contain all of the inspection attributes for a given process or product. The checklist contains a column to check off the inspection outcome (pass or fail) for each attribute. The percentage of attributes that conforms to the requirements (i.e., percent conforming) is determined by dividing the number of attributes with a passing outcome by the total number of attributes inspected and converting this ratio to a percentage. An example Quantified Checklist for sidewalk construction inspection (provided by Arizona DOT) is shown to the left. For further details on this method, refer to Transportation Research Record 1712.



ARIZONA DEPARTMENT OF TRANSPORTATION
Sidewalk Construction Inspection Checklist

Project Number: *RBM-600-1(6)L* | District: *Mesa* | Field Office: *Lukachukai*
Contractor: *VWX Constructors, Inc.* | Subcontractor: *PQR Concrete Specialties, Ltd.*
Inspection Date: *6/24/99* | Construction Stage: *Formed, concrete placement*
Inspector Signature: *A.F. Conscientious* | Inspector Office: ☒ Central ☐ Field | Sample No. *One*
Lot Location: *Station 23+301.100, 19.512 Lt. to Station 24 + 312.200, 19.512 Lt.*

Conforming ?			CHECKS
Yes	No	N.A.	
☒	☐	☐	1. The type of sidewalk conforms to the project plans.
☒	☐	☐	2. The reference stakes verify the alignment. [Standard Specifications (SS) 908-03]
☒	☐	☐	3. The reference stakes verify the grades. [SS 908-03]
☒	☐	☐	4. The dimensions of the sidewalk conform to the standard drawings. [Construction Standard Drawing C 05.20]
☐	☐	☒	5. Unsuitable material is removed to a depth of not less than 6 inches below the subgrade and replaced with suitable material. [SS 601-3.01]
☒	☐	☐	6. The forms are in good condition. [SS 601-3.02(C)]
☒	☐	☐	7. The forms are securely staked in position using clamps, spreaders, and braces to insure rigidity. [SS 908-03]
☒	☐	☐	8. The forms are clean and coated with a light oil. [SS 908-03]
☐	☒	☐	9. The subgrade and forms are watered immediately in advance of placing concrete. [SS1006-5.02]
☒	☐	☐	10. The concrete class is as specified in the project plans and the mix design is approved. [SS 908-2.01, SS 1006-3.02]
☒	☐	☐	11. Concrete is placed near its final position. [SS 601-3.03, SS908.0]
☒	☐	☐	12. Expansion joints are placed at tangent points of curb returns, at structures, and a maximum of 18 meter intervals. [SS 908-03]
☒	☐	☐	13. Expansion joints are constructed between sidewalks and driveways, abutting structures, around poles, posts, boxes curb returns and other fixtures. [SS 908-03]
☒	☐	☐	14. Contraction joints are placed at a maximum of 4.5 meter intervals. [SS 908-03]
☒	☐	☐	15. Expansion and contraction joints match the joints in the adjacent pavement or existing curb and sidewalk. [SS 908-03]
☒	☐	☐	16. Sawed joints are cut to a depth of 50 millimeters or one-third the thickness of the concrete, whichever is greater. [SS 908-03]
☐	☒	☐	17. Joint filler is placed vertically and extends full depth, beginning five millimeters below the surface of the concrete. [SS 908-03]
☒	☐	☐	18. All exposed edges and edges of concrete at expansion joints are tooled to a six millimeter radius or as shown on the plans. [SS 908-03]
☒	☐	☐	19. The surface of the sidewalk does not deviate more than six millimeters from a three meter straightedge. [SS 908-03]
☐	☒	☐	20. Curing the concrete has begun immediately following the required finishing operations. [SS 1006-6.01(A)]
☒	☐	☐	21. Curing compound completely covers the exposed surfaces. [SS 908-03]
☐	☒	☐	22. Other (describe) *Water added to the mix was not noted on the delivery ticket.*
17	*4*	*(1)*	TOTALS
			Percent Conforming = $\left(\frac{\text{yes}}{\text{yes}+\text{no}}\right)(100)=\left(\frac{17}{17+4}\right)(100)=81$ % conformance

The ***Numeric Score*** approach provides more than two possible outcomes for an inspection result. This conformance measure assigns a numeric value to each attribute inspected. The inspection result for each attribute is selected from a range or scale of values (e.g., 0 to 4). For example, to characterize the absence/presence of honeycombing or surface voids in the surface of a concrete structure, a value of “4” might represent “no honeycombing present” and a value of “0” would represent “extensive honeycombing.” Individual scores for all attributes may be totaled or combined to provide a composite score for the process or product inspected.

Although the numeric score approach will produce a quantitative score, the result for each attribute is subjectively determined by an inspector. In order to minimize this subjectivity, a numeric score system should include a clear standard reference that either describes or shows visually the condition associated with each score within the scale of score values.

Based on the preliminary results of a 2007 AASHTO Subcommittee on Construction survey on “Best Practices for Inspecting and Measuring Quality of Workmanship,” it appears that few, if any, agencies are currently using the numeric score approach. Further research and piloting of the numeric score approach is needed before it is adopted for widespread use by transportation agencies as a conformance measure for inspection data.

4.3 - Measuring Quality with Testing

In order to assess the quality of products or work items through testing, the following three criteria must be identified:

- Quality Characteristics
- Quality Measures
- Quality Limits

Each of these Quality measurement criteria is discussed below.

Quality Characteristics

As part of a complete Construction QA Program, contractor Quality Control testing and agency Acceptance testing are utilized to measure the quality of construction. The specific ***Quality Characteristics*** to be tested for QC and Acceptance should be established in an agency's QA Program document and QA Specifications. A Quality Characteristic is defined as follows:

> **Quality Characteristic** - A product characteristic that is measured through testing, either for Quality Control (QC) purposes or for conformance with Acceptance requirements.

Quality Characteristics are specific material properties or product requirements which are evaluated by QC and Acceptance testing. Quality Characteristics which are specified are normally selected because they:

- Relate to initial and long-term performance.

- Are quantifiable or measurable.

- Can be measured with good repeatability.

Many of the Quality Characteristics selected for testing with Quality Assurance Specifications are the same as those which have been used under past (Method or End-Result) Specifications. Agency QA Program documents need to identify the required Quality Characteristics to be measured in the Quality Assurance Specifications and will distinguish those characteristics required for Quality Control from those required for Acceptance. As discussed below, QA Programs and QA Specifications will normally identify a greater number of Quality Characteristics for QC than for Acceptance.

Quality Characteristics for QC

Quality Characteristics for QC are selected because they are good indicators to monitor and control production against specification targets and limits. In addition, Quality Characteristics selected for QC contribute either directly or indirectly to the long-term performance of the product. The number of Quality Characteristics which require QC testing will vary from agency to agency, but is typically a minimum of five to ten Quality Characteristics. Contractors should ensure that their Quality Control system includes testing of all Quality Characteristics needed to ensure that their production and placement processes are providing the required level of quality.

Examples of typical Quality Characteristics for QC of Hot-Mix Asphalt (HMA) and Portland Cement Concrete (PCC) are presented in the following table:

Typical Quality Characteristics Utilized for Quality Control (QC)	
Hot-Mix Asphalt (HMA)	**Portland Cement Concrete (PCC)**
• Aggregate Consensus Properties	• Aggregate Gradation
• Aggregate Gradation (Cold Feed)	• Cement Content
• PG Asphalt Binder Content	• Water Content
• Combined Aggregate Gradation	• Water/Cementitious Ratio
• Max. Theoretical Specific Gravity	• Slump
• Bulk Specific Gravity	• Air Content
• Air Voids, VMA, VFA	• Unit Weight
• Dust-to-Binder Ratio	• Compressive Strength
• Gyratory Compaction Curve	• Cover
• In-Place Density	
• Thickness	
• Ride Quality	

The Quality Characteristics identified in the previous table are examples for only two predominantly used project produced materials (HMA and PCC). Quality Characteristics utilized for QC of other transportation construction materials are normally identified in agency specifications.

Quality Characteristics for Acceptance

Quality Characteristics for Acceptance are selected because they directly relate to the long-term performance of the product. The specifying agency must determine the Quality Characteristics to be tested in order to assure good performance over the design life of the transportation product. This requires astute materials engineering. For HMA pavements, an example of two principal Quality Characteristics that can be measured, which are critical to good pavement performance, are the density of the compacted pavement and pavement smoothness. For PCC structures and pavements, we can use compressive strength, air content and smoothness. Soils Quality Characteristics that can be measured for good performance may include in-place density and gradation.

The number of Quality Characteristics which require Acceptance testing will vary from agency to agency, but is typically between three and six Quality Characteristics (depending upon the work item). Examples of typical Quality Characteristics for Acceptance of HMA and PCC are presented in the table below:

Typical Quality Characteristics Utilized for Acceptance	
Hot-Mix Asphalt (HMA)	**Portland Cement Concrete (PCC)**
• PG Asphalt Binder	• Air Content
• Air Voids	• Compressive Strength
• In-Place Density	• Cover
• Thickness	• Permeability
• Ride Quality	• Ride Quality

Again, the Quality Characteristics identified in the table above are only examples for HMA and PCC. Quality Characteristics utilized for Acceptance of other transportation construction materials are normally identified in agency specifications.

Quality Measures

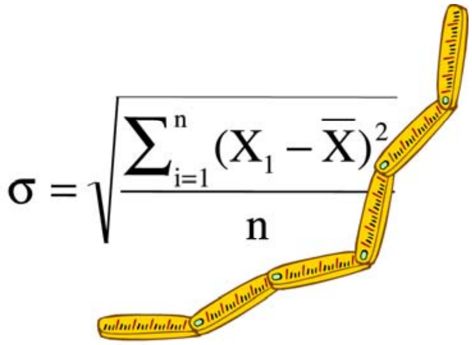
For each Quality Characteristic tested, the ***Quality Measure*** to be used to determine the actual quality of the material or product must be selected. The term Quality Measure is defined as follows:

> **Quality Measure** - “Any one of several mathematical tools that are used to quantify the level of quality of an individual Quality Characteristic.”

Application of a Quality Measure to a set of testing data provides an overall numeric representation of quality for a specific Quality Characteristic. Typical Quality Measures used in Quality Assurance are selected because they quantify the average quality, the variability, or both.

Examples of Quality Measures that may be used include:

- Mean
- Standard Deviation
- Percent Defective (PD)
- Percent Within Limits (PWL)
- Average Absolute Deviation (AAD)
- Moving Average
- Conformal Index (CI)



$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (X_1 - \overline{X})^2}{n}}$$

For example, the mean of all strength test results might be specified as the Quality Measure for a lot of Portland Cement Concrete. Or, the Percent Within Limits (PWL) of all in-place density test results might be used as the Quality Measure for a lot of Hot-Mix Asphalt.

PWL or PD are the Quality Measures that are recommended for use in Quality Assurance Specifications.

Quality Limits

A Quality Measure cannot be applied to a set of testing data without the use of appropriately developed ***Quality Limits***. Each Quality Characteristic must have Quality Limits that are established in the construction specifications. Quality Limits are defined as follows:

> **Quality Limits** - "The upper or lower limiting values provided in the specifications that are used to evaluate the acceptability of materials produced or placed."

There are three types of Quality Limits that are typically included in Quality Assurance Specifications. These are:

- Specification Limits
- Engineering Limits
- Acceptance Limits

Each type of Quality Limit serves a different specific function in assessing the quality of a product or work item. Quality Limits are used together to determine the quality of an individual Quality Characteristic.

Specification Limits are statistical limits that are applied to the test results of multiple samples when determining the quality of a lot using some Quality Measure such as PWL or PD. They are usually comprised of an Upper Specification Limit (USL), a Lower Specification Limit (LSL), or both. It is important to recognize that since these are statistical limits, individual sample test results may fall beyond the USL or LSL and still be included in the Acceptance determination.

All Quality Characteristics require ***Engineering Limits***. They are used in conjunction with Specification Limits (for those Quality Measures that apply Specification Limits). An Engineering Limit provides an absolute threshold value for individual test results. As an example, strength test results for Portland Cement Concrete are typically evaluated using the mean of three consecutive test results. However, it is still required that no individual test result falls below a specified Engineering Limit. Engineering Limits are established to identify material that does not provide the minimum required engineering properties. They usually have an Upper Engineering Limit (UEL), a Lower Engineering Limit (LEL), or both. Individual sample test results that fall beyond the Engineering Limits are considered to represent material that appears to be below an acceptable level and which should be further evaluated to determine an appropriate disposition.

Acceptance Limits are limits that are placed on the Quality Measure (e.g., the minimum allowable PWL), not on the individual test values for an individual Quality Characteristic. While the individual test values for a Quality Characteristic are evaluated with Specification Limits and Engineering Limits, it is the overall computed quality level derived for multiple test values that is evaluated against the Acceptance Limit.

One of the challenges of transitioning into Quality Assurance Specifications is that much of an agency's past historic test data cannot be used to establish Quality Limits. Although many agencies may use this past data to set the initial targets and limits for the various Quality Characteristics, it must be realized that these test results were often based upon non-random data, which may result in Quality Limits that are too loose or too stringent. To develop appropriate mathematical probability based Quality Limits, an agency must have random historic testing data that reflects the known variability of the materials produced and placed. Quality Limits should be established using known local variability, in conjunction with good national industry standards, for each Quality Characteristic.

4.4 - Using Sampling for Inspection & Testing

Establishing Populations

In order to properly quantify the quality of a specific item through either inspection or testing, we must first identify the item being measured according to the discrete ***population*** to which it belongs. A population is defined as follows:

> **Population** - "A collection of all possible individuals, objects, or items that possess some common specified characteristic(s) which can be measured."

Some examples of populations and corresponding common characteristics (including some related to transportation construction) are shown in the following table:

Example Population	Common Characteristic
• All people on a basketball team	• Height
• All people in this classroom	• Age
• All grapes in a bunch	• Size
• All 4000 psi (30 MPa) PCC in a bridge deck	• Strength
• All 19 mm HMA surface course per 5 lane-miles	• Thickness

We cannot make a valid determination of the quality of construction unless all of the observations or measurements obtained for a specific work item or material are from the same population. Therefore, it is important to establish populations in construction in a way that reasonably ensures that each work item or material being measured possesses the same specified characteristics.

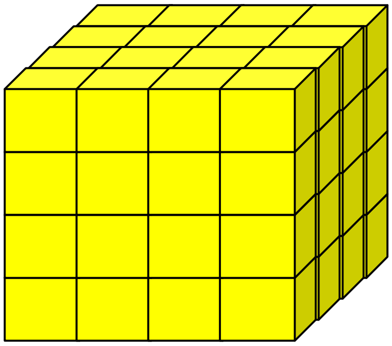
Sampling

An approach is needed to determine when and where to inspect the attributes or to test the Quality Characteristics for each population of a construction work item. This requires the application of ***sampling.*** The term sampling is defined as follows:

> **Sampling** - "The process of selecting one or more samples from a population."

Sampling is an integral part of contractor Quality Control, as well as agency Acceptance. Sampling procedures should be established and applied for both inspection and testing activities. An effective sampling system delineates a population according to measurable segments. The key elements of a sampling system include:

- Lots
- Statistical samples
- Sublots
- Samples



Each of these sampling elements is explained below.

Lots

In a Quality Assurance Program, the term ***lot*** is used to represent a population of either a constructed product (e.g., HMA, PCC, soils, steel, pavement markings, etc.) or one of its constituent materials (e.g., PG asphalt binder, cement, aggregates). A ***lot*** is defined as follows:

> **Lot** - "A specific quantity of material from a single source which is assumed to be produced or placed by the same controlled process."

To be consistent with this definition, the size of individual lots should be specified such that the ***lot size*** represents material which is in fact from the same source and which has been produced and placed essentially under the same controlled conditions. Lot sizes should be established in an agency's QA Program and QA Specifications to address both inspection and testing of all work items.

Agencies may specify a lot as the entire quantity of material produced and placed on a project for a particular product or item. A benefit of specifying the entire product quantity as a lot is that it provides more data points (samples) with which to assess the quality of the lot. Some inherent drawbacks to this approach, however, are that:

- The lot may consist of material produced and placed over an extended period of time (1 to 2 years or more).
- The entire quantity of the subject lot may not have been truly produced and placed under the same conditions (e.g., changes in equipment, weather conditions, materials source, etc.).
- Since Quality Assurance contract pay adjustments are calculated for individual lots, specifying the entire quantity for a particular item as a lot may result in a pay adjustment that is unfair to either the agency or the contractor.

Accordingly, it is recommended that lot sizes be specified as a quantity of a production run or an amount of material placed which is less than the entire product quantity.

The unit of measure selected for a lot is normally specified as a quantity of:

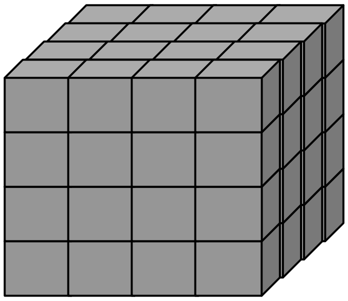
- Material production time (days).
- Produced material mass (tons/megagrams).
- Produced material volume (cubic yards/cubic meters).
- In-place material area (square feet/square meters).
- In-place material length (miles/kilometers).

The lot size and corresponding unit of measure selected is a function of each inspection attribute or Quality Characteristic that is specified to be evaluated. Examples of typical lot sizes and units of measure for some inspection attributes and Quality Characteristics are presented in the tables below:

Example Inspection Attribute	Lot Size/Unit of Measure
• Temperature of Delivered HMA	• 15,000 tons (13,608 Mg) of HMA produced
• Tack Coat Application Rate	• 25,000 lane-ft (7,620 lane-m) of Pavement Surface
• PCC Finished Dimensions	• Total Length (ft) of PCC Element
• PCC Surface Defects (Cracking)	• 5,000 square feet (465 m^2) of PCC Surface

Example Quality Characteristic	Lot Size/Unit of Measure
• Soil In-Place Density	• 7,500 lane-ft (2,286 lane-m) of Roadway Subgrade
• Cold Feed Aggregate Gradation	• 5 days of Mix production
• HMA Thickness	• 25,000 lane-ft (7,620 lane-m) of Pavement Surface
• PCC Air Content	• 1,250 cubic yards (956 m^3) of PCC placed

Complete Enumeration

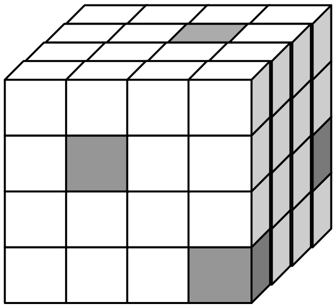


Complete Enumeration

In order to measure a particular inspection attribute or a Quality Characteristic for a lot, we could inspect or test every part of the lot. For example, let's assume that we want to determine the shear strength of structural bolts throughout a lot of 5,000 structural bolts used on a bridge project. We could sample and test every structural bolt in the lot (i.e., 5,000 individual samples). However, we wouldn't have any bolts left to use on the project. Such an approach is referred to as "**complete enumeration.**"

Similarly, let's assume that we want to determine the PCC air content throughout a lot of 1,500 cubic yards (1,147 m^3) of PCC placed in a bridge deck. We could sample and test every cubic yard (cubic meter) of PCC in the lot. This would require 1,500 individual material samples of PCC to be taken and tested. Although this is technically not complete enumeration (i.e., we haven't sampled every bit of PCC in the lot), it would still represent a significant amount of sampling and testing from the lot of PCC.

Statistical Sample



Statistical Sample
(Dark Box = Sample

Obviously, it is not practical or cost-effective for us to inspect or test any lot through complete enumeration or by means that approach complete enumeration. Accordingly, this is why we only obtain a ***statistical sample*** from a lot in order to arrive at an <u>estimated</u> measurement of the inspection attributes or Quality Characteristics for that lot. The term statistical sample (also called ***sample***) is defined as follows:

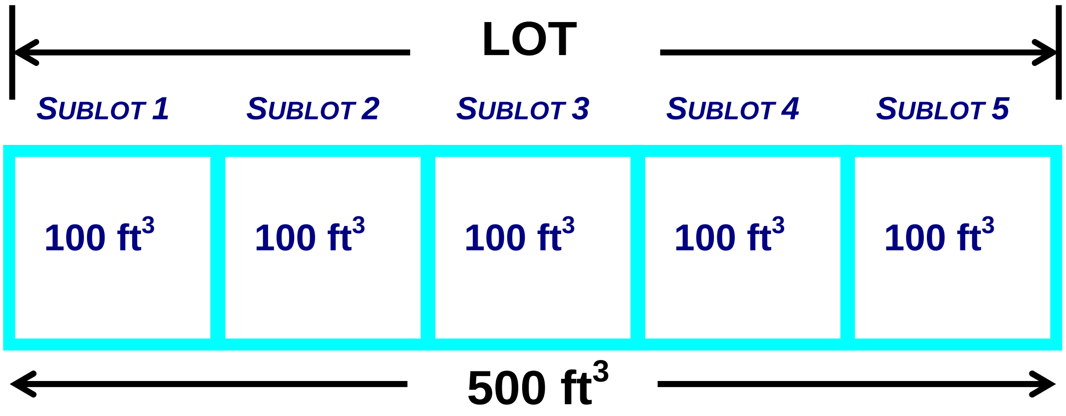
> **Statistical Sample** - "All of the samples obtained from a lot which provide information that may be used to quantify the quality of the entire lot."

Sublots

Lots are typically divided into smaller quantity amounts of uniform size which are referred to as ***sublots*.** Accordingly, a sublot is defined as follows:

> **Sublot** - “A subdivision of a lot.”

A sublot is an equal (usually) division or part of a lot from which a sample of material is obtained in order to assess the inspection attributes or Quality Characteristics of the lot. Sublots are established to ensure that samples of material obtained from the lot are not all concentrated in one location. Sublots allow samples to be taken from within different segments (beginning, middle, end) of the lot.



Sublot sizes should be identified in an agency’s QA Program and QA Specifications to address the inspection attributes and Quality Characteristics to be measured. All sublots should be inspected and tested by the contractor for Quality Control. If an agency elects to include validated QC data in its acceptance determination, the agency may elect to only inspect and test some of the sublots. Guidance issued by the FHWA in 2007 recommends that when contractor QC data is included in the agency Acceptance determination, a minimum of 7 to 10 agency Acceptance results be obtained and validated against a maximum of 20 to 30 contractor QC results. This is to ensure that the validation procedures can provide a reasonable comparison of the two data sets. One way to address this is by limiting the number of sublots for each lot to a maximum of 20 to 30 sublots.

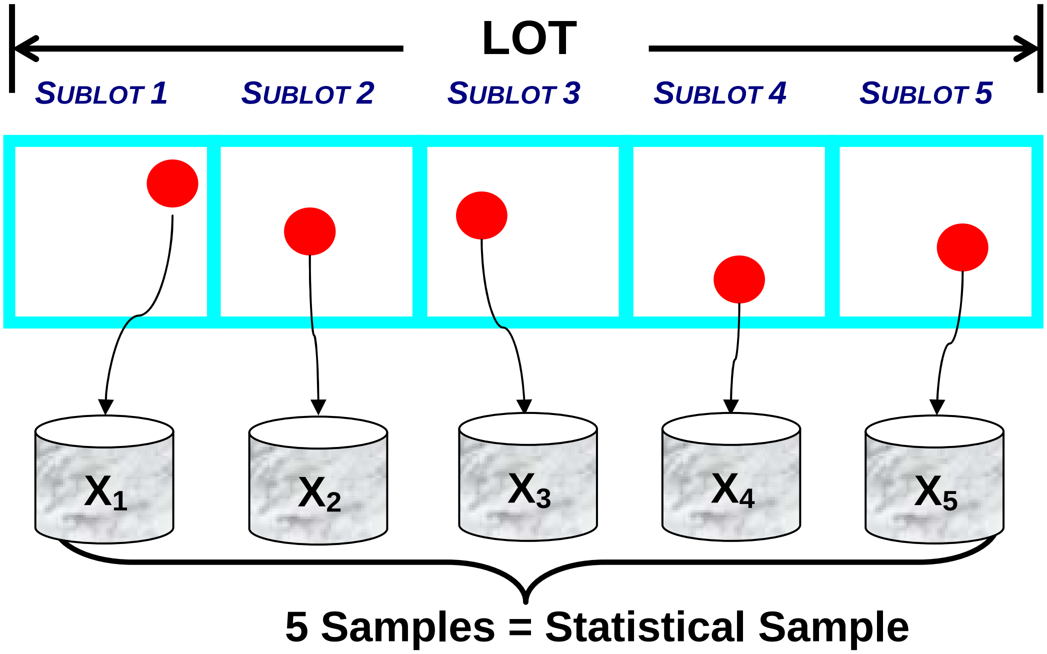
Sample

A ***sample*** can refer to either a point of inspection (i.e., visual examination or physical measurement) or an individual material sample obtained for testing. The term sample (also called ***material sample***) is defined as follows:

> **Sample** - "A small quantity of material or measurement obtained from a sublot or lot."

Note that the term "sample" is also used by mathematicians to denote a "statistical sample". The term statistical sample refers to multiple samples that are obtained from the lot and should not be confused with an individual material sample. Each sample is included in the overall statistical sample for a given lot.

Typically, one sample is obtained from each sublot of material for QC or Acceptance. Each sample is typically denoted by the term "$\mathbf{x_i}$". For example, the notation "x_1, x_2, x_3" represents the individual results for samples obtained from Sublot 1, Sublot 2, and Sublot 3, respectively.



In order to have a mathematically sound statistical sample, a lot should contain a minimum of three (3) samples. However, it is recommended that each lot be represented by a greater number of samples (typically 7 to 30). Normally, only one random sample will be obtained from each sublot for QC or Acceptance. Examples of typical sublot sizes and the corresponding number of samples (n) for a lot are presented in the following table:

Lot Size	Sublot Size	Samples per Lot (n)
7,500 lane-ft (2,286 lane-m) of Subgrade	300 feet (91 meters)	25
5 Days of Mix production	1 Day	5
15,000 tons (13,608 Mg) of HMA	500 tons (454 Mg)	30
25,000 lane-ft (7,620 lane-m) of Pavement Surface	1,000 feet (305 meters)	25
1,250 cubic yards (956 m^3) of PCC	50 cubic yards (38 m^3)	25
5,000 square feet (465 m^2) of PCC	500 square feet (46 m^2)	10

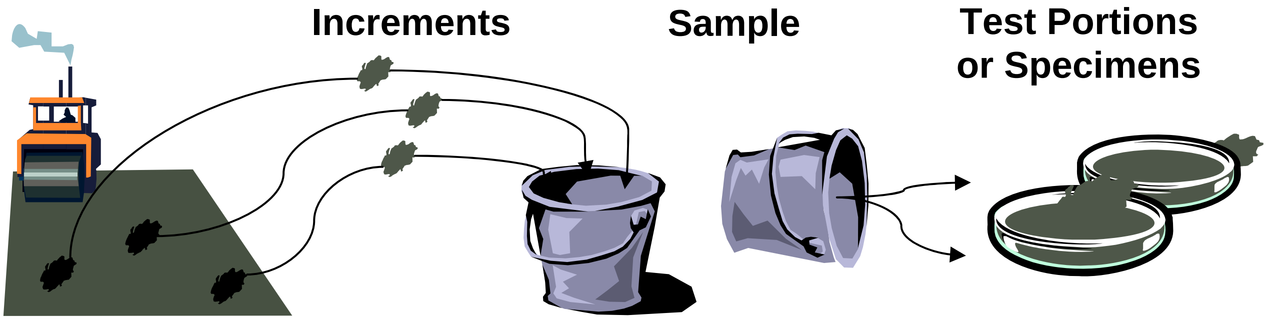
Increasing the number of samples provides a more discriminating estimate of the quality of a lot. This can reduce an agency's risk of accepting a lesser quality product or material and reduce the risk to contractors of having material that is at or above an acceptable quality level rejected.

The test results from the individual samples from each sublot are mathematically evaluated together to determine the overall quality of the lot. The type of sampling required to ensure that the samples provide a valid representation of the lot is discussed below.

Increments versus Test Portions or Specimens

A sample may be comprised of one or more ***increments*** of equal size that have been obtained from the sampling location and combined. Inspection protocols for visual examination and physical measurement should indicate whether multiple measurements (i.e., increments) are to be obtained. The number of Increments that should be obtained and combined to make up a material sample for testing is normally specified in the relevant individual AASHTO or ASTM *Methods of Sampling and Testing*.

When a material sample is prepared for testing, it may be split into multiple ***test portions*** or ***specimens***. Again, AASHTO or ASTM will normally specify if multiple specimens are required to be prepared and tested for a given test method. For example, the testing of PCC for strength requires that two (2) specimens be prepared and tested from an individual material sample. Testing of HMA in a Gyratory Compactor, likewise, requires that two specimens be prepared and tested. The final test result for an individual sample will be the average of the test values obtained from the two specimens.



4.5 - Biased Sampling

In order to obtain a valid statistical sample for a given lot of material, it is important that the individual samples are selected such that each sample within the lot has an equal probability of being chosen. For this to occur, a sampling technique based on random selection must be applied. If the selection of samples is not based on a random procedure, the statistical sample will be biased and, therefore, not truly representative of the lot of material. Such a non-random selection process is referred to as ***biased sampling***. Accordingly, biased sampling is defined as follows:

> **Biased Sampling** - "A sampling procedure whereby samples obtained from a lot do not have an equal probability of being chosen."

Conventional biased approaches to sampling which have been utilized by agencies and contractors include the following:

- Representative Sampling
- Uniform Interval Sampling
- Quota Sampling
- Selective Sampling

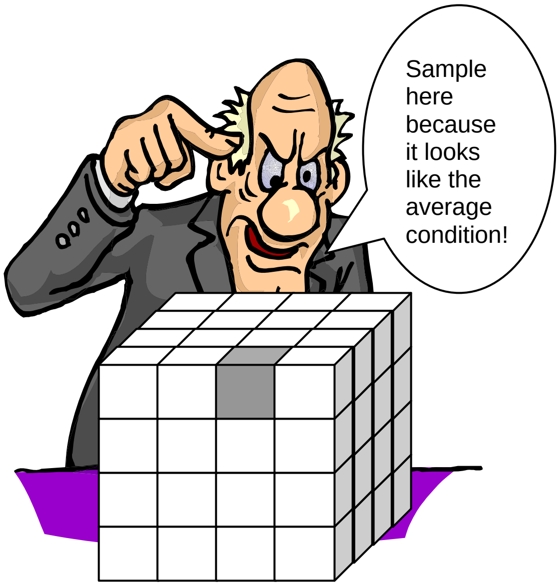
The first three forms of biased sampling listed above have absolutely no place in Quality Assurance. Selective sampling has <u>limited</u> application in a Quality Assurance environment for Quality Control or when isolating known defective material as discussed further below. Each of these types of biased sampling will be briefly explained below.

Representative Sampling

The single ***representative sample*** concept, unfortunately, continues to persist among construction and materials personnel. A representative sample is defined by AASHTO R 10 as follows:

> **Representative Sample** - “A single, non-random sample which, in the opinion of the sampler, represents an average condition of a material or an item of construction.”

Many agencies and contractors have operated under the belief that the result from a single so-called representative sample, obtained from a location at the discretion of the sampler, indicates the true quality of the product inspected or material tested. Furthermore, the belief persists that if an individual result is not within the specification requirements, there is something wrong with the material, construction, sampling, inspection, or testing.



Representative Sample
(Dark Box = Sample Obtained)

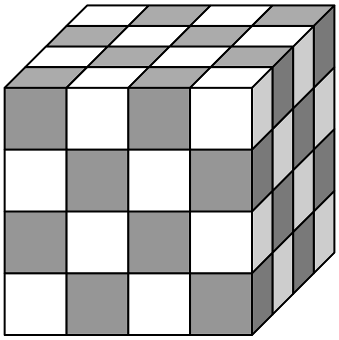
On the contrary, the term representative sample is truly a misnomer, since such a sample does not provide a meaningful representation of a lot of material. It must be understood that one or two individual representative samples do not present a valid picture of the actual variability of the material or product being evaluated. Based on probability, the result for a single sample could fall within or outside the specification requirements by chance and be due to the inherent variability in the material, or be due to variation in sampling, inspection, or testing.

Uniform Interval Sampling

The second form of biased sampling which is sometimes used by contractors and agencies is ***uniform interval sampling***. As its name implies, uniform interval sampling is defined as follows:

> **Uniform Interval Sampling** - "A non-random procedure in which samples are obtained at fixed intervals of material production or material quantity."

Almost all agencies have established "Guide Schedules" that indicate a required frequency of sampling and testing for various materials. An example Guide Schedule frequency might be one sample of PCC per 150 cubic yards (115 m^3) placed. This sampling frequency may be inappropriately applied by obtaining the first material sample from the point at which 150 cubic yards (115 m^3) of PCC is placed, followed by one sample when each subsequent interval of 150 cubic yards (115 m^3) has been reached. Obviously such uniform interval sampling introduces bias into the statistical sample since no material placed within each interval has an opportunity to be sampled. Uniform interval sampling does protect against known and unknown defects at each fixed interval; however, it does not protect against cycles and patterns of variability of the material throughout the lot.

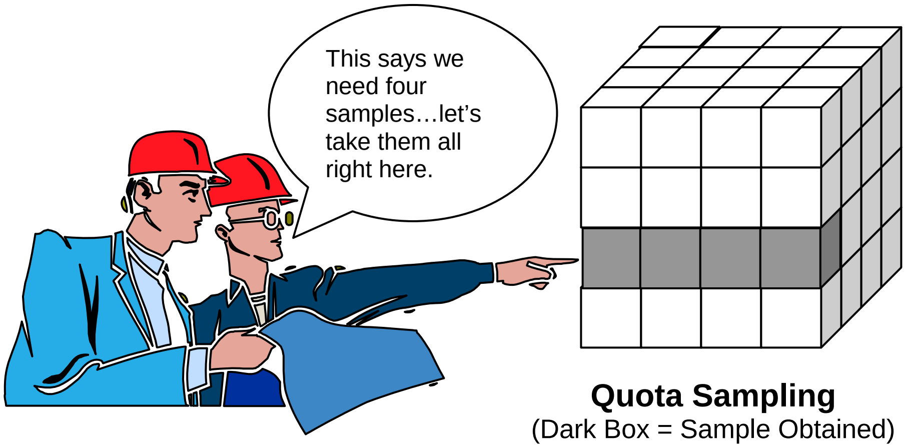


Uniform Interval Sampling
(Dark Box = Sample Obtained)

Quota Sampling

Similar to representative sampling and uniform interval sampling, ***quota sampling*** will also introduce bias into the statistical sample. Quota sampling is defined as follows:

> **Quota Sampling** - "A non-random procedure in which samples are obtained at the discretion and convenience of the sampler to satisfy the required number of samples for a lot."



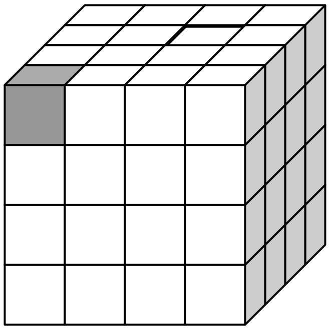
Quota Sampling
(Dark Box = Sample Obtained)

As an example, let's assume the same Guide Schedule frequency used above of one sample of PCC per 150 cubic yards (115 m^3) placed. Let's also assume that the total lot quantity of PCC to be placed is 1,500 cubic yards (1,150 m^3). Using the quota sampling approach, one would determine prior to placement that a minimum of 10 samples are required (1,500 cubic yards x 1 sample/150 cubic yards or 1,150 cubic meters x 1 sample/115 m^3) from the lot of PCC. The sampler would then obtain the 10 samples from anywhere (first 150 cubic yards, last 150 cubic yards, etc.) within the 1,500 cubic yard (1,150 m^3) lot, as long as they had met the required number of material samples. Quota sampling introduces a subjective distribution of the sampling process and does not protect against unknown defects throughout the lot.

Selective Sampling

The last form of biased sampling to be discussed is ***selective sampling***. Selective sampling is defined as follows:

> **Selective Sampling** - “A non-random procedure in which a sample is obtained only for informational purposes to guide Quality Control or Acceptance actions.”



Selective Sampling
(Shaded Box = Sample Obtained)

The two primary applications of selective sampling are:

1) To provide initial or supplemental QC information during production or placement.
2) To assist in isolating apparent non-specification material.

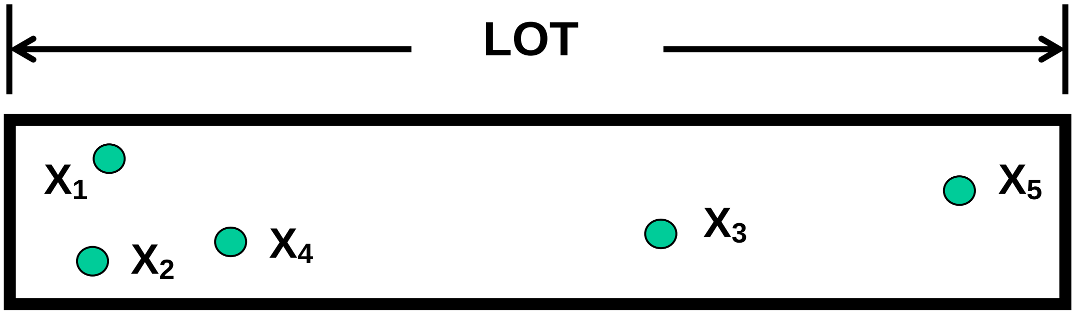
Although QC sampling and testing should be random, a contractor may want to obtain a selective sample soon after the start of production or placement just to provide some indication of whether the material appears to be meeting specification requirements. If at some point during production and placement some material appears to be out of specification, the contractor or the agency may elect to obtain a selective sample. However, this is only for the contractor’s or the agency’s information. The results of selective samples should not be included in an agency’s Acceptance determination. If the results of a selective sample indicate non-specification material has been located, then additional random sampling within the corresponding sublot should be performed as discussed below.

4.6 - Random Sampling

Random Sampling

To eliminate bias, material samples (both QC and Acceptance) obtained under Quality Assurance should be selected through ***random sampling.*** Accordingly, random sampling is defined as follows:

> **Random Sampling** - "A sampling procedure whereby each sample obtained from the lot has an equal probability of being selected."



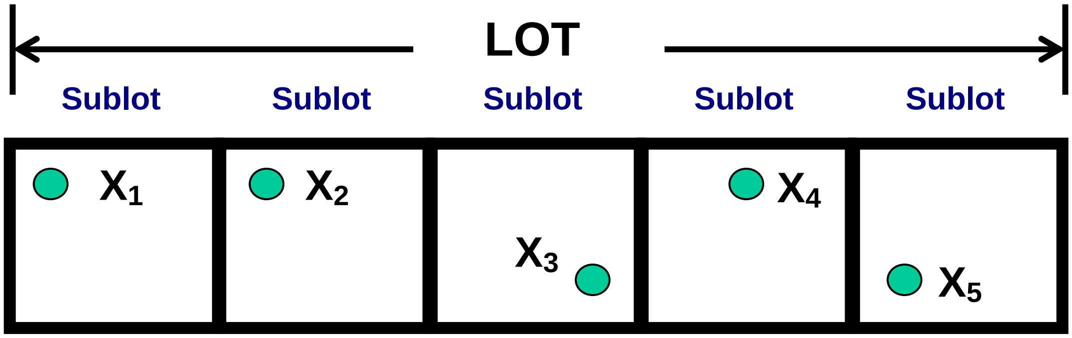
The random sampling procedure which is normally used in transportation construction is *ASTM D 3665 – Standard Practice for Random Sampling of Construction Materials*. This standard utilizes tables of random numbers to determine the random location for each material sample. Another acceptable method of obtaining random numbers is using a random number generator function on an electronic calculator or computer.

Random sampling protects against known defects, unknown defects, cycles, and patterns. It has low inherent risk, low risk in unknown situations, and high reliability. Furthermore, it does not require a knowledgeable sampler (one who knows of patterns). Truly, random sampling provides an unbiased estimate of the attributes or Quality Characteristics for a given lot.

Stratified Random Sampling

As was explained above, lots are divided into sublots to ensure that samples of material obtained from the lot are not all concentrated in one location. Sublots allow samples to be taken from within equal segments of the lot (beginning, middle, end of the lot). This is why the form of sampling normally utilized in Quality Assurance specifications is ***stratified random sampling***. Stratified random sampling is defined as follows:

> **Stratified Random Sampling** - "A sampling procedure whereby samples are randomly obtained from each sublot."



Stratified random sampling is used to ensure that random samples are obtained from throughout the lot. Without stratified random sampling it is possible, using straight random sampling, to have all of the random samples selected within the first half of a lot. Some examples of how to properly determine stratified random sampling locations are presented in Chapter 8.

4.7 - Materials Quality and Inherent Variability

Variability

Variability exists in all construction materials. It is one of the key factors that is integral to Quality Assurance and must be clearly understood. Variability in transportation materials and products is defined as follows:

> **Variability** - "Differences in measured test values for a given Quality Characteristic within a stable pattern due to chance, or outside this normal pattern due to assignable cause."

Variability can be controlled, but cannot be eliminated. With construction materials, even under controlled production, we can expect to find some amount of variation throughout a given lot. This is perhaps one of the most important findings from the 1959 AASHO (AASHO became AASHTO in the 1970s) Road Test in Ottawa, Illinois. Even with well-trained inspectors, well-equipped testing laboratories, competent contractors, and an intensive effort on the part of the Road Test officials, it was not possible to meet the AASHO Road Test specifications 100% of the time. It is important to keep in mind, when measuring any material Quality Characteristic, that each material and process has some inherent variability.

Inherent Variability

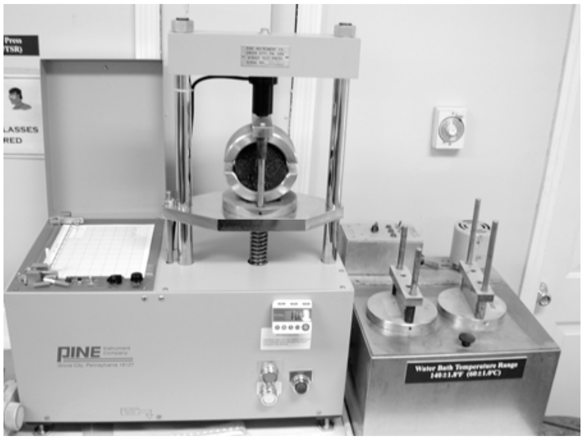
In transportation construction, we want to minimize variability. The level of quality of any material or product is associated with the level of variability. There are four (4) primary components or sources of ***inherent variability*** in individual test results for material samples. These components of inherent variability are:

- Sampling Variability
- Testing Variability
- Material Variability
- Construction (Production and Placement) Variability

Each of these sources of inherent variability is discussed further below.

Sampling variability is caused by variation that is inherent in the sampling methods or procedures used to obtain a material sample. Even when the person obtaining a sample carefully follows standard sampling methods or procedures, some amount of sampling variability will occur.

Likewise, ***testing variability*** is the result of variation inherent in performing a test method and variation inherent in the test equipment. Even when the person performing a test carefully follows standard testing methods and even when the test equipment is properly calibrated, some amount of testing variability will occur.



Additional sampling variability and testing variability (i.e., beyond the expected or accepted range) can be introduced through deviations from standard sampling methods and test procedures by the person(s) performing the sampling and testing, or as a result of test equipment that is not properly calibrated or properly functioning. Sampling and testing variability, combined, have been stated as comprising up to 50 percent of the total overall variation in test results. It is important not to compound or add to the expected range of inherent variability due to sloppy practices. This is why it is important that sampling and testing personnel be properly trained and qualified. Consistent and careful adherence to proper sampling and testing procedures can minimize these two components of overall inherent variability.

Material variability is essentially due to the inherent variation that naturally exists in a given material. It is quite unrealistic to expect perfect homogeneity in any raw or processed source of construction materials (soils, aggregate, HMA, PCC, steel, paint). As stated by Willenbrock:

> "Nature avoids absolutes –
> variation is the rule."

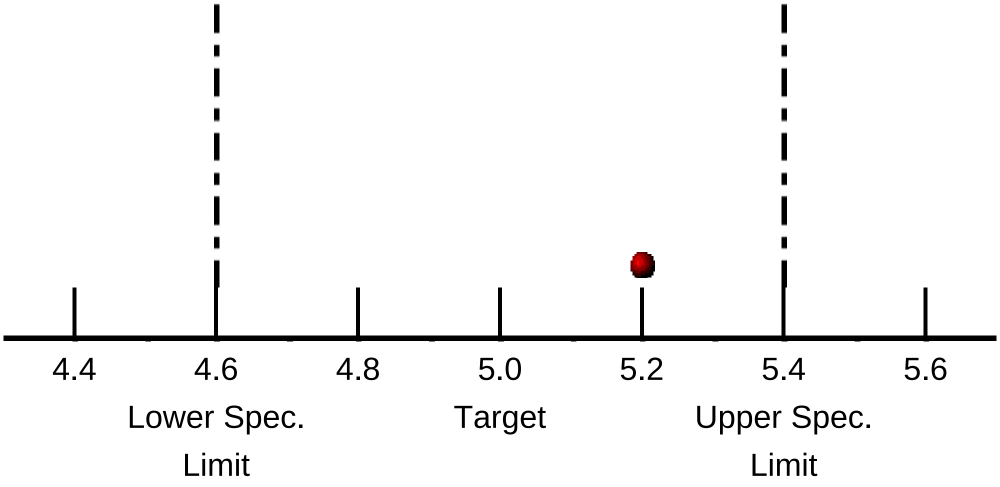
The inherent variation for most construction materials, on a relative basis, is usually small.

Construction variability is the result of variation that is inherent in production methods and construction operations. The largest amount of construction variability is generally attributed to the production and placement process. Additional construction variability (i.e., beyond the expected or accepted range) can be introduced through inconsistent production methods and construction operations. This is why good, consistent Quality Control, both at the plant and in the field, is essential in minimizing the amount of construction variability as a component of overall inherent variability.

Relating Inherent Variability and Quality

Equipped with an understanding of the principle of inherent variability, we can illustrate how random sampling and inherent variability relate to the quality of a given lot of material through the following simplified sampling examples.

Example 4-A: A technician randomly obtains one material sample of HMA (Statistical Sample of n = 1) from a 50 Ton (45 Mg) lot of HMA and determines the PG Asphalt Binder content of this sample. The test result for this single sample is plotted below against the target and Specification Limits.

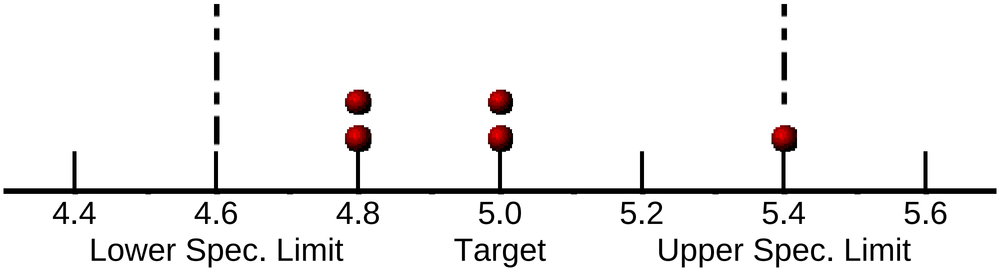


(Example 4-A – PGAB Content for Statistical Sample of n = 1)

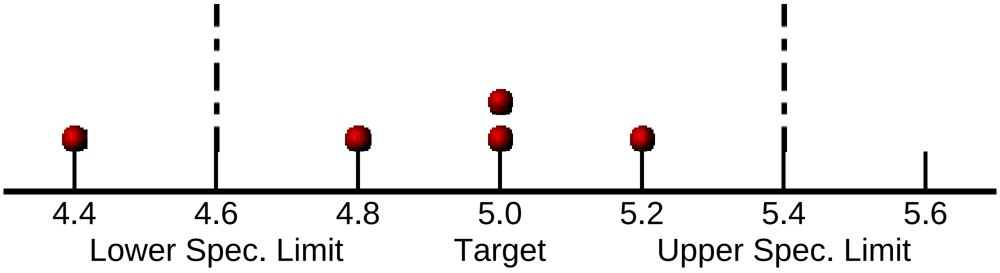
Example 4-A - Question: How well does this individual sample result represent the probable PG Binder content for every material sample from the entire 50 Ton (45 Mg) lot of HMA?

Example 4-A - Answer: It doesn't! We cannot use a single sample to determine whether material passes/fails or is in/out of specification. As discussed above, one individual representative sample or even a single random sample does not present a valid picture of the actual variability of the material Quality Characteristic being evaluated. A Sample Size of n = 1 does not provide a meaningful statistical sample.

Example 4-B: The same technician now randomly obtains two separate statistical samples of five material samples (two statistical samples of n = 5) from the same 50 Ton (45 Mg) lot of HMA and determines the PG Asphalt Binder content of each sample. The test results for each statistical sample of five material samples are plotted below against the same Target and Specification Limits.



(Example 4-B – PGAB Contents for Statistical Sample #1)



(Example 4-B – PGAB Contents for Statistical Sample #2)

Example 4-B - Question: Which of the two statistical samples (# 1 or # 2) above is more representative of the probable PG Binder content of the entire 50 Ton (45 Mg) lot of HMA?

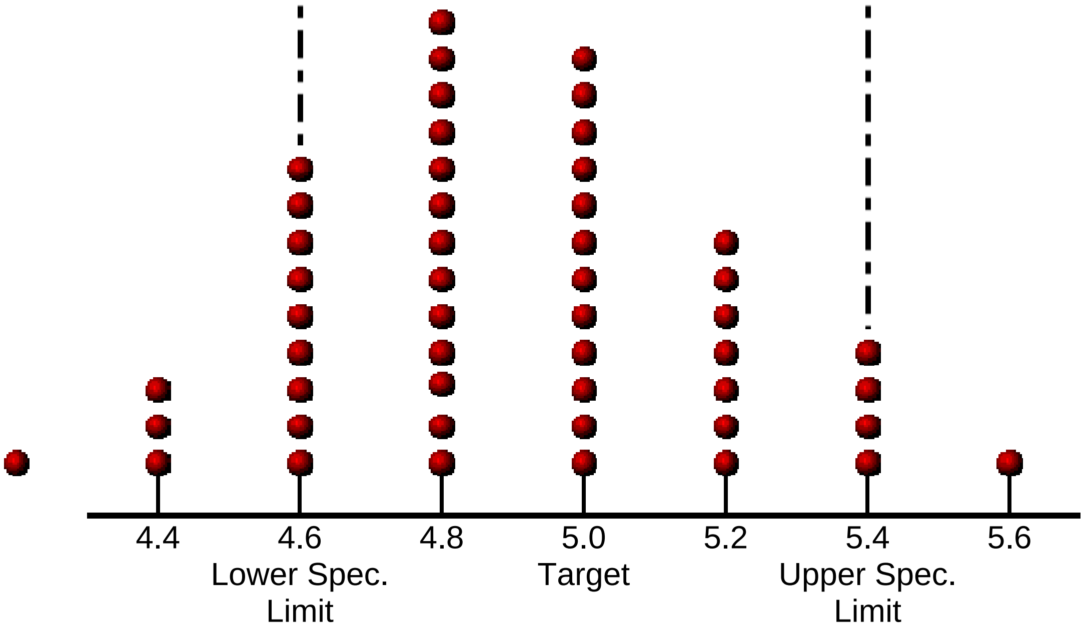
Example 4-B - Answer: Neither! Each statistical sample shows some amount of variability. Both statistical samples are representative of the PG Binder content of the lot of HMA.

Example 4-B - Question: For Statistical Sample #2, should material represented by the single sample test result (4.4) beyond the Lower Specification Limit (LSL) be rejected?

Example 4-B - Answer: No! Based on probability, the test result for a single material sample could fall within or outside the Specification Limits by chance and be due to inherent variability. A single test result should not be used to accept or reject material.

One way to obtain a more complete picture of the true variability of the PG Asphalt Binder content of the 50 Ton (45 Mg) lot of HMA in Examples 4-A and 4-B above would be to test one material sample from every Ton (45 Mg) of HMA in the lot.

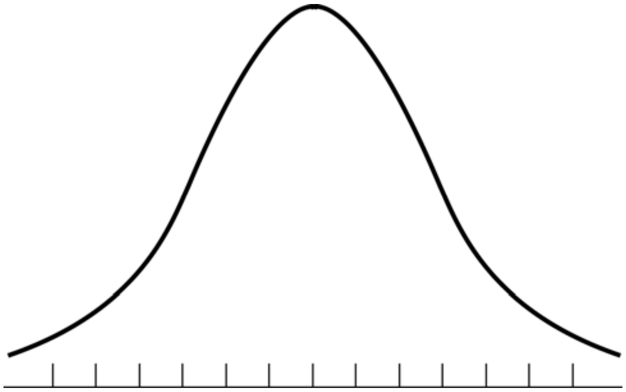
Example 4-C: In order to obtain one material sample from each Ton (Megagram) of HMA, the 50 Ton (45 Mg) lot is divided into 50 sublots. Let’s assume that the same technician randomly obtains one sample from each 1 Ton sublot (statistical sample of n = 50) and determines the PG Asphalt Binder content of each sample. The test result for each of the fifty material samples is plotted below.



(Example 4-C – PGAB Contents for Statistical Sample of n = 50)

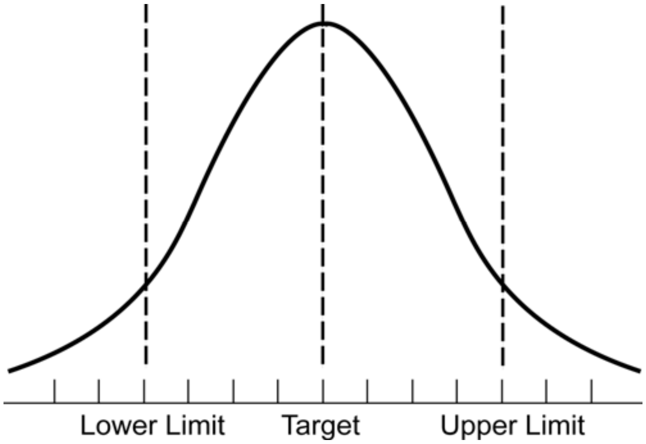
Normal Distribution

What we see in Example 4-C is a true picture of the overall PG Binder content variability of the 50 Ton (45 Mg) Lot of HMA. We see that most of the sample test results are centered or clustered at or between the lower limit (4.6%) and the upper limit (5.4%). We find fewer sample test results just beyond the upper and lower Specification Limits. Note, however, that several of the sample test results do fall outside of the Specification Limits. This pattern is what is referred to as a ***normal distribution***. The sampling results for any normal distribution form what is referred to as a ***normal distribution curve*** or "**bell-shaped curve.**" If we were to sample and test an entire lot of most construction materials through complete enumeration, the test results would form a normal distribution curve similar to that obtained in Example 4-C.



4.8 - Testing Targets and Limits Based on Normal Distribution

The principle of normal distribution and the bell-shaped curve are important tools which are used to measure the quality of a lot of material. As discussed in Chapter 1, quality is defined as "conformance to requirements." Transportation construction specifications normally identify targets and/or limits for individual Quality Characteristics. Unfortunately, many agencies previously failed to properly apply the principle of normal distribution when developing and applying Specification Limits for construction materials acceptance.



Targets are typically established based on a desired engineering value related to material performance (e.g., 4% air voids in HMA). Specification Limits must be designed so that a conscientious contractor or material producer, applying good Quality Control procedures in producing the product, will run a minimum risk of having acceptable material rejected. The design of these limits must consider the safety, performance, and durability of the product, which work together to minimize life-cycle costs.

Past and still some present practices rely largely upon the use of engineering judgment when establishing the desired quality and corresponding Specification Limits for a particular Quality Characteristic. These "variability-assumed specifications" are then used to control the production and placement process, as well as to make Acceptance decisions. This type of specification results in a greater risk of having satisfactory material rejected. This is because the total inherent variability of the specific material Quality Characteristic being considered has not been properly taken into account. The Specification Limits need to more accurately reflect the known inherent variability of the material being produced and placed.

All too often, “conformance to requirements” has been determined through the practice of evaluating the test results for an individual material sample against the specified targets and limits. This practice is essentially an “In/Out” or “Pass/Fail” approach to periodically assess construction quality based on one small piece of information.

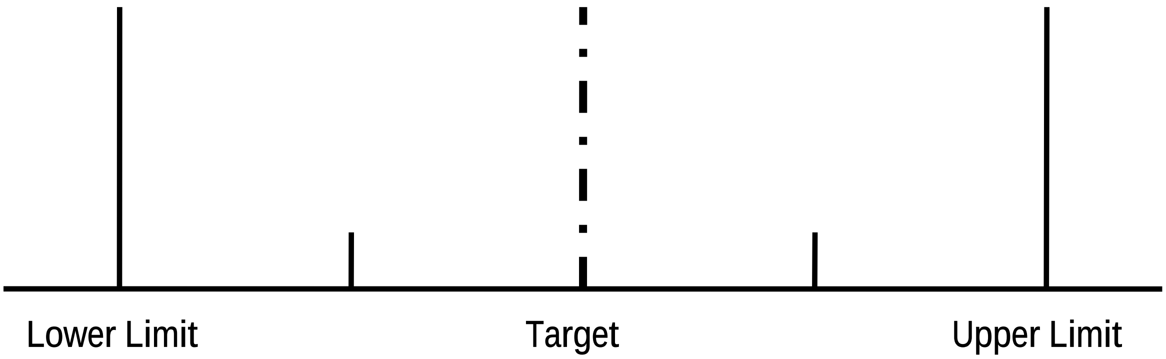
However, as illustrated through Examples 4-A, 4-B, and 4-C above, the approach of evaluating the quality of a large quantity of material with a single test result is not valid. Inherent variability and a corresponding distribution of test results exist for any lot of construction material. An individual sample cannot tell us what percentage of material is centered around the specified target or how much overall variability exists within the lot of material.

It is possible for each individual material sample test result for a given lot to fall inside the Specification Limits (Example 4-B – Statistical Sample # 1), yet based on the normal distribution, we know that some amount of material in the lot is outside of the Specification Limits.

It is also possible for an individual material sample test result to fall outside of the Specification Limits (Example 4-B – Statistical Sample # 2) and erroneously conclude that the material represented by this single sample is not acceptable. Again, based on normal distribution, we know that a small percentage of the material in any lot of material will typically be outside of the Specification Limits (unless the limits have been set extremely wide).

It should now be clear why the traditional Pass/Fail Acceptance approach of simply determining whether an individual sample test result falls inside the specified Upper and Lower Limits does not provide an adequate measure of the composition and quality of a given lot. In order to properly determine the quality and hence acceptability of a lot of material, we must evaluate the lot variability using a statistical sample comprised of multiple random material samples.

Targets and Specification Limits should be established recognizing their relationship to the normal distribution and material quality. This can be done using historical contractor and agency testing data, as long as the data is not biased (i.e., it should be obtained through random sampling and not through biased sampling techniques). In many cases, the actual extent of the variation of material as it exists in the real world is not always available from past data because of the practice of representative sampling, sampling with n = 1, discarding some of the test measurements for some arbitrary reason, or sampling on some biased basis. Past record data tends to reflect only mean values and not a true measure of the inherent variability of materials.

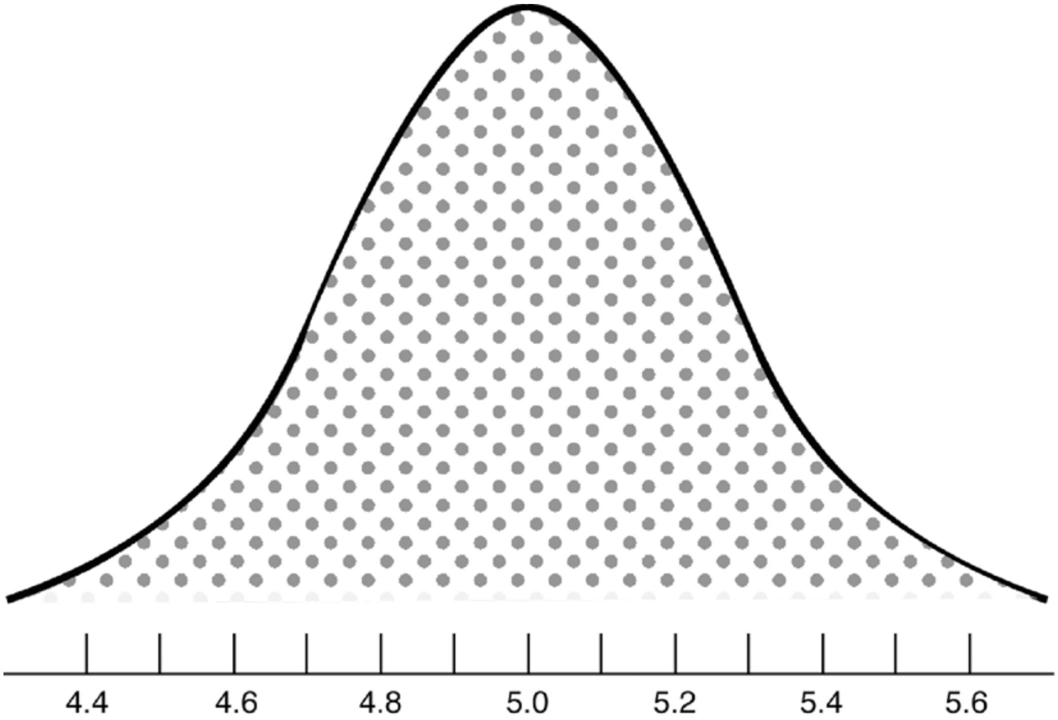


Pilot projects or special research studies can also be used to obtain adequate testing data to establish targets and limits which reflect the inherent variability of a particular material. Targets and limits used for QC and Acceptance will be more fully presented in Chapters 9 and 10.

The example below illustrates how a special research study might be conducted to determine the inherent variability of the same HMA mix used in examples 4-A, 4-B, and 4-C above.

Example 4-D: A special research study utilizes five different HMA plants to produce 2,500 Tons (2,250 Mg) of HMA in order to estimate the inherent variability of the HMA population. Each HMA plant produces 500 Tons (450 Mg) of the HMA using the same aggregates and PG Asphalt Binder using similar production equipment and methods.

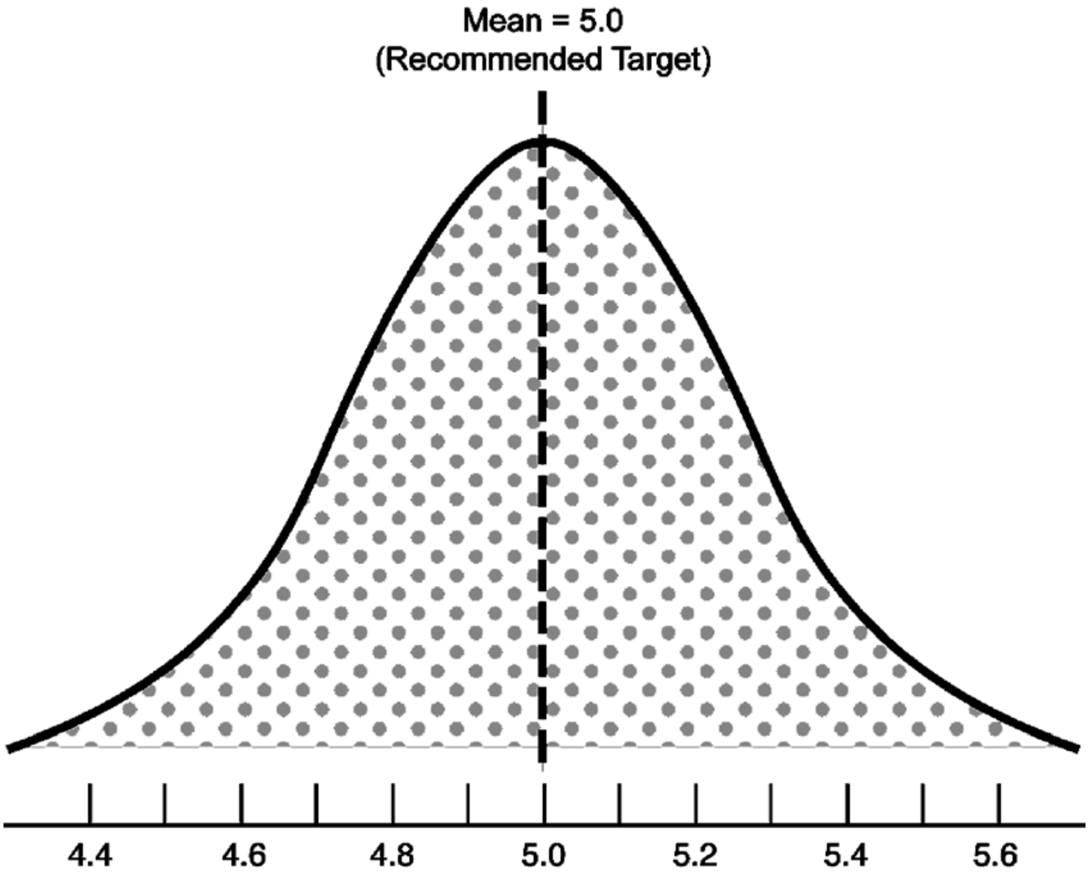
Several technicians are used to obtain one sample from every Ton (Megagram) of the 2,500 Tons (2,250 Mg) of HMA (Statistical Sample of n = 2,500). The technicians determine the PG Asphalt Binder content of each sample. The normal distribution curve for the statistical sample (n = 2,500 material samples) is plotted below.



(Example 4-D – Normal Distribution Curve for Statistical Sample of n = 2500)

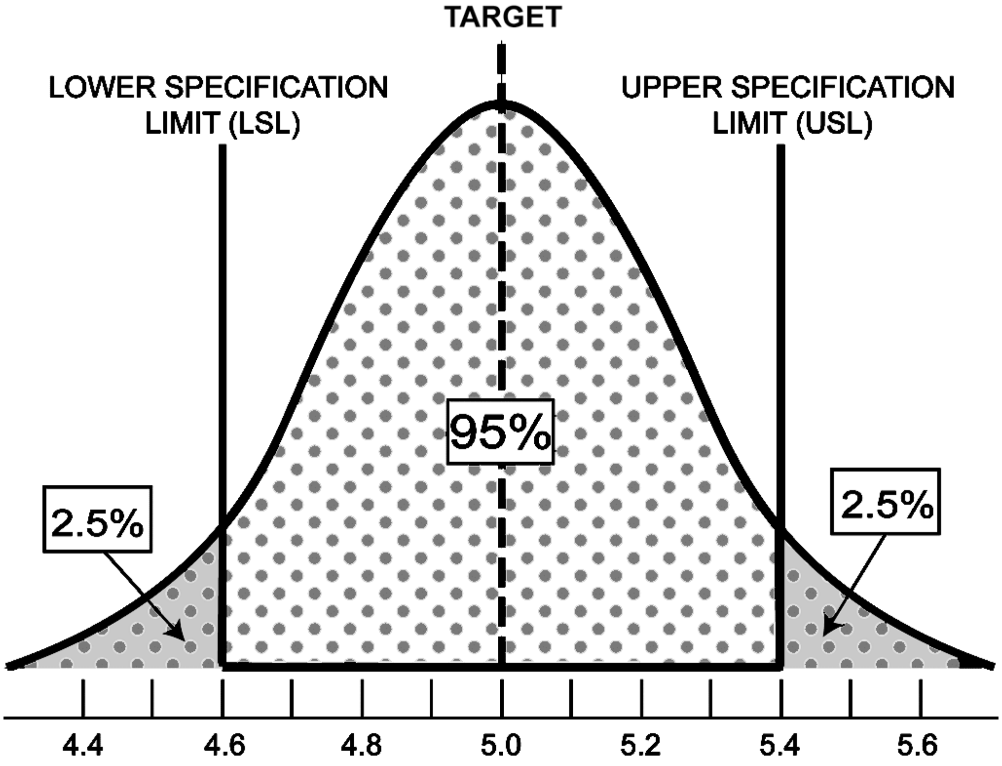
The normal distribution obtained in Example 4-D above can be used to establish realistic Target and Specification Limits for PG Asphalt Binder content for this type of HMA Mix that reflect the inherent variability (Sampling Variability + Testing Variability + Material Variability + Construction Variability).

The average or *mean* test value of the 2,500 individual material samples is determined to be 5.0%. Note that this value coincides exactly with the center or mid-point of the bell-shaped normal distribution curve. This value could be selected as the Specification Target, as long as it is within the range of desired engineering values related to material performance.



(Specification Target Based on Example 4-D Normal Distribution)

The sample test values vary from the mean test value by a maximum of +/- 0.7% (between 4.3% and 5.7%). However, most of the test values are closely bunched under the normal distribution curve around the mean between 4.6% and 5.4%. As briefly described in Section 4.3, *Specification Limits* are the statistically-based Quality Limits used to evaluate the quality of a lot. Specification Limits are typically established such that approximately 95 percent of the material contained in a normally distributed population will fall within those limits. This means that roughly 5 percent of the material in a population is expected to lie within the two “tails” of the normal distribution curve or outside of the Specification Limits. Accordingly, it would appear that 4.6% should be selected as the Lower Specification Limit (LSL) and that 5.4% should be selected as the Upper Specification Limit (USL).



(Specification Limits Based on Example 4-D Normal Distribution)

In this case, it would appear that the special research study has confirmed that the Target (5.0%) and Specification Limits (4.6%, 5.4%) used in Examples 4-A, 4-B, and 4-C are realistic and achievable.

4.9 - Validity of Sampling Data

The principles associated with normal distribution can be applied to a statistical sample (i.e., group of material samples) to determine the quality of a lot of material. This is predicated, however, on the following key assumptions:

1) ***Multiple*** ($n \geq 3$) samples are used to evaluate the lot quality.

2) All samples used to evaluate the lot quality are r***andomly*** obtained.

3) The samples are obtained from the same lot under c***ontrolled conditions***"

Each of these key assumptions related to the validity of sampling data is predicated on the material being normally distributed. These key assumptions are discussed below.

Validity of Sampling Data – Assumption #1: Multiple Sampling

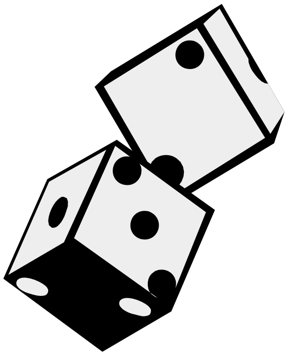
One or even two random material samples do not provide a valid picture of the associated variability of a material Quality Characteristic for a given lot. When Acceptance of a lot is based only on a single sample (statistical sample of n = 1), the agency's risk of accepting out-of-specification material is extremely high. The contractor, likewise, runs a risk of having in-specification material rejected based on such limited information.

As presented in the examples in Section 4.7, it should now be clear that the material samples representing a lot will be normally distributed due to inherent variability. Therefore, an individual sample could fall anywhere within the normal distribution curve (i.e., close to the mean, just inside the Upper or Lower Limits, or in the tail beyond the Upper or Lower Limits). One material sample neither gives information about the variability nor indicates where the true mean is.

The only way to reduce both the agency's and the contractor's risk is to quantify the variability or normal distribution of the lot. Accordingly, in order to properly determine the normal distribution and hence the quality of a lot of material, we must use a statistical sample comprised of ***multiple material samples***. Most Quality Assurance Specifications require a minimum of three (3) samples to estimate the quality of a lot. However, as the statistical sample size is increased to say, seven (7) to thirty (30) samples, we will obtain a better estimate of the variability or normal distribution of the lot and further reduce the agency's risk and the contractor's risk.

Validity of Sampling Data – Assumption #2: Random Sampling

The principles associated with the normal distribution cannot be applied if samples are obtained from a lot in a biased manner. The bell shape of the normal distribution curve is based on mathematical probability. In order to have a valid representation of the lot, individual material samples must be selected such that each sample has an equal probability of being chosen from the lot. This can only be achieved by using ***random sampling*****.**



Accordingly, samples obtained using biased sampling techniques (representative sampling, uniform interval sampling, quota sampling, selective sampling) cannot be used to evaluate testing data with Quality Level Analysis.

Validity of Sampling Data - Assumption #3: Controlled Conditions

In order to have a valid assessment of the quality of a given lot, we must ensure that all of the sample data being evaluated for the lot represents construction material that is produced, placed, sampled, inspected, and tested under the same ***controlled conditions***. The term controlled conditions is defined as follows:

> **Controlled Conditions** - Consistency or uniformity in the methods of material production, placement, sampling, and testing.

The material must be produced from the same mix design at the same facility using a consistent process. It must be placed using uniform equipment and methods. Sampling, inspection, and testing of material samples must also be performed following standard procedures in a consistent and uniform manner.

Significant deviations from controlled conditions during production, placement, sampling, inspection, or testing will introduce variability that is beyond the <u>typical</u> (i.e., expected or accepted) inherent variability. If material production and/or placement conditions are changed, the corresponding material should be assigned to a new lot.

A quantity of material which is identified as a significant, visible, apparent deficiency within a lot, and which is attributed to an absence of controlled conditions, should be isolated from the lot. As discussed in Section 4.10 below, additional samples should be obtained from the location in question and the material should be evaluated separate from the lot.

4.10 - Sampling Protocols to Address Specific Situations

Agencies normally determine the point of obtaining samples from each sublot based upon safety, ease, economics, minimum disturbance to the production or placement operation, and quality of the sampling operation. As an example, for HMA, AASHTO T 168 (ASTM D 979) allows agencies to sample materials for Quality Characteristics either at the production facility, before the paver, after the paver, before compaction, or after compaction. However, the QA Specifications should clearly identify only one of these points of sampling (e.g., at the production facility, after the paver) for material samples to be obtained for both contractor QC testing and agency Acceptance testing. This is important because the Specification Limits are established based on sampling from that specific point of sampling, and changing the location of sampling may make the results of test data analysis invalid. Obtaining samples from a location different than the specified point of sampling can also increase the amount of sampling variability.

When sampling any material, it is important that the individual Increments for a sample be obtained as close as possible to the predetermined random sample location. Unless specified differently by an AASHTO or ASTM Test Method, a 2-foot (0.6 meter) radius from the exact random sampling location is accepted practice for locating and obtaining multiple Increments for a sample.

In addition to identifying sampling locations, agency specifications will also normally specify the frequency of sampling for QC and Acceptance. However, circumstances may be encountered which are not specifically addressed by agency specifications or

AASHTO or ASTM methods. In order to ensure that biased sampling practices do not occur, standard protocols should be developed and uniformly followed for such sampling situations, including the following:

- Lot/Sublot sizes resulting in less than three samples.
- Sampling from partial sublots.
- Sample locations at edge of field placement.
- Sampling from locations of visible deficiency.

Recommended sampling protocols to address each of the above specific sampling situations are discussed below.

Lot/Sublot Sizes Resulting in Less Than Three Samples

As discussed earlier, a minimum of three samples is required in order to perform a Quality Level Analysis. When the total quantity of any construction material is small, the lot or sublot size as defined by the agency in the Quality Assurance Specification may result in less than three material samples. If it is known ahead of time that the total quantity of the material to be provided is small, then the best approach is to establish a sampling plan that will provide at least the required number of samples (or more when possible). Accordingly, QA Specifications should indicate the specific protocol to be followed for such situations. For example, one approach is to decrease the sublot size to ensure a minimum of 3 to 4 sublots of equal size to represent the lot. This can be accomplished by dividing the total lot quantity by the desired minimum number of sublots and determining sample locations randomly within each sublot. More rigorous sampling frequencies will in some cases necessitate additional technicians and inspectors and will in most cases require pre-planning in order to properly sample the material at the increased frequency.

Some agencies also specify quantities below which Quality Level Analysis procedures are not applied. For small quantity situations where QLA is not specifically called for, the agency may evaluate the material through an “Acceptance Procedure for Small Lots.” Under such procedures, the contractor should still perform some minimum frequency of QC inspection and testing. The agency should also perform some Acceptance inspection and testing to determine the quality of the product or material.

Sampling from Partial Sublots

When lots are nearing conclusion or when production is suspended, sublots may be “cut off” early prior to obtaining the required sample for that sublot. Again, QA Specifications should indicate the specific protocol to be followed for such situations. For example, when the lot is defined as a large quantity (e.g., 10,000 Tons of HMA) the lot spans several days of production and partial sublots may be “picked up” at the start of the next production day. Material samples that are not yet obtained during a partial sublot production on one day will be obtained early in the next day’s production. However, when the lot is defined as a smaller quantity (e.g., the total quantity produced during one day), then there will be many instances of partial sublots. In some cases these sublots will be represented by samples (when the random sample location occurred prior to the end of production) and in some cases they will not. Both situations are undesirable. A sample obtained from a partial sublot represents a smaller quantity of production than the other samples; however, when a sample is not obtained, the sublot goes untested. Sublot sizes should be equal if possible, but if the last sublot is smaller than the rest of the sublots, you still provide a fair measure of the lot quality.

For example, an HMA facility had a 1,500 Ton (1,360 Mg) order to ship to an agency project. The agency defined a lot as one day's production and a sublot as a quantity not to exceed 500 Tons (450 Mg). The contractor's Quality Control personnel used stratified random sampling and obtained material samples for the first two 500 Ton (450 Mg) sublots. The last sample was randomly determined to occur at 480 Tons (435 Mg) in the last sublot. Production was stopped at 450 Tons (408 Mg) due to equipment problems in the field and the production day was ended. As a result, only two samples were obtained to represent the lot. In this situation, the most appropriate course of action would be to obtain a sample to represent the partial sublot prior to the end of production, since having fewer than three (3) samples will not allow Quality Level Analysis to be performed. Another alternative is to combine the two sublots that were tested with a subsequent lot of production for the same material. The Federal Aviation Administration (FAA) utilizes this method under their P 401 HMA specification. Under P 401, the lot will contain as few as three samples and as many as six.

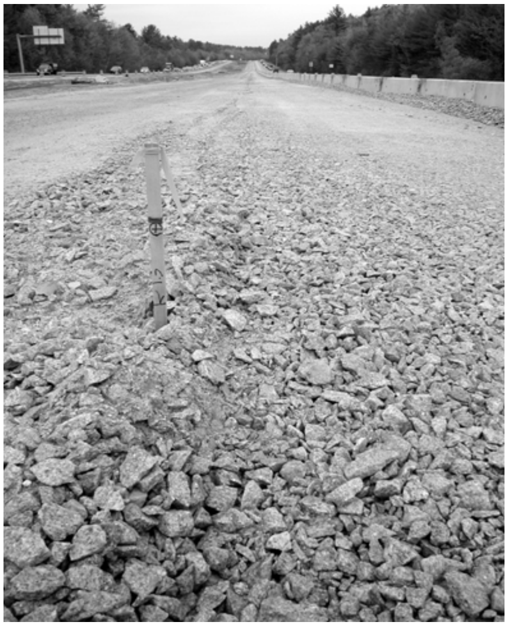
Another possibility is for the agency to prescribe cut-offs for partial sublots or suspended lots (typically at half the size of the usual sublot), beyond which additional samples must be obtained. If it is known that a sublot will be cut short of the originally anticipated quantity, then the previously selected random number to determine the location of the sample should be used in conjunction with the adjusted quantity to determine the location of the sample. If the sublot is cut short without prior notice, then the previously selected random number for that sublot can be used in conjunction with the abbreviated sublot size to determine a new random location.

Sample Locations at Edge of Field Placement

When determining locations of samples using the length and width of the placed area, there may be instances where the sample is located near the edge of the placement (which may be a longitudinal edge or a transverse edge) or near a structure (e.g., manhole). Agencies typically define in their specifications that samples located near an edge be "pushed back" a prescribed distance, for example 1-foot (0.3 m). This can be accomplished by prescribing a "no-sample" zone around the edges of the placed area and subsequent correction of any randomly selected material sample locations to be outside of this zone.

Sampling from Locations of Visible Deficiency

A quantity of material which is identified as a significant, visible, apparent deficiency within a lot should be isolated, and either rejected or further evaluated through selective sampling plus additional random sampling within the affected sublot. What constitutes a significant, visible apparent deficiency should be clearly defined by the agency. Selective sampling may be used to determine the limits of the deficiency or to directly quantify impacted areas. Additional random samples are obtained to properly quantify the actual quality of the material in question and to support an appropriate disposition of the material.



4.11 - Re-Sampling and Re-Testing

Re-Sampling vs. Re-Testing

The term ***re-sampling*** refers to the process whereby the agency or the contractor determines that a new material sample is required to replace the original sample for an individual sublot.

The term ***re-testing*** refers to the process of performing another test to confirm the initial test. Re-testing should be performed using a second test portion or specimen prepared from the same original sample.

These two terms are often incorrectly used interchangeably with one another or are confused with the term selective sampling. The practices of re-sampling and re-testing are also sometimes improperly applied by agency and contractor personnel. The proper and improper applications of these practices are explained below.

Appropriate Application of Re-Sampling and Re-Testing

Re-sampling is warranted if it is determined that:

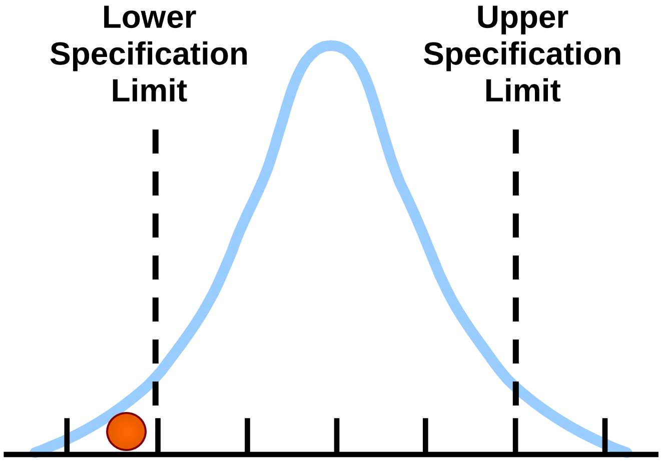
- The sample was not obtained from the same 0opulation under controlled conditions (obtained from visibly defective/rejectable material).
- The sample was not randomly obtained.
- The sample was not properly obtained in accordance with the required AASHTO/ASTM sampling procedure.

Re-resting is warranted if it is determined that:

- The test was not properly performed in accordance with the required AASHTO/ASTM test procedure.
- The test equipment was not properly calibrated or properly functioning.

Improper Applications of Re-Sampling and Re-Testing

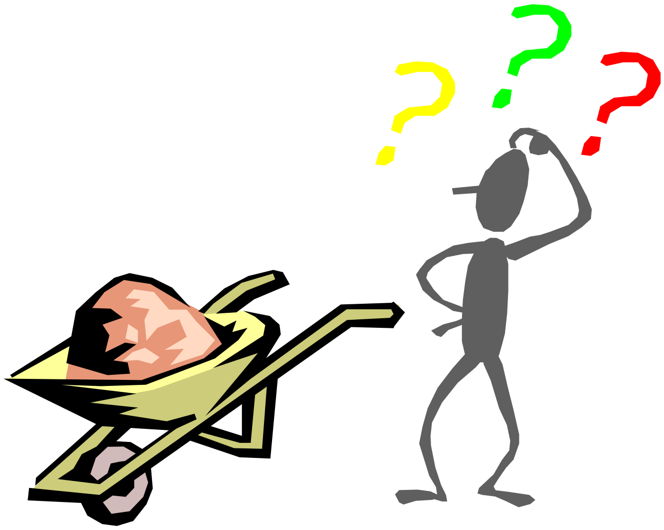
One of the most frequent instances where re-sampling is <u>improperly</u> applied occurs when an individual material sample test result is found to be outside of the Specification Limits (or the Engineering Limits). The contractor or the agency subsequently decides to obtain a new sample (often called investigational, confirmation, or referee sampling).



Unless it is determined that the sample was not obtained randomly, under controlled conditions, or in accordance with proper sampling procedures, then re-sampling is <u>not</u> warranted. As explained earlier, the material samples representing a lot are usually expected to be normally distributed due to inherent variability. Based upon probability, an individual sample from a lot could fall anywhere within the normal distribution curve, including the tails. This test result could fall beyond the Specification Limits. This is why Acceptance decisions should be based on multiple random material samples, instead of passing judgment on an individual sample.

If the agency or contractor is concerned about the test result for an individual sample, then re-testing of a split from the same sample may be used to confirm the initial test result. <u>Additional</u> random material samples (not re-samples) can be obtained and tested to <u>supplement</u> (not replace!) the original sample. This will provide a better estimate of the lot variability or normal distribution and hence the true lot quality.

Re-sampling should also not be used to evaluate questionable or known non-specification material. As defined above, this is not the purpose of re-sampling.



A quantity of material which is identified as a significant, visible, apparent deficiency within a lot should be isolated and rejected or further evaluated through selective sampling plus additional random sampling within the affected sublot. Note that the additional random samples are being obtained to properly quantify the actual quality of the material in question and to support an appropriate disposition of the material.

- END OF CHAPTER 4 -

CHAPTER 5

Contractor Quality Control Roles and Responsibilities

Chapter 5

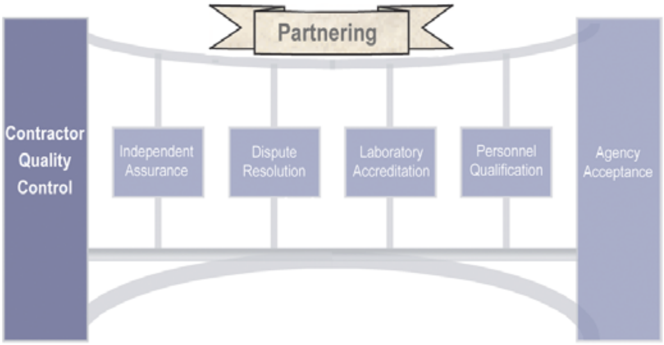
Contractor Quality Control Roles and Responsibilities

Chapter Overview

In this Chapter, the following responsibilities and activities necessary for effective Quality Control are presented:

5.1 - Overview of Contractor QC Function and Responsibilities

Responsibility for Quality Control



As discussed in Chapter 2, Quality Control serves as one of the two towers among the six core elements of a Quality Assurance Program. Quality Assurance places responsibility for Quality Control in the hands of the ***contractor***. The term contractor refers to all contracted parties who are involved with building an individual project, including: the ***prime (general) contractor***; ***subcontractors***; and all ***producers***; ***fabricators***; and ***manufacturers*** who provide construction materials for the project. Accordingly, the term contractor is used throughout this document to refer, either collectively or individually, to any of these parties.

Each of these contractor parties is defined as follows:

Prime (General) Contractor - "The company which has the primary construction contract for an agency project and which assumes overall responsibility for completing the work."

Subcontractor - "A company which is responsible for field placement or installation of an individual item of work under contract to the prime contractor."

Producer - "A company which produces and supplies project produced materials (e.g., aggregates, HMA, PCC) for either the prime contractor or a subcontractor."

Fabricator - "A company which produces fabricated structural materials (e.g., precast/prestressed concrete structural elements, fabricated structural steel) for either the prime contractor or a subcontractor."

Manufacturer - "Company which manufactures and supplies standard manufactured materials for the prime contractor, a subcontractor, or a fabricator."

Quality Control is not just the responsibility of the prime contractor. Each of the five contractor parties defined above has an important role in performing effective Quality Control. Each individual contractor should have in place his/her own QC system to ensure that their product or completed item of work will meet the quality requirements set forth by the contracting agency. The prime contractor, however, has overall responsibility for managing Quality Control and must coordinate the efforts of all of the other contractor parties. The prime contractor must take the lead to ensure the adequacy of each lower tier contractor's Quality Control system and should assure itself that each lower tier has effective Quality Control that will yield the specified level of quality.

Quality Control Function

All of the steps and activities that go into manufacturing, fabricating, producing, or placing a product constitute a ***process***. The function of Quality Control is to ensure that each process is consistently providing a given product in conformance with specification requirements. A process that is capable of achieving this is said to be ***in control***.

Quality Control, therefore, seeks to maintain all processes in control. This is why the term ***process control*** is sometimes used synonymously with Quality Control.

Quality Control should not be viewed as a separate activity or function within a contractor's organization, but rather must be integrated throughout the organization. In other words, QC is not simply the responsibility of a Quality Control Staff. It is not about relying on QC inspection and testing personnel to make quality happen. While it is true that Quality Control does require sampling, testing, and inspection by qualified QC personnel, quality can only be achieved by skilled frontline workers who are properly trained to produce and place materials that conform to specification requirements. This is an important point which should be understood by all of a contractor's employees.

Successful Quality Control utilizes a comprehensive, systematic, and continuous approach to producing and placing a product. QC must be performed on a real-time basis. It is not reactive, but rather is proactive. Quality Control activities should focus on <u>preventing</u> problems or defects from occurring, not finding them after the fact. This requires all contractor personnel to adopt a ***Zero Defects*** philosophy. This does not mean that no defects will ever occur. Rather, the concept of Zero Defects is a TQM philosophy defined by author Philip Crosby as follows:

> **Zero Defects** - "Do the job right the first time."

This should not be viewed merely as a slogan to be printed and posted on worksite bulletin boards. It is a philosophy or attitude that must be continuously embraced and applied by every worker to each activity of a specific manufacturing, production, or placement process. To make this more tangible to workers, each contractor organization should establish quality goals using Zero Defects as the target, similar to project safety goals of zero lost-time accidents. The Zero Defects attitude seeks to prevent problems or "non-quality" from occurring in the first place.

Individual transportation agencies' Quality Assurance Specifications will identify the minimum Quality Control activities required by the contractor. However, a truly quality-conscious contractor doesn't simply attempt to just meet minimum specification requirements for QC. Contractors who fully embrace the principles of Quality Assurance in transportation construction recognize Quality Control as a sound business investment that pays dividends resulting from:

- Reduced potential for rework.
- Increased productivity.
- The ability to avoid related schedule delays.

Accordingly, a good contractor Quality Control system doesn't react to or try to accommodate agency specification requirements, but rather implements QC procedures as standard practice.

A contractor Quality Control system begins with the proper QC organization and a well-written Quality Control Plan. It includes sampling, testing, and inspection. QC must address activities at contractor manufacturing, fabrication, and production facilities as well as at field placement locations. It also requires maintaining good records. Each of these Quality Control functions is more fully discussed throughout this chapter.

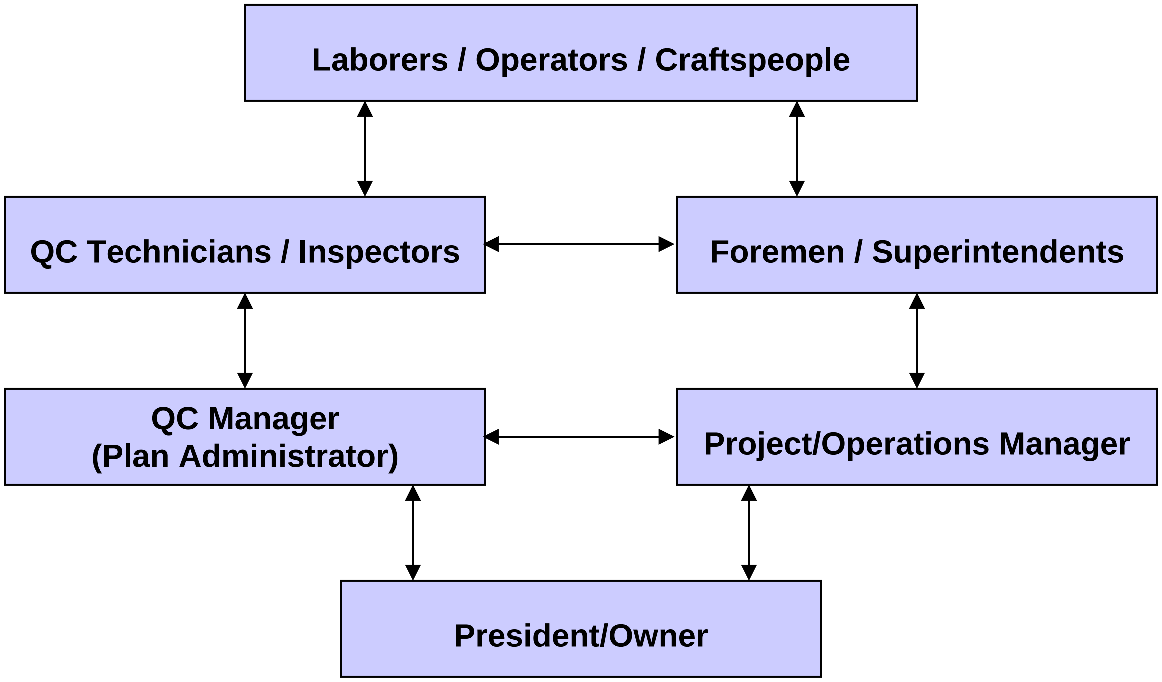
5.2 - Quality Control Organization Requirements

Optimal Contractor Organizational Structure

Quality Control must be understood and applied as a shared responsibility of everyone in the contractor's organization. A contractor's Quality Control system should be developed and monitored by a core QC staff. However, as discussed above, quality is not attained by the presence or activities of a few people labeled as ***Quality Control Personnel*** (i.e., QC Manager, QC Plan Administrator, QC Technicians, QC Inspectors). Quality Control begins with the frontline ***production personnel*** (i.e., skilled laborers, equipment operators, craftspeople) who are actually manufacturing, fabricating, mixing, placing, or finishing construction materials.

An effective contractor Quality Control organizational structure provides a team of QC personnel that functions, neither above nor below but, parallel to the team of production personnel. The primary function of the QC personnel is to continuously monitor and measure each production or placement process to determine whether or not it is in control. The information obtained by the QC personnel is shared with the production personnel to confirm that the product is in conformance with specification requirements or to determine process corrective action needed when it is not. This requires teamwork between the QC personnel and the production personnel. This teamwork has to start at the frontline of production and placement operations and progress up to the top managers.

The graphic below illustrates the optimal contractor organizational structure necessary to achieve effective Quality Control. This organizational structure is applicable to each of the five contractor parties defined above (i.e., prime contractor, subcontractors, producers, fabricators, manufacturers), regardless of the size of the company.

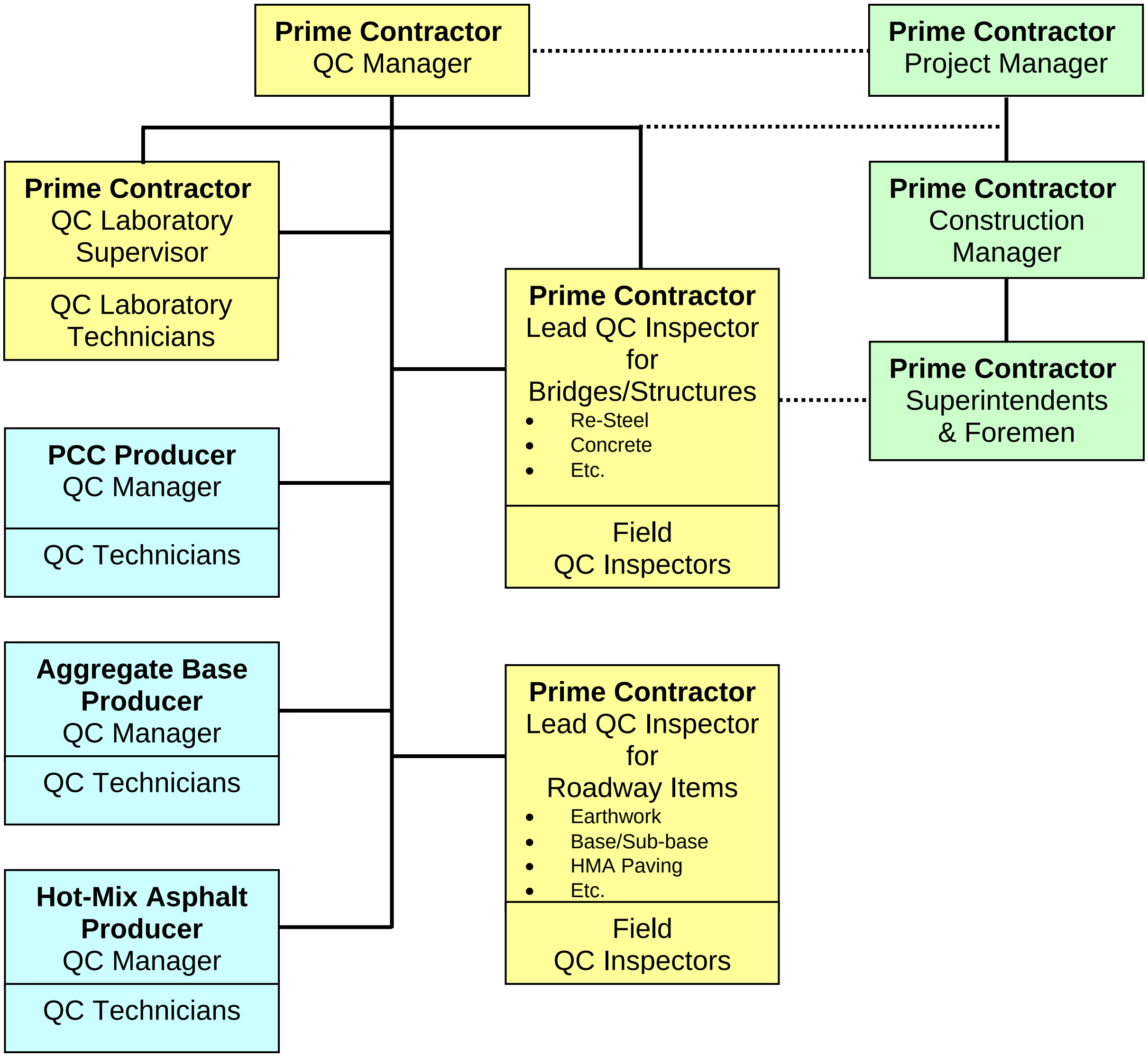


(Optimal Contractor Organizational Structure for Effective QC)

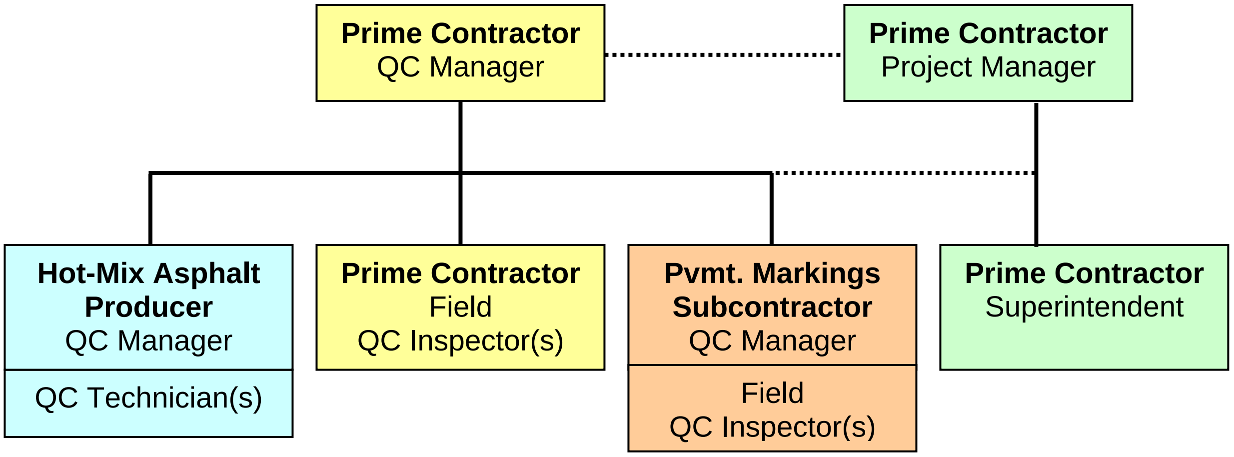
Transportation Project Quality Control Organization

There is no “one size fits all” Quality Control organization structure that can be applied to transportation construction projects. However, as discussed above, each contractor party (i.e., prime contractor, subcontractors, producers, fabricators, manufacturers) should have a QC system and structure in place.

The contractor QC organization will vary depending on the size and complexity of the construction project and the individual operations therein. An example of a Quality Control organization for a major highway construction project and an example of a QC organization for a HMA resurfacing project are shown below.



(QC Organization Chart for Major Highway Construction Project)



(QC Organization Chart for HMA Resurfacing Project)

Regardless of project size, the overall Quality Control organization for a transportation construction project should be led by the prime contractor's QC staff. Unfortunately, some prime contractors who do not fully understand Quality Control choose to utilize a QC Consultant to implement Quality Control on an individual construction project. While some QC personnel within the prime contractor's organization may be consultant staff (e.g., technicians, inspectors), it is strongly recommended that the top QC person (i.e., QC Manager or QC Plan Administrator) be a full-time employee of the prime contractor. The reason for this is to maintain the required focus on quality by all contractors' personnel and to develop the teamwork necessary between QC personnel and production personnel within and between each contractor party. It is generally not possible to achieve this through a temporary or outside Quality Control Manager.

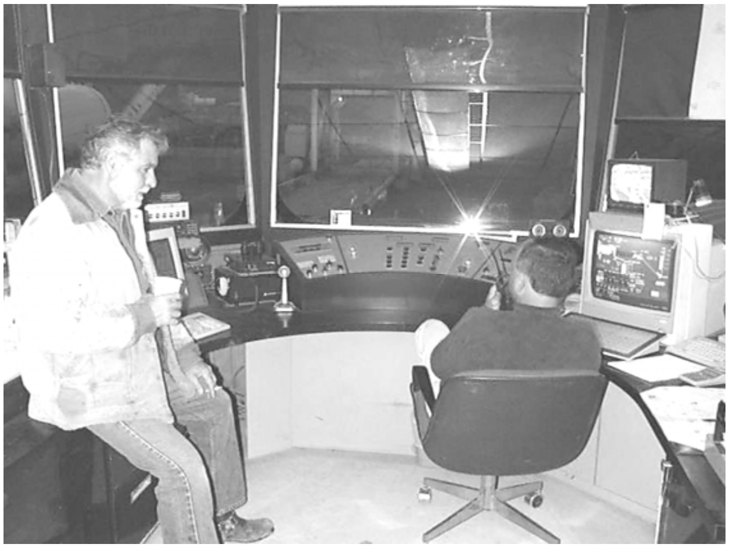
Quality Control Personnel Requirements

Most agency Quality Assurance Specifications will identify the minimum contractor Quality Control personnel required for a project. Such specification requirements typically include the following types of QC personnel:

- Quality Control Manager or QC Plan Administrator
- Production facility QC technicians/inspectors
- QC laboratory personnel
- Field QC technicians/inspectors

The responsibilities and minimum qualifications typically required for these QC personnel are described below.

Quality Control Manager or QC Plan Administrator



Each contractor party (i.e., prime contractor, subcontractors, producers, fabricators, manufacturers) involved with a transportation construction project should have a ***Quality Control Manager***. The QC Manager has primary responsibility and authority for developing and implementing the many details of the company's Quality Control system(s). As is further discussed below (Section 5.3), the QC system for each major category of work performed by the contractor should be sufficiently documented in one or more Quality Control Plans. This is why the QC Manager may also be referred to as the ***QC Plan Administrator***. The prime contractor's QC Manager has overall responsibility for managing Quality Control of all work items on a construction project and must work with the QC Manager of each manufacturer, fabricator, producer, and subcontractor to ensure that their QC systems are providing products that conform to specification targets and limits for quality.

The principal duties of each QC Manager include:

- Establishing the contractor's QC system.
- Preparing complete and functional Quality Control Plans.
- Managing the activities of all QC personnel (technicians/inspectors).
- Communicating routinely with production personnel to ensure quality.
- Initiating work suspension and corrective action when a process is found to be out of control or producing non-conforming materials.
- Ensuring proper QC documentation and records.

A Quality Control Manager should be properly qualified to perform the responsibilities discussed above. It is recommended that each QC Manager possess a combination of education and hands-on experience in Quality Control. The minimum education requirements should include formal classroom training and qualification/certification through a comprehensive course on Quality Assurance. The QC Manager should also have relevant hands-on experience in applying the requirements of a Quality Assurance Program and Quality Assurance Specifications on transportation construction projects. A list of web addresses for typical agency QA Specification requirements, including the qualification/certification of Quality Control Managers (QC Plan Administrators), is provided in **Appendix E**.

Production Facility QC Technicians/Inspectors

Each manufacturer, fabricator, and producer should have a sufficient number of qualified technicians or inspectors at their production facilities to perform Quality Control testing and inspection. The number of ***production facility QC technicians/inspectors*** required by the manufacturer, fabricator, or producer will depend upon the production operation and average volume of material produced. Manufacturers or fabricators, who regularly generate large quantities of standard manufactured materials or fabricated materials on a continuous basis, may require several QC technicians. Producers, who typically produce varying quantities of project produced materials (e.g., aggregate, HMA, PCC), may require only one or two QC technicians to perform Quality Control activities. On large construction projects, the prime contractor or subcontractor that a producer is providing materials to may also provide production facility QC technicians/inspectors to augment the producer's QC staff or to periodically audit the producer's operations.

The principal duties of each production facility QC technician/inspector include:

- Performing QC sampling, testing, and inspection at the production facility.
- Preparing and signing standard QC Test/Inspection Report Forms.
- Providing regular feedback to production personnel (foremen/superintendents) and the QC Manager/QC Plan Administrator based on QC inspection and testing.

A more detailed outline of production facility QC activities is presented in Section 5.7.

Each Production Facility QC technician/inspector should be properly qualified to perform the responsibilities discussed above. Formal qualification/certification requirements for QC technicians/inspectors are normally specified for various project produced materials and fabricated structural materials by the contracting agency. Required qualification/certification programs specified for producer and fabricator QC technicians/inspectors include:

- National programs, such as:
    - American Concrete Institute (ACI)
    - American Society for Nondestructive Testing (ASNT)
    - American Welding Society (AWS)
    - National Association of Corrosion Engineers (NACE)
    - Precast/Prestressed Concrete Institute (PCI)

- Regional programs:
    - Mid-Atlantic Region Technician Certification Program (MARTCP)
    - New England Transportation Technician Certification Program (NETTCP)
    - Western Alliance for Quality Transportation Construction (WAQTC)

- Individual state programs

Manufacturer QC technicians/inspectors (i.e., for standard manufactured materials) are typically required to be qualified in accordance with either:

- Recognized organization standards for each manufacturing industry.
- Qualifications based on relevant experience acceptable to the agency.

A list of web addresses for typical agency QA Specification requirements, including the qualification of production facility (HMA and PCC) QC technicians/inspectors, are summarized in **Appendix E**.

QC Laboratory Personnel

Although individual manufacturers, fabricators, and producers normally have testing laboratories at their production facilities, a project QC laboratory may be necessary to perform some QC testing. This is typically a requirement on larger construction projects. The project QC laboratory may be located on the construction site or may be a consultant laboratory offsite. ***QC laboratory personnel*** normally include a Laboratory Supervisor and Laboratory Technicians. The number of technicians needed will be determined by the volume of QC sampling and testing performed by the QC laboratory.

The principal duties of the QC laboratory personnel include:

- Obtaining QC samples of material from the construction project site or from production facilities.
    - Performing laboratory testing on QC samples.
    - Preparing and signing standard QC Test Report Forms.
    - Providing feedback to production personnel based on QC testing results.
- Identifying materials which do not conform to the requirements of the relevant specifications or QC Plan and discussing with the QC Manager.

All QC laboratory personnel should be properly qualified to perform the responsibilities discussed above. QC laboratory personnel should be qualified/certified for each of the materials items that they sample and test. Qualification/certification requirements for QC laboratory personnel are normally specified for various materials by the contracting agency. Required qualification/certification programs for QC laboratory personnel performing sampling and testing of project produced materials, fabricated materials, or standard manufactured materials are normally the same as described above for production facility QC technicians/inspectors. A list of web addresses for typical agency QA Specification requirements, including the qualification of QC laboratory personnel, are summarized in **Appendix E**.

Field QC Technicians/Inspectors

Quality Control activities during placement or installation of materials at the construction project site should be performed by experienced and properly qualified ***field QC technicians/ inspectors***. These QC personnel are generally employed by or under direct contract to the prime contractor, the subcontractor actually placing or installing the materials, or the material producer. Qualified field QC technicians/inspectors should be provided for each major work item category addressed by the QA Specifications (e.g., earthwork, sub-base and base material, pavements, geotechnical items, structural concrete). The number of field QC technicians/inspectors required should be sufficient to provide proper QC inspection and testing for each active work item.

The principal duties of each field QC technician/inspector include:

- Performing QC sampling, testing, and inspection of field placement operations.
- Preparing and signing standard QC Test/Inspection Report Forms.
- Providing regular feedback to production personnel (foremen/superintendents) and the QC Manager/QC Plan Administrator based on QC inspection and testing.

A more detailed outline of field QC activities is presented in Section 5.8.

Field QC technicians/inspectors should be qualified to perform all QC testing or inspection duties required for each major work item for which they are responsible. Testing performed by field QC technicians/inspectors is normally only for project produced materials (i.e., earthwork, geotechnical items, sub-base and base courses, Hot-Mix Asphalt, Portland Cement Concrete, structural steel coatings, and pavement markings). Field inspection is required during placement of these project produced materials as well as for the installation of fabricated structural materials or standard manufactured materials. Field QC technicians/inspectors can be qualified to perform testing and inspection for multiple work items. Formal qualification/certification requirements for field QC technicians/inspectors are normally specified for various major work items by the contracting agency.

Required qualification/certification programs specified for field QC technicians/inspectors include:

- National programs, such as:
  - American Concrete Institute (ACI)
  - American Welding Society (AWS)
  - National Association of Corrosion Engineers (NACE)

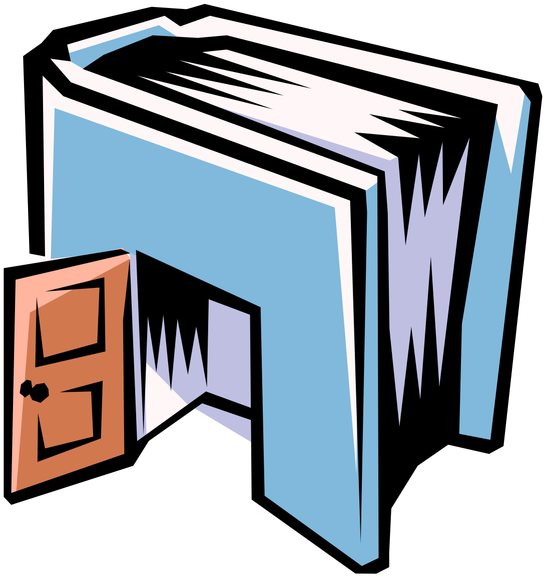
- Regional programs:
  - Mid-Atlantic Region Technician Certification Program (MARTCP)
  - New England Transportation Technician Certification Program (NETTCP)
  - Western Alliance for Quality Transportation Construction (WAQTC)

- Individual state programs

A list of web addresses for typical agency QA Specification requirements, including the qualification of field QC technicians/inspectors, are summarized in **Appendix E**.

5.3 - Quality Control Operating Documents

Contractor Quality System Manual



Agencies may require the QC system for each contractor (i.e., prime contractor, subcontractors, producers, fabricators, manufacturers) to be sufficiently documented in a ***Quality System Manual***. A Quality System Manual (QSM) is defined as follows:

> **Quality System Manual** - "A written document that describes the overall Quality Control operating procedures of a contractor party (e.g., prime contractor, subcontractor, producer, fabricator, manufacturer)."

A Quality System Manual documents the contractor's policies for achieving quality and the assignment of responsibility and accountability for Quality Control within the contractor organization. It also describes the minimum QC requirements expected of upper or lower tier contractor parties with whom the contractor works. While a Quality System Manual may not be a specific requirement in agency Quality Assurance Specifications, contractors who recognize the many benefits of quality in their operations will prepare and utilize this document. A Quality System Manual is normally a requirement for producers, fabricators, or manufacturers to obtain industry recognized certification of their production facilities (e.g., PCI). Guidelines for the preparation of Quality System Manuals are typically issued by industry organizations that administer production facility certification programs. In addition, ISO10013 contains guidelines on the development and preparation of Quality System Manuals. AASHTO Materials Standard R 38 includes standards for the preparation of Quality System Manuals for standard manufactured materials.

Quality Control Plans

Agency Quality Assurance Specifications normally require one or more ***Quality Control Plans*** (QC Plans) on each transportation construction project. Quality Control Plans are defined as follows:

> **Quality Control Plan** - "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 processes "in control" and meet the agency specification requirements."

The QC Plan is intended to identify the key project personnel and procedures that will be used to:

a) Maintain all production and placement processes "in control."

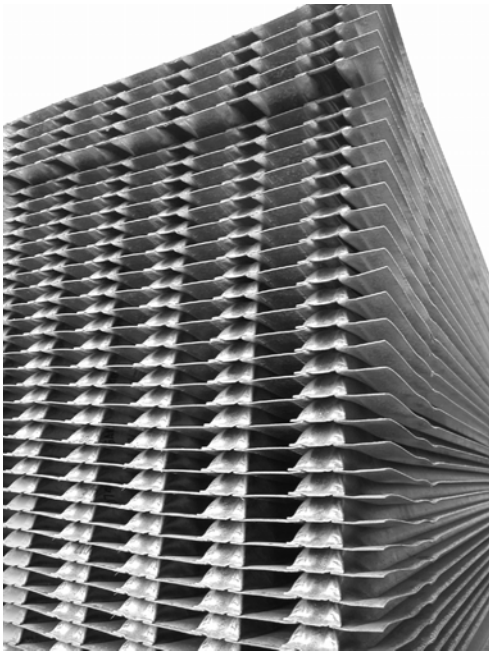
b) Quickly determine when a process is "out of control."

c) Take corrective action to bring a process "back into control."

In short, a Quality Control Plan is intended to provide a roadmap for all contractor parties on a construction project to tangibly apply the TQM "Zero Defects" philosophy and prevent problems or "non-quality" from occurring in the first place.

Agency specifications will identify those work item categories that require a QC Plan. A separate QC Plan is typically prepared for each major work item category on the project. However, some agencies will accept a single comprehensive QC Plan, as long as it satisfactorily addresses (usually in separate sections), each major work item category. The QC Plan work item categories may include the following:

- Earthwork
- Drainage and Water Systems
- Sub-base and Base Material
- Pavements
- Geotechnical Items
- Safety Hardware
- Landscape and Roadside Items
- Traffic Control Devices
- Piles and Sheeting
- Structural Portland Cement Concrete
- Structural Steel



5.4 - QC Plan Requirements

Quality Control Plan Preparation

Overall responsibility for preparing and implementing the QC Plan(s) for a transportation construction project lies with the prime contractor's QC Manager. As mentioned previously, this is why the prime contractor's QC Manager may also be referred to as the QC Plan Administrator. Each Quality Control Plan should identify the QC processes of all manufacturers, fabricators, producers, or subcontractors involved with the major work item addressed by the QC Plan. Accordingly, the prime contractor's QC Manager (QC Plan Administrator) must work closely with the QC Manager of each manufacturer, fabricator, producer, and subcontractor to ensure that their individual QC systems are sufficiently documented in the QC Plan. One approach to achieve this is to combine each contractor party's QC information into a single stand-alone QC Plan. Another approach is to insert separate QC Plans prepared by subcontractors, producers, and fabricators in an appendix of the primary QC Plan.

The QC systems for manufacturers' items (i.e., standard manufactured materials) are generally established to provide standard products which do not change from project to project. Accordingly, manufacturers are typically required to maintain a Quality System Manual (rather than a project-specific Quality Control Plan). Manufacturer Quality System Manuals may be required to be submitted directly to transportation agencies on some periodic basis (annually or biannually) for acceptance or audit. If a manufacturer's Quality System Manual has been approved through this type of process, it is not necessary to include this document in a construction project Quality Control Plan. However, such manufacturer's Quality System Manuals should be referenced in the relevant project Quality Control Plan.

Quality Control Plan Submittal

Each draft QC Plan should be submitted for review by each relevant contractor party's QC Manager prior to submittal to the agency for acceptance. This will ensure that the Quality Control Plan accurately reflects each contractor's role in the production and placement of the subject major work item and allow an opportunity to resolve any conflicts or inaccurate information contained in the QC Plan.

Once all contractor parties are in agreement with a Quality Control Plan, it should be submitted to the appropriate agency project representative (typically the Project Manager or Resident Engineer) for review and "approval" or "acceptance." (Note: As is further explained in Chapter 6 (Section 6.3), due to legal or liability considerations, some agencies indicate their action to be "acceptance" rather than "approval" of the QC Plan.) Agency QA Specifications will normally specify the requirements for contractor submittal of QC Plans.

Some agencies require that a draft of all contractor Quality Control Plans be submitted prior to the pre-construction conference for the project (typically 5 days prior). This allows an opportunity at the pre-construction conference for the contractor to provide a walk-through and initial discussion of the QC Plan contents with the agency. Other agencies require QC Plans to be submitted for review and approval (or acceptance) a minimum number of days prior to the start of construction activity on the subject work item (typically 30 days prior). Either approach is intended to provide adequate time for agency review, subsequent meetings to discuss questions or comments, and possible re-submittal of the Quality Control Plan if necessary. Quality Assurance Specifications will normally indicate that the contractor cannot start work on an individual work item until the agency has approved (or accepted) the corresponding QC Plan.

A list of web addresses for typical agency QA Specification requirements, including the submittal of Quality Control Plans, are summarized in **Appendix E**.

Quality Control Plan Format and Contents

As mentioned above, each Quality Control Plan should sufficiently document the QC processes of all contractor parties (i.e., prime contractor, subcontractors, producers, fabricators, manufacturers) involved with the production and placement of materials for a particular major work item category. A QC Plan is not intended to be a generic or "boilerplate" document, but rather must be project-specific. It should reflect the actual QC processes that will be applied on an individual construction project.

The preparation and submittal of a QC Plan cannot be viewed as a "paper exercise". Each Quality Control Plan should be written in a straightforward and plain-speaking manner so that it can serve as a working, usable document. At the risk of sounding cliché, "quality, not quantity" is desired. Details are very important, however, and each QC Plan should be comprehensive in the level of information provided.

Agency Quality Assurance Specifications will normally identify the minimum required QC Plan contents, but do not always prescribe a specific format. A list of web addresses for typical agency QA Specification requirements, including the minimum Quality Control Plan contents typically specified by agencies, are summarized in **Appendix E**. The items presented below are recommended for inclusion in any QC Plan. They are summarized to follow both a recommended QC Plan format along with the specific minimum contents.

- **Terms and Definitions (optional) –** Presents and defines any significant terms used throughout the Quality Control Plan in order to establish a uniform understanding of essential concepts and to avoid potential confusion later. Examples of such terms include *Action Limits*, *Control Strip, Random Sample,* etc. All terms defined in the QC Plan should reflect agency definitions.

- **Applicable Specifications –** The work item(s) addressed under the QC Plan will generally reference the applicable agency Quality Assurance Specification as well as other relevant specification documents. A list of those specifications should be presented (with relevant section numbers where applicable) in order to facilitate lookup and review of pertinent information that is not contained within the QC Plan itself. Examples of such applicable specifications include:

  - Standard Specifications
  - Supplemental Specification
  - Project Special Provisions
  - Project Drawings

- **Quality Control Organization –** The Quality Control Plan should identify the specific QC Personnel and briefly describe their responsibilities and relevant qualifications. Personnel responsibilities should clearly indicate the levels of authorization to enforce hold points on the work, as well as points of contact for each individual identified. This information should be provided for each of the following personnel:

  - QC Plan Administrator
  - Contractor QC Managers
  - Production Facility QC Technicians/Inspectors
  - QC Laboratory Personnel
  - Field QC Technicians/Inspectors

- **Quality Control Laboratories –** The QC Plan should include a list of all laboratories (primary QC laboratories as well as subcontractor or producer laboratories) used to test materials along with their location, as well as any relevant accreditations, certifications, or qualifications. The listing should include the name and points of contact for the laboratory manager in order to facilitate communications between personnel during the project.

- **Materials Control –** The source(s) of all constituent materials (project produced, fabricated, or standard manufactured materials) planned to be used for the specific work item addressed by the Quality Control Plan. The QC Plan should also address the procedures for shipment, storage, or possible processing (e.g., RAP) of the constituent materials in order to control the quality of the materials being provided prior to production and installation. Materials Control information should address:

  - Material Types and Sources of Supply
  - Material Properties
  - Mix Designs
  - Processing of Existing Materials
  - Material Storage and Stockpiling

- **Quality Control Sampling and Testing –** The QC Plan should detail the processes used to determine appropriate sample locations in accordance with specified frequencies, as well as the management of sampled materials. Information should include identification of the following:

    - Lot and Sublot Sizes
    - Random Sampling Plan
    - Sample Identification System
    - QC Sampling and Testing Requirements
    - QC Test Result Reporting
    - QC Sample Storage and Retention Procedures

- **Production Facility Management –** The Quality Control Plan should include all relevant information regarding production facility management. The purpose of this information is to provide production facility QC personnel with a clear understanding of the production process and corresponding QC activities and procedures (including sampling, testing, inspection, analysis of test information, reporting, etc.) that will be utilized to meet quality requirements in accordance with the project specifications. Such information will include:

    - Schedule of Production Operations
    - Production Facilities and Equipment
    - Pre-Production QC Activities
    - Production Quality Control Activities
    - Production Facility Control Charts (examples)
    - Procedures for Corrective Action of Non-Conforming materials
    - Production QC Inspection Reporting

- **Field Management –** The QC Plan should include all relevant information regarding field management as it relates to Quality Control. The purpose of this information is to provide field QC personnel with a clear understanding of the placement or installation process and corresponding QC activities and procedures (including sampling, testing, inspection, analysis of test information, reporting, etc.) that will be utilized to meet quality requirements in accordance with the project specifications. Such information will include:

  - Schedule of Field Placement Operations
  - Field Placement Facilities and Equipment
  - Control Strip Procedures (when applicable)
  - Field Quality Control Activities
  - Material transportation and Delivery QC Activities
  - Pre-Placement QC Activities
  - Placement QC Activities
  - Finishing and Curing QC Activities
  - Placement Control Charts
  - Procedures for Corrective Action of Non-Conforming materials
  - Field QC Inspection Reporting

- **Other Relevant Contractor QC Plans –** The Quality Control Plan should include (in appendices) any relevant QC Plans included from other contractor parties as part of the Quality Management system. These may include:
  - Subcontractor QC Plans
  - Producer QC Plans
  - fabricator QC Plans

Model Quality Control Plan

To assist contractors in developing good Quality Control Plans, a "Model Quality Control Plan" is included in **Appendix F**. The format and outline of the Model QC Plan follow the information presented above. This recommended format and content has been developed based on the guidelines contained in the *AASHTO Quality Assurance Implementation Guide* (1996) and is also based on the experience of contractors, state agencies, and the FHWA. It is suggested that agencies adopt this Model QC Plan as a standard reference document in their Quality Assurance Program or in their Quality Assurance Specifications.

Quality Assurance Technologist

Appendix F
Typical "Model Quality Control Plan"

State Route 99 Construction Project
Anytown, USA
Transportation Agency Contract #54321

ABC Contractors, Inc.

NETTCP
MODEL QC PLAN

Construction Quality Control Plan

Section 1 - Earthwork

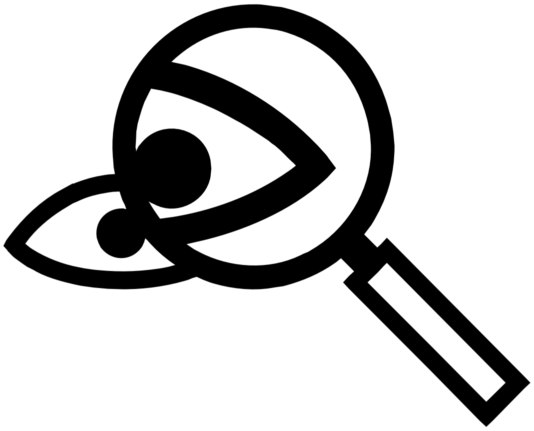
December 2, 2002 Draft

Submitted By: ______________________ **ABC Contractors, Inc.** ________ **Date**

Approved By: ______________________ **Transportation Agency** ________ **Date**

December 2002 PILOT **F-5**

5.5 - Visual Inspection for Quality Control



Contractor Quality Control is often seen as primarily focused on sampling and testing. However, ***visual inspection*** is also essential to achieving quality. Inspection activities are almost entirely visual by definition, involving observations and measurement of equipment, materials, environmental conditions, and workmanship. It is equally important to ensure a proper level of visual inspection at both production facilities and field placement sites.

Past inspection practices of checking for defective work after production or placement cannot ensure quality. QC inspection activities need to be prevention-based, not detection-based. Obviously it is more effective to check and correct something that could negatively impact the final quality of a product prior to or near the beginning of a particular production or placement activity, rather than after the operation is well underway or nearly complete. This approach to inspection is key to the Zero Defects concept of TQM discussed previously in this chapter. As discussed below, a successful contractor Quality Control system does not just rely upon periodic formal inspection performed by QC personnel, but utilizes continuous inspection for quality by frontline production personnel as well.

Inspection by Production Personnel

Although the primary function of contractor production personnel (laborers, operators, foremen, and superintendents) is to produce or install specific items of work, they must also play a QC role through ***self-inspection***. A good contractor Quality Control system doesn’t wait for the QC Inspectors to come by and place their “stamp of approval” on material production or placement activities. It begins with the laborers, operators, foremen, and superintendents who are on the frontline of production and placement.

Contractor personnel who are dedicated to providing a product of the highest possible quality are active participants in continuous self-inspection for quality even though it is not their job to perform formal QC sampling, testing, and inspection. To put it another way, Quality Control is not merely a discreet, departmentalized function of the contractor's organization that exists in a vacuum, but rather an integrated element of the entire process of production and construction.

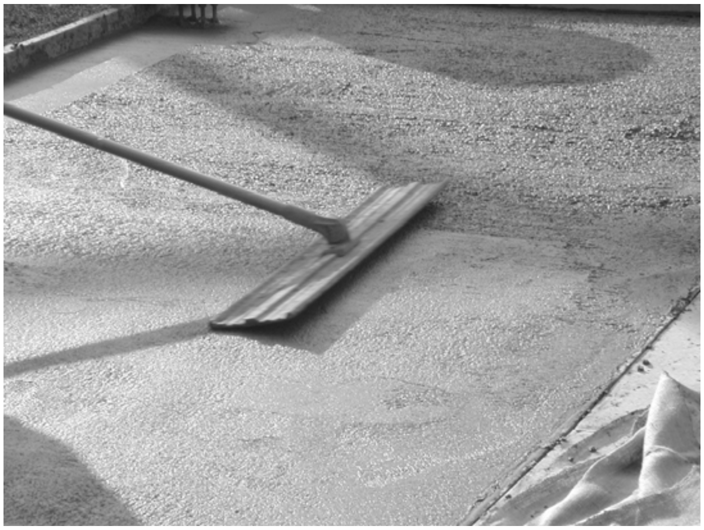
While it may seem obvious that production personnel need to take responsibility for upfront inspection of the materials they use and the quality of their work, the requirements for achieving quality, unfortunately, may not always be clearly understood by these workers. In order for frontline production personnel to provide continuous self-inspection for quality, they must first have a uniform understanding of how to achieve quality, including:

- The correct tools and equipment required to perform the work.
- What constitutes proper functioning equipment and equipment conditions or circumstances that can result in non-quality.
- How to keep these tools and equipment suitably clean and properly maintained.
- What specification-compliant materials look like at a production facility as well as when delivered at the field placement location.
- Proper procedures for shipping, handling, and storage of materials.
- Proper practices for placement or installation of the materials.
- What "quality workmanship" of the finished work looks like.

When production personnel are equipped with sufficient knowledge of these details, they are then capable of knowing what to look for throughout the production, placement, or installation operations for individual work Items.

Self-inspection practices by frontline production personnel should include observations of the production or placement process that may not be explicitly stated in Quality Assurance Specifications, but will nonetheless impact the quality of the product. Regularly scheduled maintenance and calibration inspections, and replacing, reconfiguring, or recalibrating worn or malfunctioning components are important Quality Control inspection activities. For example, inspecting and subsequently replacing a worn screen deck on an aggregate crusher or in an HMA production facility may have a larger overall impact on the product quality than a month's worth of gradation testing by QC personnel and subsequent corrective action that attempts to engineer a solution that "works around" the root cause of the problem.

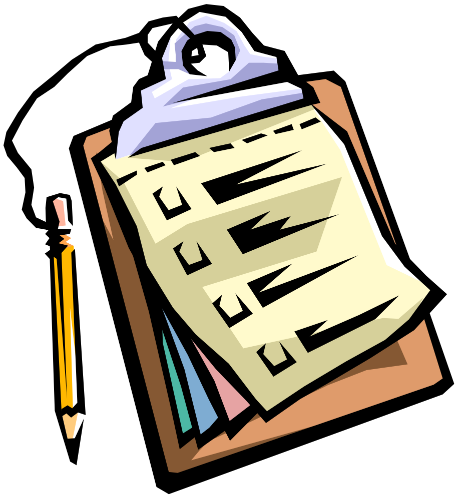
Skilled laborers and foremen should be capable of identifying unacceptable materials prior to incorporation in the work. For example, if epoxy coated rebar is delivered to a project site and is found through initial visual inspection to have corrosion or damaged coating requiring more than minor touch up, the material should not be incorporated in the work. The laborers or foremen working with this material should take initial responsibility for accepting or rejecting such material. Of course, these production personnel should always communicate their findings and proposed actions with their QC inspectors or technicians.



"Quality of Workmanship," while not always very well defined in many Quality Assurance Specifications, is also very important to monitor and inspect. For example, over-finishing concrete flatwork (i.e., adding extra water to concrete surfaces to gain workability during finishing) will result in a layer of weak mortar at the surface that will be more prone to chipping and spalling. Such practices that result in poor workmanship must be clearly understood by and prevented by frontline production personnel through continuous self-inspection.

It is important to incorporate self-inspection activities by production personnel as an integral part of the Quality Control system in order to ensure the quality of the product. The contractor who strives to provide a high-quality product (and in the process earn a responsible profit) must strive to create a quality culture throughout the company, not just in the QC Department. Ideally, the contractor's production personnel are aware of how their actions can affect the quality of the product and are motivated to communicate with their superiors and with QC personnel when they encounter inspection issues that identify the need for preventive or corrective action. Accordingly, contractors must invest in the continual education and training of their work force in order to maximize their involvement in the process of inspection for Quality Control.

Inspection by QC Personnel



Obviously inspection for Quality Control cannot rely solely upon self-inspection by production personnel. Even the most quality-conscious workers performing self-inspection cannot be expected to identify every potential quality problem or defect. Therefore, formal QC inspection must be performed by qualified contractor Quality Control technicians/inspectors under the direction of the QC Manager. The intent of inspection by QC technicians/inspectors is to provide <u>structured monitoring</u> of individual production or placement <u>processes</u> to ensure that they are providing a quality product. Like the self-inspection efforts of production personnel described above, formal QC inspection activities are aimed at preventing problems or non-quality work from occurring at both production facilities and field placement sites.

The minimum QC inspection activities conducted by QC technicians and inspectors should be as outlined in the contractor Quality Control Plan. However, capable Quality Control inspection personnel do not rely strictly on the QC Plan and will recognize the need to increase their level of inspection effort to address specific circumstances as necessary.

As a minimum, formal QC inspection must be provided on a daily basis for each active production or placement operation. Production facility QC technicians/inspectors should conduct daily QC inspection prior to, during, and after production. This applies to production operations at facilities producing either standard manufactured materials, fabricated materials, or project produced materials. Likewise, field QC technicians/inspectors should conduct daily QC inspection prior to, during, and after placement of all materials. Field QC inspection activities should be structured to address each major phase of a placement or installation operation.

QC inspection activities should include both visual observation (e.g., uniformity of material, effect of operations practices on quality) and check measurements (e.g., temperature, dimensions of forms or material) for each of the following four primary components:

- Equipment
- Materials
- Environmental Conditions
- Product Workmanship

A brief description along with examples of each of these QC inspection components is presented below. It should be noted that the examples provided are not all-inclusive and are intended only to illustrate the types of QC inspection activities that should be provided for various production and placement operations.

QC Inspection of Equipment

Inspection of ***equipment*** by QC personnel should include visual checks to ensure that both the equipment used for installation of the product, as well as equipment used to test material properties, is in good working condition and is properly maintained. Periodic calibration of equipment should also be performed.

Examples of QC inspection activities of equipment at production facilities are as follow:

- Precast Concrete Facility Equipment – Check forms (i.e., clean, not dented up); check and calibrate vibrating equipment. Calibrate pressure air meters used to determine air content of freshly mixed concrete.
- Concrete Plant Equipment – Visual checks of silos, bins, belts; calibration of scales, water and admixture tanks and discharge system.
- PVC Pipe Manufacturer Equipment – Visual checks and calibration of automated assembly equipment; check product on the assembly line (defective product indicates problem is likely with equipment).

Examples of QC inspection activities of equipment in the field are as follow:

- HMA Paving Equipment – Check vibratory rollers to ensure frequency and amplitude gauges are properly functioning.
- Pavement Marking Equipment – Check and calibrate temperature gauges; check spray nozzles for proper aperture and clogging.
- Concrete Conveyance Equipment- Check for cleanliness, soundness, appropriate opening sizes for charging and discharging mechanisms.

QC Inspection of Materials

Inspection of ***materials*** should include an examination of the material properties and physical condition of the materials at each stage of production and placement. It also includes reviewing materials Certificates of Compliance (COC) received from fabricators or manufacturers to ensure the correct material type is being used and that the materials meet specification requirements.

Examples of QC inspection activities of materials at production facilities are as follow:

- Aggregates – Visual checks of aggregates on belt appear to be correct types and in correct proportions for particular HMA or PCC mix.
- Recycled Asphalt Product (RAP) – Visual checks for uniformity of material size; checks to ensure no foreign material is present in stockpiles.
- PG Binder – Check manufacturer COC to confirm correct type/grade of binder is delivered at HMA production facility and that manufacturer (Supplier) testing meets specification requirements.

Examples of QC inspection activities of materials in the field are as follow:

- Roadway Embankment Material – Use visual soil classification to confirm that correct material is being delivered and placed; take check measurements of large boulders in lift to ensure they do not exceed maximum size permitted; observe that all organic materials are removed from the material.
- Epoxy Coated Rebar – Check manufacturer certification and rebar markings for correct type/grade of rebar; inspect for dirt/contaminants, damage to epoxy, or corrosion.
- Hot Mix Asphalt – Ensure that delivered materials do not exhibit excessive steam (indicates presence of moisture) or blue smoke (indicates excessive heat).

QC Inspection of Environmental Conditions

Inspection of ***environmental conditions*** should include visual monitoring and measurements to ensure that the proper physical environment (e.g., cleanliness of storage containers/surfaces, particulates in air, moisture levels, temperatures, precipitation, etc.) is being provided for storage, production, placement, and curing of individual materials or products.

Examples of QC inspection activities of environmental conditions at production facilities are as follow:

- <u>Producer Stockpiles and Bins</u> – Inspect stockpiles and bins for proper storage (different aggregates adequately separated, maintained free of excess moisture, no segregation).
- <u>HMA Production Facility</u> – Check temperature of PG Binder storage tanks; check to ensure proper temperature is maintained in drum mixer.
- <u>Steel fabrication/Coatings Facility</u> – Check and monitor shop for levels of dust or airborne particles; take measurements of ambient air temperature and humidity.

Examples of QC inspection activities of environmental conditions in the field are as follow:

- Sub-base Material – Visually assess subgrade and sub-base material to ensure moisture conditions appear to be near optimum (i.e., not frozen, too wet, or too dry) prior to and during sub-base placement.
- HMA Paving Operation – Take temperature measurements of ambient air and existing surface HMA is to be placed on; visually check cleanliness of existing surface (i.e., no tracked dirt, gravel, leaves or other debris).
- Structural PCC Curing – Monitor adequacy of continuous moisture for curing; take check measurements of surface temperature under blankets (i.e., cold weather) and internal temperature (i.e., hot weather/mass concrete).

QC Inspection of Product Workmanship

Inspection of ***workmanship*** is focused on the quality of an item directly attributable to the process of production, placement, or installation by human labor and equipment. It is particularly (though not exclusively) applicable to those production or placement processes that are less automated.

QC inspection of workmanship at production facilities is generally applicable only to fabricated materials and manufactured materials.

Examples of QC inspection activities of workmanship in the field are as follow:

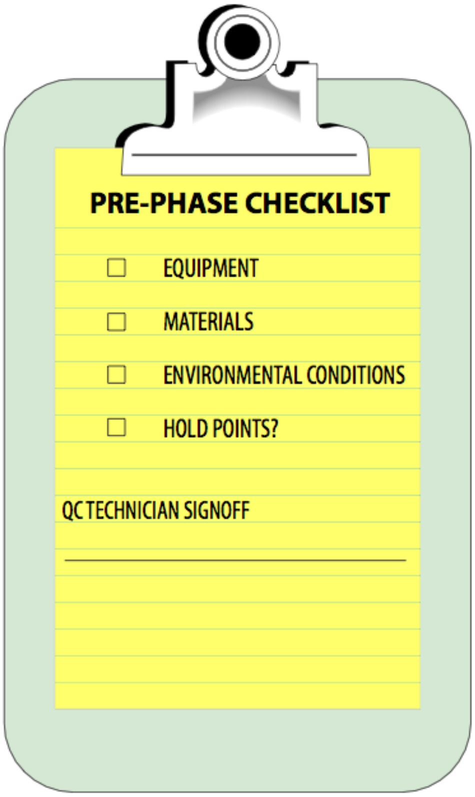
- Earthwork Placement – Take check measurements of earthwork lift depths to ensure placement does not exceed maximum allowable depth.
- HMA Placement – Monitor quality of HMA mat for segregation; check to ensure tight joints with minimal lute work (i.e., workers not “broadcasting” HMA).
- Concrete Placement – Check that correct type(s) of rebar have been set in forms; check installed rebar for proper locations/spacing and depth of cover prior to concrete placement.

QC Inspection Documentation and Feedback

All Quality Control inspection activities performed by QC technicians/inspectors should be documented on standard ***Inspection Report Forms*** (IRFs) on a daily basis. It is recommended that separate IRFs be developed and used for production facility inspection and field placement inspection for each major Work Item category. Inspection Report Forms should address each of the four primary components of QC inspection (i.e., equipment, materials, environmental conditions, product workmanship) discussed above. The format of the IRFs should ideally include an outline or checkbox listing of key inspection items along with space for noting specific observations, measurements, or reviews of manufacturer Certificates of Compliance.

To make effective use of Quality Control inspection, QC Personnel should provide timely feedback and input to production personnel on findings of their QC inspection activities. Accordingly, the IRFs should also provide space for documenting specific corrective actions or other instructions provided to production personnel responsible for the particular operation inspected.

Standard Inspection Report Forms, or similar forms, may also be used by contractor QC personnel who may be required to periodically audit the Quality Control activities of lower tier contractors (i.e., subcontractors, producers, fabricators, manufacturers). The results of such inspections should be shared in a timely manner with the QC personnel of the audited contractor.



In addition to daily Inspection Report Forms, “Pre-phase Checklists” may also be utilized prior to the start of a major production or placement operation. Pre-phase checklists should include all inspection components (equipment, materials, and environmental conditions) that are determined to have an impact on the quality of the production or placement operation. They are typically used in conjunction with a “signoff” system by QC inspection personnel (pre-production signoff, pre-placement signoff) to indicate that sufficient checks have been made to assure the process is in control to achieve the specified quality.

Each pre-phase checklist will normally identify “hold points” on the production or placement operation when non-compliant conditions are identified by QC personnel. When hold points are invoked, the production or placement operation is not permitted to proceed until satisfactory corrective action has been taken and the QC technician or inspector has provided final signoff on the pre-phase checklist.

5.6 - QC Sampling and Testing Requirements

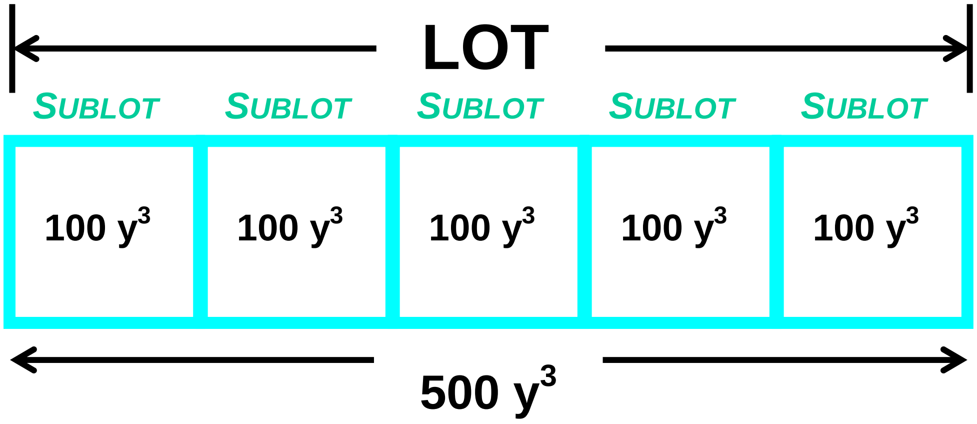
Quality Control sampling and testing should be conducted only by QC technicians or inspectors who are properly qualified to perform the specific sampling and testing methods required. As part of an effective Quality Control system, daily QC sampling and testing should be conducted throughout (at startup, during, and after) production or placement of all materials. QC sampling and testing at production facilities includes manufactured, fabricated, or project produced materials. Construction materials that require Quality Control sampling and testing during field placement will normally only include project produced materials.

Quality Control sampling and testing provides measurement of specific materials properties or Quality Characteristics, which were explained in Chapter 4. The primary function of QC sampling and testing is to monitor and guide each production or placement process. Quality Control testing data is used to determine the degree of uniformity or the measured variability of materials or products during production or placement. This information is used to identify whether a specific production or placement process is “in control” and, therefore, provides information to guide QC personnel in making adjustments or corrective actions to the process.

In addition, Quality Control testing data is used by contractors to monitor the quality and acceptability of a given material or product. As will be further discussed in Chapter 6, QC test results may also be included in an agency’s final acceptance determination for individual work items.

Frequency of QC Sampling and Testing

Contractor Quality Control sampling and testing should be conducted at sufficient frequencies to represent defined quantities of material. As was explained in Chapter 4, materials used for individual work items are evaluated by lots. Each lot of material must represent material from the same source and be produced or placed under the same controlled process. Each lot is typically stratified or divided into sublots of equal size in order to assess the Quality Characteristics of the lot. To provide a mathematically representative assessment of the quality of each lot, the minimum number of sublots will usually be four (4) or five (5). Most agency Quality Assurance Specifications will identify the minimum required QC sampling and testing frequency using lot and sublot sizes. Normally one QC sample is required to be tested from each sublot. A list of web addresses for typical agency QA Specification requirements, including the lot and sublot sizes specified by agencies for Quality Control sampling and testing, is provided in **Appendix E**.



QC Sampling and Testing Methods

Most agency Quality Assurance Specifications will also identify the Quality Characteristics subject to QC sampling and testing, as well as the corresponding sampling locations and test methods to be used. The required methods of sampling and testing will normally be standard AASHTO designated test methods. Where AASHTO standard sampling or test methods do not exist, ASTM test methods are typically specified. While not encouraged, some agencies will specify their own sampling or testing methods, which are usually AASHTO or ASTM methods with some minor variation in the procedure.

A list of web addresses for typical agency QA Specification requirements, including the minimum Quality Control sampling and testing requirements (i.e., Quality Characteristics, sampling locations, and testing methods) specified by agencies, are provided in **Appendix E**.

While an agency's minimum sampling and testing requirements must be met, each contractor should design a Quality Control sampling and testing program that provides sufficient data to ensure proper control of their specific production or placement operation. For each production facility or placement operation, specific Quality Control sampling and testing protocols should be developed to accommodate the particular equipment and methods being used. In some cases it may be beneficial for the contractor to propose additional QC sampling and testing where it is found to be helpful in controlling product quality. For example, a contractor's QC testing program at an HMA drum mix plant required that composite belt samples be obtained for gradation testing (in addition to the agency minimum required extracted aggregate gradation analysis) in order to better calibrate belt feeds. While this procedure was used routinely throughout production to gain better control of the product at this particular production facility, not all HMA drum mix plants may require this additional testing.

Random QC Sampling and Testing

Quality Control samples obtained from each sublot should be randomly selected using a random sampling procedure. As was explained in Chapter 4, random sampling will avoid bias in the QC testing data, which provides a truer picture of the quality of material being produced or placed.

Contractor Quality Control personnel are normally responsible for selecting the random QC sampling locations for each production or placement operation. Most agencies require random sampling locations to be determined in accordance with ASTM D 3665 or by use of a random number generating function on a calculator or computer. All random QC sample locations should be determined prior to the start of the applicable production or placement operation (typically at the beginning of the day) and documented by QC personnel on Standard Test Report Forms. A copy of the completed Random Sampling Report Forms should be provided to appropriate agency inspection personnel ideally during the startup of the production or placement activity each day.

Selective QC Sampling and Testing

In addition to random sampling as described above, contractors will usually also perform non-random or selective sampling. Testing performed using selective sampling is sometimes also referred to as Contractor Information Testing (CIT). As was explained in Chapter 4, selective samples are used to provide initial or supplemental Quality Control information to assist in monitoring the production or placement process or to gauge the effect of corrective adjustments to the process.

There is no prescribed frequency for selective QC sampling and testing. Selective QC samples are normally obtained on an as-needed basis in the judgment of Quality Control personnel. Selective QC sampling and testing is typically performed just after the start of an individual production or placement operation to confirm that the process is providing the required product quality. When visual Quality Control inspection identifies apparent non-conforming materials at any point in the production or placement process, selective QC samples may be obtained to assist in determining the actual product quality and the root cause(s) of the deficiency.

Since selective sampling is non-random and therefore biased, the test results of selective QC samples should never be combined for Quality Level Analysis with random QC samples for a given lot. A selective QC sample provides only a snapshot of the Quality Control process and the product quality.

QC Sample Identification System

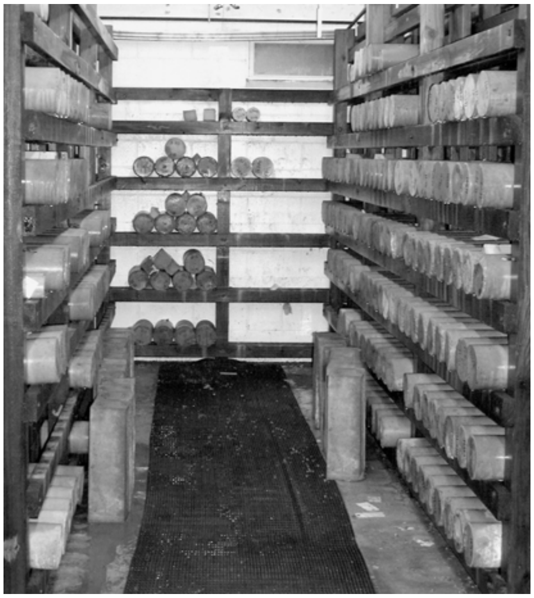
Another important responsibility of Quality Control personnel is to ensure that all QC samples are clearly and properly identified. Agency Quality Assurance Specifications may state a particular system for identification of QC samples. Otherwise, QC personnel must implement a reliable system for labeling QC samples obtained from all production and placement operations. The importance of establishing and consistently applying a QC sample identification system cannot be overemphasized. Improper labeling of QC samples can result in QC testing data from different lots being combined or selective QC sample data to be combined with random QC sample data, thus causing any subsequent analysis of the QC data to be flawed.

Typical information that is necessary in a QC sample identification system includes:

- Project Name or Number
- Material Type (e.g., Ordinary Borrow, 12.5mm HMA, #9 Epoxy Rebar)
- QC Sample Type (e.g., QC Random, QC Selective)
- Lot Number and Sublot Number
- Sample Location (e.g., Median, Shoulder, East Wingwall)
- Station, Offset, Depth
- Sample Date
- QC Technician or Inspector

QC Sample Storage and Retention Procedures

It is also important for Quality Control personnel to establish and implement a sound system for storage and retention of QC samples. Agency Quality Assurance Specifications may outline specific procedures for sample storage and retention. Storage practices prior to testing should ensure that all QC samples are kept in a suitable location that protects them from damage and which provides the proper environment for curing the material or maintaining the required material properties.



It is recommended practice for all QC samples to be split prior to testing, in accordance with relevant sampling and testing procedures. The split sample portion of material not used for initial testing should be retained in the original sample storage device with proper identification. The split sample should be stored in an appropriate Sample Storage Room at the QC laboratory which performed the initial testing for a reasonable period following testing (typically a minimum of 30 to 60 days).

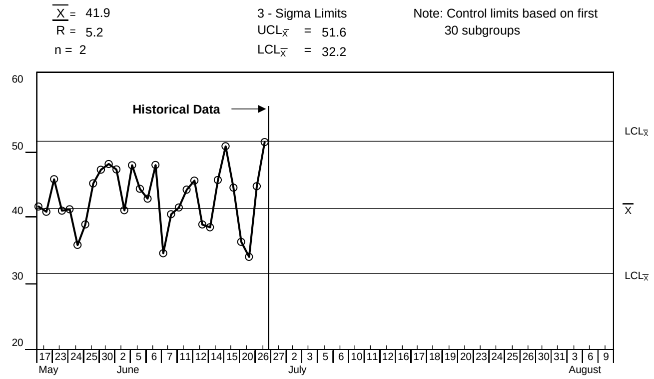
Analysis and Application of QC Test Results

Timely analysis of QC data provides a powerful tool for Quality Control personnel to confirm whether an individual production or placement process is in control and to determine the measured quality level of materials. It is important that QC personnel evaluate QC test data on a real-time basis. Waiting until significant time has elapsed (e.g., end of the month, end of the project) or until significant quantities of material have been produced or placed to evaluate test results does not constitute effective Quality Control. Accordingly, Quality Control personnel must ensure that QC test results are properly reviewed and that timely corrective action, based on these test results, is taken and documented when necessary to control material quality.

While it is important for analysis of QC test results to be performed on a real-time basis, it is also necessary to have sufficient data (i.e., number of test results) to provide meaningful analysis. As was explained in Chapter 4, due to the normal variability inherent in any lot of material produced or placed, the test results of a single QC sample (or even an individual agency sample) cannot be used to determine the overall quality of the lot. Instead, multiple test values throughout the lot (i.e., sublot test results) must be used to characterize the lot of material. As is briefly explained below, the two primary tools for analysis of multiple Quality Control test results are:

- Control Charts
- Quality Level Analysis

Most agency Quality Assurance Specifications require the use of ***control charts*** by contractor QC personnel. The proper development and use of control charts is presented in detail in Chapter 9. Control charts are used to plot and monitor consecutive QC test results for an individual Quality Characteristic throughout production or placement of a work item. The QC test results can be tracked on the control chart against a process target value and upper and lower “Control Limits”. Control Limits are established by the contractor (not the agency) based on the historic variability of the contractor’s individual production or placement process.



Control Chart for Average $(\overline{X})$ for 3/8" Sieve (Percent Passing)

By plotting and monitoring the QC test results on a control chart, QC personnel are able to identify patterns or trends in the results that indicate whether the process is in control or if the process is moving away from the desired control range. Based on control chart information, QC personnel should coordinate on a timely basis with production personnel to determine when adjustments or corrections to the production or placement process are needed. Control charts should always be used to monitor production at manufacturer, fabricator, and producer facilities. They may also be used to assist in Quality Control during field placement of materials.

Agency Quality Assurance Specifications may require that the contractor use their QC test results to periodically assess the quality level of materials throughout production and placement operations. The primary tool included in Quality Assurance Specifications that is typically used to evaluate multiple QC test results is a ***Quality Level Analysis (QLA)*** procedure. As will be more fully explained in Chapter 8, Quality Level Analysis is a mathematical tool used to measure the level of material variability against the Target and Specification Limits for an individual Quality Characteristic of a lot. The specific QLA procedure to be used is prescribed by the agency in the Quality Assurance Specifications.

As discussed above, the test results of multiple QC samples should be monitored and evaluated by Quality Control personnel using control charts and Quality Level Analysis procedures. Additionally, as briefly explained in Chapter 4, agency Quality Assurance Specifications may include Engineering Limits (sometimes referred to as “Suspension Limits”) that individual QC test results must be evaluated against. The rationale for using Engineering Limits is to identify material that has a measured value that is beyond the expected range of normal or acceptable variability.

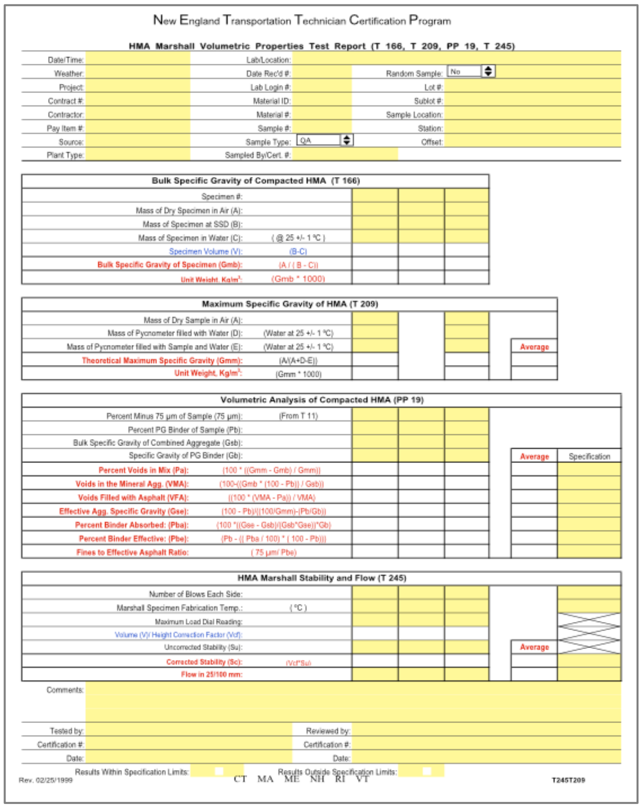
When an individual QC test result for a given lot is outside of the Engineering Limits, Quality Assurance Specifications may require the contractor to suspend the production or placement operation and take appropriate corrective action to bring the production or placement process back in control. In addition, the specification may require that the contractor perform additional QC testing on the sublot represented by the nonconforming test result. Based on the supplemental QC sampling and testing, material in the affected sublot may be required to be re-worked (if possible), barred from placement (if located during production), or removed (if already placed in the field).

QC Sampling and Testing Documentation and Feedback

All Quality Control sampling and testing performed by QC technicians or inspectors should be documented on standard ***Test Report Forms*** (TRFs) on a daily basis. It is recommended that separate TRFs be developed for each sampling or testing activity or group of related tests conducted at the production facility or field placement location for each major work item category.

The Test Report Forms should use the correct sampling or test method nomenclature and should be designed to follow the line by line steps of the sampling or testing procedure with entry lines or boxes for recording each measured or calculated value. The TRFs should also include space for providing comments, and should provide for the name and relevant qualification/certification number of the QC technician or inspector performing the sampling or testing.

Examples of Standard Test Report Forms are contained in **Appendix G**.



New England Transportation Technician Certification Program

HMA Marshall Volumetric Properties Test Report (T 166, T 209, PP 19, T 245)

Date/Time:		Lab/Location:			
Weather:		Date Rec'd #:		Random Sample:	No
Project:		Lab Login #:		Lot #:	
Contract #:		Material ID:		Sublot #:	
Contractor:		Material #:		Sample Location:	
Pay Item #:		Sample #:		Station:	
Source:		Sample Type:	QA	Offset:	
Plant Type:		Sampled By/Cert. #:			

Bulk Specific Gravity of Compacted HMA (T 166)

Specimen #:				
Mass of Dry Specimen in Air (A):				
Mass of Specimen at SSD (B):				
Mass of Specimen in Water (C):	(@ 25 +/- 1 °C)			
Specimen Volume (V):	(B-C)			
Bulk Specific Gravity of Specimen (Gmb):	(A / (B - C))			
Unit Weight, Kg/m³:	(Gmb * 1000)			

Maximum Specific Gravity of HMA (T 209)

Mass of Dry Sample in Air (A):					
Mass of Pycnometer filled with Water (D):	(Water at 25 +/- 1 °C)				
Mass of Pycnometer filled with Sample and Water (E):	(Water at 25 +/- 1 °C)				Average
Theoretical Maximum Specific Gravity (Gmm):	(A/(A+D-E))				
Unit Weight, Kg/m³:	(Gmm * 1000)				

Volumetric Analysis of Compacted HMA (PP 19)

Percent Minus 75 µm of Sample (75 µm):	(From T 11)					
Percent PG Binder of Sample (Pb):						
Bulk Specific Gravity of Combined Aggregate (Gsb):						
Specific Gravity of PG Binder (Gb):					Average	Specification
Percent Voids in Mix (Pa):	(100 * ((Gmm - Gmb) / Gmm))					
Voids in the Mineral Agg. (VMA):	(100-((Gmb * (100 - Pb)) / Gsb))					
Voids Filled with Asphalt (VFA):	((100 * (VMA - Pa)) / VMA)					
Effective Agg. Specific Gravity (Gse):	(100 - Pb)/((100/Gmm)-(Pb/Gb))					
Percent Binder Absorbed: (Pba):	(100 *((Gse - Gsb)/(Gsb*Gse))*Gb)					
Percent Binder Effective: (Pbe):	(Pb - ((Pba / 100) * (100 - Pb)))					
Fines to Effective Asphalt Ratio:	(75 µm/ Pbe)					

HMA Marshall Stability and Flow (T 245)

Number of Blows Each Side:						
Marshall Specimen Fabrication Temp.:	(°C)					
Maximum Load Dial Reading:						
Volume (V)/ Height Correction Factor (Vcf):						
Uncorrected Stability (Su):					Average	
Corrected Stability (Sc):	(Vcf*Su)					
Flow in 25/100 mm:						

Comments:

Tested by:		Reviewed by:	
Certification #:		Certification #:	
Date:		Date:	

Results Within Specification Limits: ☐ Results Outside Specification Limits: ☐

Rev. 02/25/1999 CT MA ME NH RI VT T245T209

For those production or placement processes which utilize control charts, all relevant QC test results should be transferred from the completed Test Report Forms onto the control charts by QC personnel on a daily basis. Likewise, whenever Quality Level Analysis is performed, the results should be documented. Any recommendations or actions indicated by these tools for analysis of QC test results should be shared on a timely basis with production personnel and agency personnel.

Further guidelines for documenting and maintaining appropriate Quality Control sampling and testing records are presented below in **Section 5.9**, **Quality Control Records**.

5.7 - Quality Control Activities at Production Facilities

As has been presented, there are many activities that should be performed by contractor production personnel and QC personnel to ensure a quality product. The total number of qualified production facility QC technicians/inspectors present should be based on the contractor's ability to effectively carry out the activities indicated in their Quality Control Plan.

An overall contractor Quality Control system for a given transportation construction project must begin at the production facilities (i.e., manufacturers, fabricators, and producers) for manufactured and fabricated materials as well as project produced materials. With this in mind, there are some general activities that should occur on a daily basis in the performance of Quality Control that are not specific to an individual production facility. These general QC activities are summarized below in terms of the phases of the production process (pre-production, start of production, during production, post-production). This summary does not take into account every agency's individual requirements, nor does it attempt to dictate when and where specific Quality Control procedures are appropriate.

Pre-Production QC Activities

  - Arrive prior to the start of production in order to set up the work for the day.
  - Alert responsible personnel of your presence.
  - Verify that the production job is still scheduled and not delayed.

- Verify anticipated production totals (important since determination of sublot sizes and/or required number of random samples may depend on production total).

- Turn on any equipment required for sampling and testing (warm-up, calibrate, prepare and/or maintain as necessary to meet test procedure requirements).
- Begin filling out required records of daily information, sometimes referred to as a ***QC Production Facility Diary***, which should include time arrived at facility, weather information (precipitation, temperature), the presence of other QC or agency personnel at the facility (names and times present), as well as any significant production delays or cancellations and the causes for delays or cancellations.
- Select random numbers and determine random sample locations (in accordance with agency requirements).
- Check any job mix formulas entered into production facility automation and verify against the approved job mix formula.
- Verify materials being used are from an approved source.
- Inspect source materials for proper storage and identify any problematic occurrences (e.g., segregation in stockpiles).

QC Activities at Start of Production

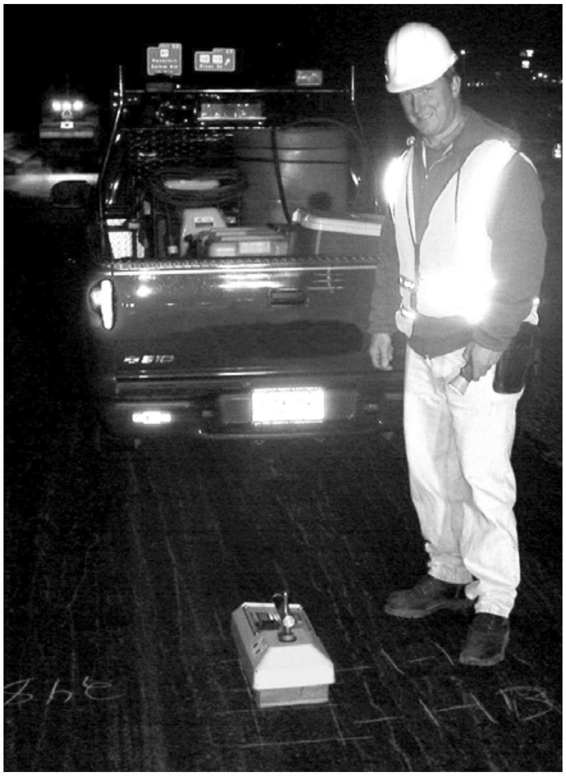
- Monitor initial material production in order to verify correct material is being produced.
- Assess the general condition of the material produced through a combination of visual observation of the process and the product and/or testing as required.
- Perform any required start-up tests as necessary to ensure process is in control.
- Consider obtaining selective samples from the initial production in order to begin characterizing the product.

- Reject any material produced during start-up that is found to be in non-conformance or of unacceptable quality.
- Alert production personnel as to the nature of the non-conformance and determine the cause(s) and take appropriate corrective actions.
- Communicate with Quality Control personnel in the field any information that might be helpful in achieving a quality product.

QC Activities During Production

- Continue monitoring both the process and the product during production to ensure quality.
- Perform any regular visual inspection of production facility components and operations during production.
- Identify production facility practices or materials that do not conform to the requirements of the relevant specifications or QC Plan.
- Discuss appropriate process corrective action with the production facility foremen/superintendents and the Quality Control Manager.
- Prepare and sign standard QC Inspection Report Forms.
- Obtain QC samples of material at the production facility using random locations determined during pre-production.
- Label all Quality Control samples with required information (e.g., lot, sublot, date, etc.) and store samples in an orderly manner for the duration as prescribed by the agency and as outlined in the QC Plan.
- Perform required Quality Control testing at frequencies as indicated by the Quality Control Plan.
- Perform any additional selective sampling when required to either verify proper production or to gauge the effect of corrective actions taken when the product is unacceptable.
- Perform any required re-sampling or re-testing in accordance with agency guidelines and as indicated in the Quality Control Plan.

- Prepare and sign standard QC Test Report Forms.
- Compare the results of testing performed on the material to any Specification and/or Engineering Limits as indicated in the QC Plan.
- Plot QC test results on control charts and use control charts as an analytical tool to gauge the degree of control over the production process.
- When test results are unacceptable in terms of any limits or when control charts indicate trends that will negatively impact the quality of the product, investigate the causes of the problem immediately.



- Provide regular feedback to production personnel and the QC Manager/QC Plan Administrator based on QC inspection and testing results.
- Ensure suspension of transport of nonconforming materials from the production facility.
- Communicate with Quality Control personnel in the field in order to convey test information regarding the product.
- Get feedback from Quality Control personnel in the field as to any installation issues that are affected by product characteristics and make adjustments to the delivered product where such adjustments maintain the product within the required limits and improve the installation process in the field.
- Communicate with agency personnel as required in accordance with the guidelines in the Quality Assurance Specification and the QC Plan.

- Accommodate agency in terms of making the production facility laboratory available for use by agency technicians or inspectors (when necessary).
- Submit to audits of Quality Control activities by other contractor QC personnel or agency personnel (including audits of both equipment and testing procedures).
- When an assignable cause for inferior product is determined correct the situation and document all corrections in the ***QC Production Facility Diary***.
- Perform any daily Quality Control activities at required frequencies and record any information or results gathered from such activities in the ***QC Production Facility Diary***.
- Perform any regular calibration and/or verification of laboratory equipment in accordance with required frequencies.
- Keep records of all Quality Control activities updated on a regular basis.

Post-Production QC Activities

- Make sure that all information (random numbers, sample locations, results of testing, visual observations, etc) has been recorded on proper Inspection Report Forms and Test Report Forms.
- Place all completed Inspection Report Forms and Test Report Forms in ***QC Production Facility Record Book***.
- Update any production summary records as required by the agency.
- Fill out any required certifications based on the results of Quality Control testing.
- Clean up the laboratory facility and all equipment used prior to leaving the production facility.
- Perform any preparatory work for the next production day.

5.8 - Quality Control Activities in the Field

Field Quality Control activities (like production facility QC activities) consist of sampling, testing, and inspection on a day-to-day basis, as well as other related activities on a less frequent basis (including attendance at pre-job conferences). Those contractors (i.e., prime contractor, subcontractors) responsible for actual field placement on transportation construction projects must ensure continued coordination and communication between the production personnel and QC personnel at the field placement location.

The general activities that occur on a daily basis in the performance of field Quality Control that are not specific to a particular manufactured/fabricated product or project produced material are summarized below in terms of the phases of placement or installation of the product (pre-placement, start of placement, during placement, and post-placement).

Pre-Placement QC Activities

- Arrive prior to the time scheduled for installation in order to set up work for the day and to perform any pre-installation inspection activities.
- Alert responsible personnel of your presence.
- Verify that the placement job is still scheduled and confirm any anticipated material delivery totals.
- Establish that all relevant pre-placement/installation items are inspected and are acceptable prior to delivery of materials.
- When non-acceptable items are discovered, alert responsible parties to provide correction prior to installation.
- Inspection Report Forms or pre-phase checklists may be used to provide uniformity of inspections for pre-placement/installation items.
- Inspect any equipment to be utilized in the placement/installation process to ensure that the equipment is in good operating condition and meets the minimum requirements for such equipment in accordance with agency guidelines and the Quality Control Plan.
- QC personnel may assist in the coordination of on-site activities to maximize the efficiency of the installation process.
- Set up or turn on any equipment required for sampling and testing (warm-up, calibrate, prepare and/or maintain as necessary to meet test procedure requirements).

- Begin filling out required records of daily information, sometimes referred to as a ***QC Field Diary***, which should include time arrived at the job site, weather information (precipitation, temperature), the presence of other QC or agency personnel at the jobsite (names and times present), as well as any significant installation delays or cancellations and the causes for delays or cancellations.

- Select random numbers and determine random sample locations (in accordance with agency requirements).

QC Activities at Start of Placement

- Monitor initial material placement in order to verify material is being handled and placed properly.

- Assess the general condition of the placement/installation procedures through a combination of visual observation of the process and/or testing as required.

- Any non-standard installation procedures that are not in accordance with the Quality Control Plan must be identified and eliminated.

- Consider obtaining selective samples from the initial material delivery in order to begin characterizing the product.

- Alert production facility QC technicians of any installation issues that may require adjustment of one or more material properties in order to maintain consistency.

QC Activities During Placement

- Continue monitoring the process of installation to ensure appropriate methods are being used in accordance with the Quality Control Plan.
- Perform visual inspection of field placement or installation operations.
- Identify field placement practices or materials which do not conform to the requirements of the relevant specifications or QC Plan.
- Discuss appropriate process corrective action with the field foremen/superintendents and the Quality Control Manager.
- Prepare and sign standard QC Inspection Report Forms.
- Obtain QC samples of material at the field placement site using random locations determined during pre-placement.
- Label all Quality Control samples with required information (e.g., lot, sublot, date, etc) and store samples in an orderly manner for the length of time as specified by the agency in the QA Specifications and as outlined in the QC Plan.
- Perform required Quality Control testing at frequencies as indicated in the Quality Control Plan.
- Perform any additional selective sampling when required to either verify material properties or to measure the influence of placement/installation on the material.
- Perform any required re-sampling or re-testing in accordance with the Quality Control Plan.

- Prepare and sign standard QC Test Report Forms.
- Compare the results of QC testing performed on the material to any Specification and/or Engineering Limits as indicated in the agency QA Specifications and Quality Control Plan.
- Plot QC test results on control charts and use control charts as an analytical tool to gauge the degree of control over the placement/installation process.
- When results are unacceptable in terms of any limits or when control charts indicate trends that will negatively impact the quality of the product, investigate the causes of the problem immediately.
- Provide regular feedback to production personnel (both in the field and at production facilities) based on QC inspection and testing results.
- Isolate any visually deficient work as a result of either unacceptable material quality or unacceptable Workmanship.
- Ensure suspension of field placement of nonconforming materials.
- Communicate with production facility QC technicians to convey test information regarding the product and/or the appropriate installation of the product.

- Communicate with agency personnel the results of testing in accordance with the guidelines in the Quality Assurance Specifications and the QC Plan.
- Submit to audits of Quality Control activities by other contractor QC personnel or agency personnel.
- When an assignable cause for inferior product quality as a result of field handling and placement/installation is discovered correct the situation and document all corrections in the ***QC Field Diary***.

Post Placement QC Activities

- Place all completed Inspection Report Forms and Test Report Forms in ***QC Field Record Book***.
- Make sure all information (random numbers, sample locations, results of testing, visual observations, etc) has been recorded on proper Inspection Report Forms and Test Report Forms.
- Update any field placement summary records as required by the agency.
- Fill out any required certifications based on the results of field Quality Control testing.
- Clean up all equipment used prior to leaving the job site.
- Perform any preparatory work for the next field inspection day.

5.9 - Quality Control Records

As discussed previously, all contractor Quality Control activities (i.e., inspection, sampling, and testing) conducted at both production facilities and field placement locations must be properly documented. This documentation cannot be viewed as merely a paperwork exercise, but rather as a necessary QC tool. The information documented provides valuable data for controlling each production or placement process and for improving these processes over time. Accordingly, a well designed and properly maintained ***QC Records System*** is an important part of each contractor Quality Control system.

The primary objective of a QC Records System is to provide a rational process to organize, evaluate, store, and retrieve all QC documentation. The organization of the QC Records System should facilitate the immediate, executive level review of pertinent information such as the results of a Quality Level Analysis on a daily basis, or a summary of all QC sampling and testing for required Quality Characteristics. It should also provide for the collection and storage of the documents that record individual QC test results (e.g., QC test results for gradations run at a PCC production facility) and inspection, thus forming a complete history of QC activities. Subsequent analysis (via control charts, for example) of such a history can be an invaluable tool used to improve production and placement processes in the future, thereby limiting future non-compliance, improving overall quality, and enhancing profitability.

Most agencies require that QC records be maintained in accordance with basic guidelines provided in Quality Assurance Specifications. This, however, should not discourage contractors from innovation in the manner of collection, storage, analysis or presentation of QC information, as long as the minimum agency requirements are fulfilled. Organized and accurate records are in the long run more important for the contractor in terms of "what it tells them about their process" than the immediate effect of simply "complying with requirements." Described below are the typical key components of a QC Records System.

QC Daily Diary

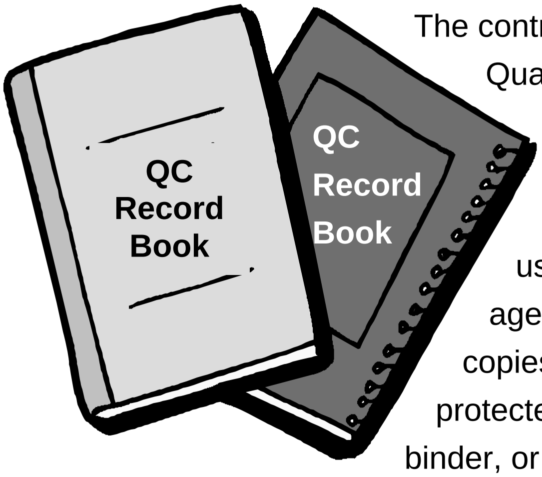
The QC Manager responsible for each production facility or field placement operation should maintain a ***Quality Control Daily Diary*** (QC Daily Diary). The QC Daily Diary should be used to document all major activities or actions related to the Quality Control system that occur each day. Its function is similar to a Project Diary that is typically required to be kept by a Project Manager or Resident Engineer on transportation construction projects. The Daily Diary is not intended to replicate or supersede individual Inspection Report Forms or Test Report Forms, but rather serves as a summary record of key actions taken by QC personnel.

The type of information usually recorded in the QC Daily Diary includes:

- The day's weather or environmental conditions.
- Summary of production or placement activities completed.
- Any issues of non-quality identified by production personnel or QC personnel.
- Any corrective actions recommended or taken by QC personnel.
- Discussions held with production personnel, other contractors' QC personnel, or agency personnel.
- Visitors to production facility or field placement operation.

QC Record Book

Each contractor party (i.e., prime contractor, subcontractor, producer, fabricator, manufacturer) should maintain a ***Quality Control Record Book*** (QC Record Book) for the major work item(s) that they produce or place. The function of the QC Record Book is to store all formal QC documents used or prepared by QC personnel for a specific production or placement operation. Maintaining the QC Record Book is the responsibility of each contractor's QC Manager with assistance by other QC personnel. The contractor must maintain a complete record of all Quality Control sampling, testing, inspections, and related QC activities. Although greater use is made today of computers for recording such information, a completely paperless system is usually not possible or practical. Accordingly, most agencies require that printed records (originals or copies) of all QC documents be maintained in a protected book format, typically using a three-ringed binder, or several binders.



Each QC Record Book should contain the following documents:

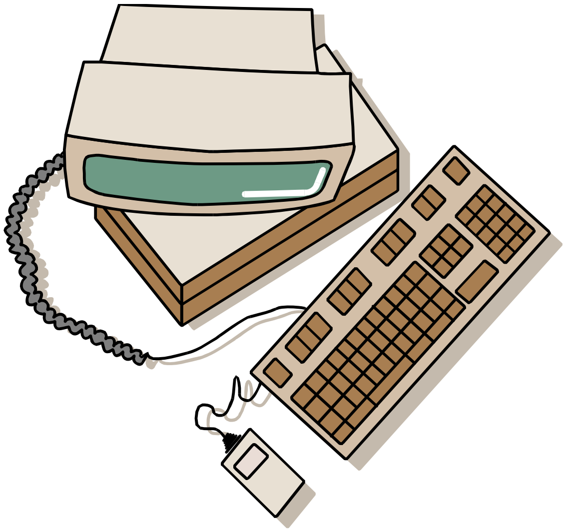
- Signed copy of the current approved QC Plan.
- Original signed copies of all completed standard Inspection Report Forms.
- Original signed copies of all completed pre-phase checklists
- Original signed copies of all completed random sampling location forms.
- Original signed copies of all completed standard Test Report Forms.
- Current copy or printout of all control charts generated.
- Current copy or printout of all Quality Level Analyses performed.
- Current summaries of all individual QC test results to date (by lot and sublot).
- Summary sheets of material quantities produced or placed (by lot and sublot).

Each contractor party (i.e., prime contractor, subcontractor, producer, fabricator, manufacturer) involved with a given construction project should retain the original copies of their QC documents in their own QC Record Book. The QC Record Book(s) maintained by the prime contractor, however, should also include copies of QC documentation prepared by other contractor parties, including those from all offsite production operations as well as from all onsite placement operations. This is to ensure that the prime contractor's QC Manager (QC Plan Administrator) is fully aware of the status of all QC operations and the corresponding quality of all materials produced and placed for the project.

The QC Record Book for each off-site production operation (e.g., HMA or PCC producer, prestressed concrete fabricator, steel rebar manufacturer) should be maintained at the location of production. The contractor parties involved with field placement operations (i.e., prime contractor, subcontractors) should maintain their QC Record Books at the project site. Each QC Record Book should be kept in a readily accessible location for reference by all QC personnel or for review by agency Acceptance personnel.

All required Quality Control documents should be placed in the QC Record Book in a timely manner. This is to ensure that the records are available on a real-time basis for use by contractor QC personnel in monitoring their production or placement processes. Agency Quality Assurance Specifications may specify a maximum time period for completing QC documents and entering them into the Record Book. As a general rule, it is recommended that Quality Control personnel ensure that all required QC records (originals or copies) are placed in the QC Record Book within 24 to 48 hours after they are completed.

Contractor Quality Control Database



A complete QC Records System should allow for easy access to QC data by the prime contractor's QC personnel as well as other contractor parties' QC personnel. It should also allow access by agency personnel, as needed, for audit or review purposes. Computer databases are useful tools for storage, analysis, and retrieval of Quality Control sampling, testing, and inspection data. They can be designed to generate control charts, evaluate production or placement quality levels (e.g., Quality Level Analysis), and provide summaries of QC test results to date. Accordingly, many contractors have moved toward using a ***Quality Control database*** (QC database).

A QC database can be developed using standard database software or may be custom-made to address an individual contractor's needs. QC databases should be designed to address the contractor's individual Quality Control system. However, their design should also permit sharing of data between the contractor, other contractor parties, and the agency. Given these parallel needs, it is generally advantageous to adopt a Quality Control database that uses a software platform common to both the contractors and the agency. Contractors may, therefore, be required or encouraged by agencies to use specific database software.

Data security is obviously important to protect original data once entered into the QC database. Access to the QC database can be provided to outside parties (other contractors or agency personnel) on a read-only or similar limited basis. Or instead of providing direct access to the QC database, the contractor can share files containing QC data. Data sharing may be accomplished via a Local Area Network (LAN), an Intranet system, or an Internet connection.

Submittal of QC Records to the Agency

Agency Quality Assurance Specifications may require that the contractor periodically submit copies of some or all Quality Control records to the agency. As a minimum, QC sampling and testing results are typically required to be submitted, particularly if the agency permits the contractor QC test results to be included in the acceptance determination.

Even if not specifically required by the QA Specifications, contractors are encouraged to share copies of their QC sampling, testing, and inspection results to the agency on a regular basis. This helps to ensure that agency personnel are apprised of the status of Quality Control findings, be they positive or negative. Timely submittal of QC records to the agency will enhance communications and can help avoid potential points of conflict or dispute. As a general rule, it is recommended that Quality Control records, particularly QC Test Report Forms and Inspection Report Forms, be submitted to the appropriate agency personnel within one working day after the QC activity and corresponding documentation is completed.

Certification and Retention of QC Records

Some agencies require that some or all documents contained in the contractor’s QC Records System include a certification statement attesting to the validity of the information contained in the document. Such certification statements, when required, are normally prepared by the QC Manager or other authorized QC personnel (i.e., QC technicians, QC inspectors). An example of the type of certification statement that may be required is as follows:

> ”*It is hereby certified that the information contained in this record is accurate, and that all work documented herein complies with the requirements of the contract. Any exceptions to this certification are documented as part of this record.*”

In addition to certification of QC records, agencies typically have minimum requirements for retention of QC records. For example, on highway construction projects that are funded by federal aid, the original records covering materials sampling, testing and inspection must be retained for a minimum period of 3 years. Each state agency may also have additional requirements for records retention.

Reporting of Fraudulent Activities

Contractor QC personnel (as well as any other contractor personnel) have a responsibility to ensure that all activities related to contractor records are conducted properly. There are federal and state criminal penalties associated with fraudulent activities on state agency highway construction projects. These activities include but are not limited to falsification of data, falsification of certifications, bribery, kickbacks, and gratuities.

If there is suspicion of fraudulent activities on federal aid projects they should be reported to the Office of Inspector General at 1-800-424-9071 or by email: hotline@oig.dot.gov. In addition, these activities should also be reported to the appropriate state authority.

- END OF CHAPTER 5 -

CHAPTER 6

Agency Acceptance Roles and Responsibilities

Chapter 6

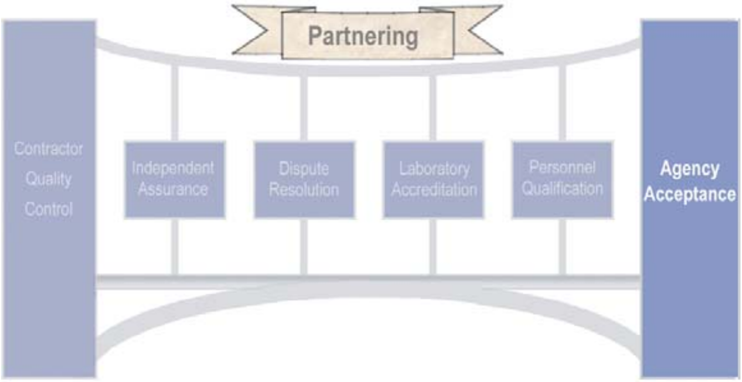
Agency Acceptance Roles & Responsibilities

Chapter Overview

In this chapter, the following responsibilities and activities necessary for Acceptance are presented:

6.1 - Overview of Acceptance Function and Responsibilities

Responsibility for Acceptance



As presented in Chapter 2, Acceptance serves as the second of the two towers among the six core elements of a Quality Assurance Program. Quality Assurance places responsibility for Acceptance entirely with the ***agency***. The term agency refers to any government entity that routinely engages contractors (i.e., prime contractors) to construct transportation projects. Based on the definition contained in the *AASHTO Guide Specifications for Highway Construction* (1998) an agency is defined herein as follows:

> **Agency** - “Any organization, constituted under federal, state, or municipal laws, that is responsible for administering contracts for highway or transportation construction.”

As part of its administration of each transportation construction project, the agency is responsible for Acceptance of the completed work. Agencies that are typically involved with contracting out and accepting work on transportation construction projects include:

- Federal Agencies (e.g., FAA, FHWA)
- State Agencies (e.g., State DOT, Turnpike Authority, Aviation Authority)
- Local Agencies (e.g., County, City, Town)

Historically, Acceptance of all materials produced and placed on a transportation construction project has been the responsibility of the agency. Under a Quality Assurance Program and with the use of QA Specifications, this primary role remains unchanged. Accordingly, all Acceptance activities (i.e., Acceptance sampling, testing, and inspection) must be performed by the agency, independent of the contractor's Quality Control activities.

To reiterate what was briefly explained in Chapter 2 (Section 2.3), one of the fundamental principles of Quality Assurance is the clear separation of responsibility for Quality Control by the contractor from the responsibility for Acceptance by the agency. In short, the agency's Acceptance system should <u>not</u> allow contractors to perform any Acceptance functions (i.e., Acceptance sampling, testing, and inspection). However, as discussed further below (Section 6.6), contractor personnel may <u>assist</u> the agency in Acceptance sampling (e.g., contractor permitted to operate coring rig to obtain core).

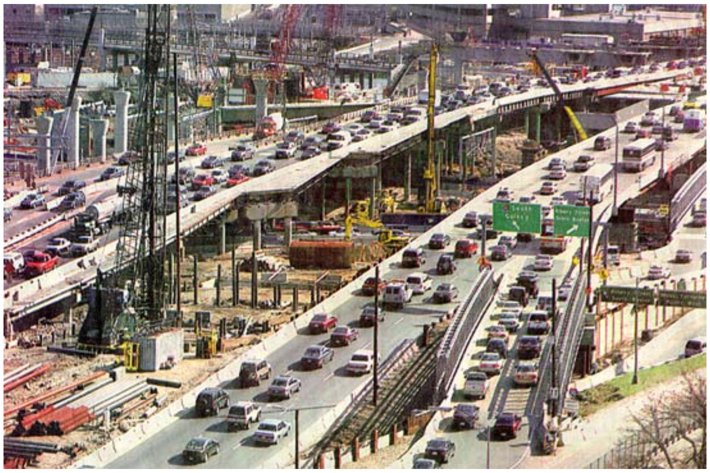
As is discussed later in this chapter, the agency may permit validated contractor QC data to be included in its final Acceptance determination. However, the overall responsibility for conducting Acceptance sampling, testing, and inspection and for evaluating this information to determine the acceptability of all material produced and placed, remains with the agency.

Acceptance activities (i.e., Acceptance sampling, testing, and inspection) may be performed by either:

- Qualified agency personnel, or
- Qualified personnel of a ***designated agent*** (i.e., consultant)

Under the latter approach, the designated agent should be engaged to perform the Acceptance services under contract directly with the agency. The use of a designated agent, however, does not eliminate the need for agency involvement in the Acceptance system. As a minimum, the agency must have its own responsible personnel to direct the activities of the designated agent, and to make final interpretations of all Acceptance information and corresponding decisions on the acceptability of all materials produced and placed by the contractor. The term agency, therefore, is used throughout this manual to refer to either a transportation agency or the agency and their designated agent.

With Quality Assurance, the responsibility for Acceptance by the agency (or their designated agent) is applicable regardless of the ***contracting method*** used for project construction. The traditional method of contracting by most agencies is referred to as ***Design-Bid-Build***. Under this approach, the agency prepares complete plans, specifications, and an estimate package (*Design*), then advertises and awards the construction contract to the lowest responsible bidding contractor (*Bid*). The contractor subsequently constructs the project per the agency's plans and specifications (*Build*).



In recent years, another contracting method has emerged in transportation construction, particularly on very large or complex projects, referred to as ***Design-Build***. Under the Design-Build approach, the agency prepares a preliminary engineering package (generally 20 to 30% level) that sets forth specific criteria for completing the design and construction of the project and solicits proposals from interested contractors. Rather than using the traditional low-bid approach, the basis for selection of a contractor under Design-Build is usually a combination of: 1) adherence to proposal criteria; 2) project time; and 3) project cost. Under the Design-Build contracting method, the responsibility for Acceptance remains with the agency. The agency may retain a designated agent to perform some or all of the Acceptance activities, as discussed above. However, in no event should the responsibility for Acceptance activities (i.e., Acceptance sampling, testing, inspection, and final determination of product acceptability) be assigned in any way to the contractor.

Acceptance Function

The role of the agency in performing Acceptance activities is distinctly different from Quality Control. Under a properly functioning Quality Assurance Program, the agency cannot and should not attempt to control the contractor's production and placement processes. As explained in Chapter 5, the Quality Control function is the responsibility of the contractor. The overall objective of contractor QC is to ensure that each manufacturing, fabrication, production, or placement <u>process</u> consistently yields a product that meets the specification requirements. Contractors must, therefore, <u>control</u> their production and placement processes to achieve the specified quality. The agency must respect the contractor's responsibility for performing Quality Control. This does not mean that the agency should "turn a blind eye" to the contractor's QC activities. The agency should periodically evaluate the contractor's Quality Control activities to ensure that they are being performed as outlined in the approved QC Plan.

The function of Acceptance, therefore, is not focused on directing the methods (i.e., processes) used to achieve conformance to specification requirements (i.e., quality). Rather, the primary objectives of the agency Acceptance system are to:

(1) <u>Measure</u> the <u>quality</u> of all materials produced and placed by the contractor.

(2) <u>Determine</u> the corresponding <u>payment</u> the contractor should receive.

The first Acceptance objective (quality measurement) is achieved through three (3) general Acceptance activities:

- Monitoring the adequacy of contractor QC activity.
- Performing Acceptance inspection to identify visually deficient work.
- Performing Acceptance sampling and testing for key Quality Characteristics.

Through its Acceptance activities the agency is obtaining information to confirm that all products produced and placed meet the specified quality level. Accordingly, each of these Acceptance activities must be performed by the agency independent of the contractor's QC activities.

The second Acceptance objective (determine contractor pay) is performed using the information obtained through the three agency Acceptance activities outlined above (i.e., monitoring the contractor's QC, Acceptance inspection, and Acceptance sampling and testing).

As explained in Chapter 2, contractor Quality Control test results may be used to augment the agency's Acceptance testing information provided that the QC results are from random samples that are validated by the agency. Determination of contractor pay is normally based on the computed quality level using either the agency Acceptance test results only, or by including validated contractor QC test results (the latter approach will follow one of three options as explained further below in Section 6.9).

However, the agency's determination of Acceptance and corresponding pay is not based solely on test results. The quality of workmanship of all completed work is also evaluated through the agency's Acceptance inspection activity. If visibly defective material is identified in the in-place product, typically, either corrective action is required by the contractor (possibly including removal), or the agency may assess an adjustment (i.e., reduction) of pay to the contractor.

Contractor pay may also be adjusted based on the adequacy of the contractor's QC activities. If it is found that the contractor is not performing effective Quality Control per the approved QC Plan, the agency should communicate this to the contractor in a timely manner. In the event the contractor is non-responsive to such feedback, the agency retains the authority to require appropriate corrective action and/or withhold payment for the affected item of work.

The agency's Acceptance activities must be performed on a continuous and timely basis throughout each stage of production and placement. They should not occur after all work on a project is completed. This is to ensure that sufficient data is available to confirm that the specified quality is being met and to avoid potential disputes with the contractor.

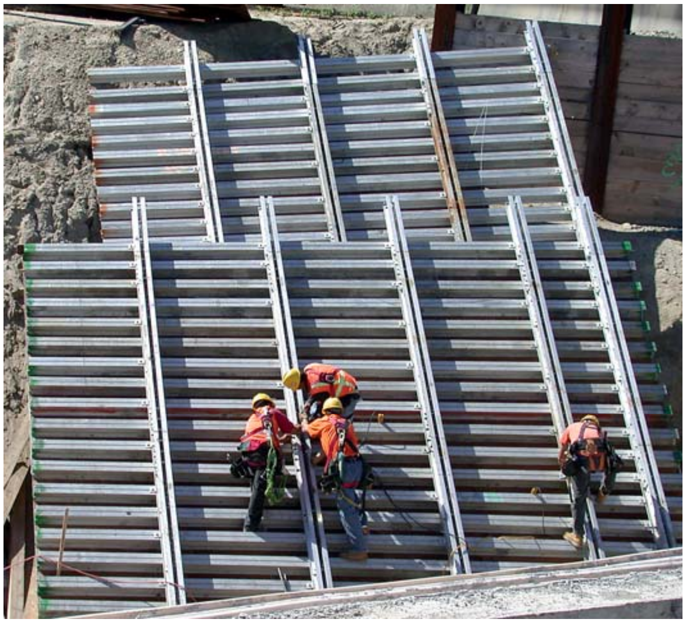
The agency should use the results of its Acceptance activities (i.e., monitoring the contractor's QC, and Acceptance inspection, and Acceptance sampling and testing) to provide <u>feedback</u> to the contractor. However, the contractor should not rely on this feedback to control processes, but rather should use it as information to assess the effectiveness of the Quality Control system.

An effective agency Acceptance system requires all of the activities described above. It also requires an appropriate Acceptance Organization and the maintenance of good records. Each of these Acceptance functions is more fully discussed throughout this chapter.

6.2 - Acceptance Organization Requirements

Optimal Agency Organizational Structure

The Acceptance system must operate as a shared effort by different personnel within the agency. While specific titles for organizational units and personnel that perform the Acceptance function will vary from agency to agency, the types of Acceptance staff in each agency are generally similar.



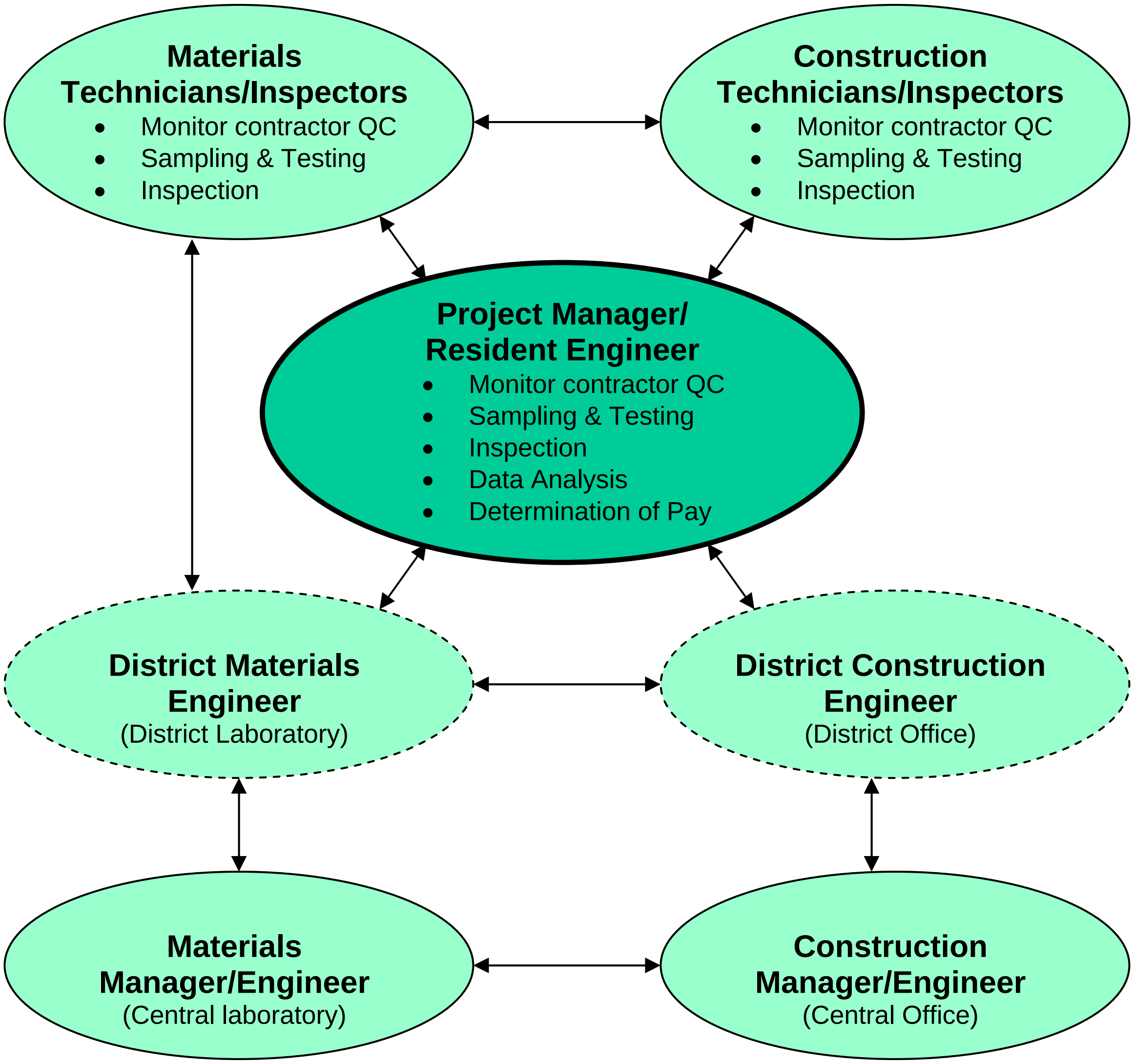
Most agencies are typically structured to include a ***Construction*** function and a ***Materials*** function. In some agencies, the Materials duties are managed by a separate unit led by a Materials Manager/Engineer, while the Construction duties are managed by another unit led by a Construction Manager/Engineer. In other agencies, the Materials function is integrated within the Construction unit. The overall Construction and Materials functions are usually administered from the agency's Central Office. In addition, many agencies will be further organized into District or Regional offices that include Construction and Materials units.

Regardless of how an agency is structured, an effective agency Acceptance organizational structure requires an ***Acceptance Team*** approach that includes both Construction personnel (i.e., Project Manager/Resident Engineer, field inspectors) and Materials personnel (i.e., Materials Engineer, laboratory technicians, production facility technicians/inspectors, field technicians/inspectors). While the overall responsibility for administration of construction contracts usually lies with Construction personnel, the Acceptance of all materials produced and placed should occur as a shared responsibility of Construction personnel and Materials personnel.

Within some agencies there may exist the view that under Quality Assurance, Acceptance is simply about sampling and testing and, therefore, is something addressed by the Materials personnel. As explained earlier, the full scope of Acceptance activities includes: monitoring the contractor's QC, inspection (at production facilities and in the field), sampling and testing (at production facilities and in the field), and determining contractor pay. This requires teamwork between the Construction personnel and the Materials personnel.

The Acceptance Team must begin with the frontline project level Acceptance staff (i.e., Construction inspectors and Materials technicians/inspectors) under the leadership of the Project Manager/Resident Engineer. Periodically, the Project Manager/Resident Engineer may need to consult with personnel further up the agency organization structure in both the Construction unit (e.g., Area Construction Engineer, District Construction Engineer, agency Construction Manager/Engineer) and the Materials unit (e.g., District Materials Engineer, agency Materials Manager/Engineer). Some Acceptance sampling and testing may be performed by agency personnel who do not report directly to the Project Manager/Resident Engineer (e.g., Materials technicians/inspectors). Ultimately, however, all Acceptance data collection (i.e., sampling, testing, inspection), all *data analysis, and the determination of product quality and corresponding contractor pay o*n an individual project should be coordinated through or performed by (or under the direction of) the Project Manager/Resident Engineer.

The graphic below illustrates this optimal agency operating structure to provide an effective Acceptance system.



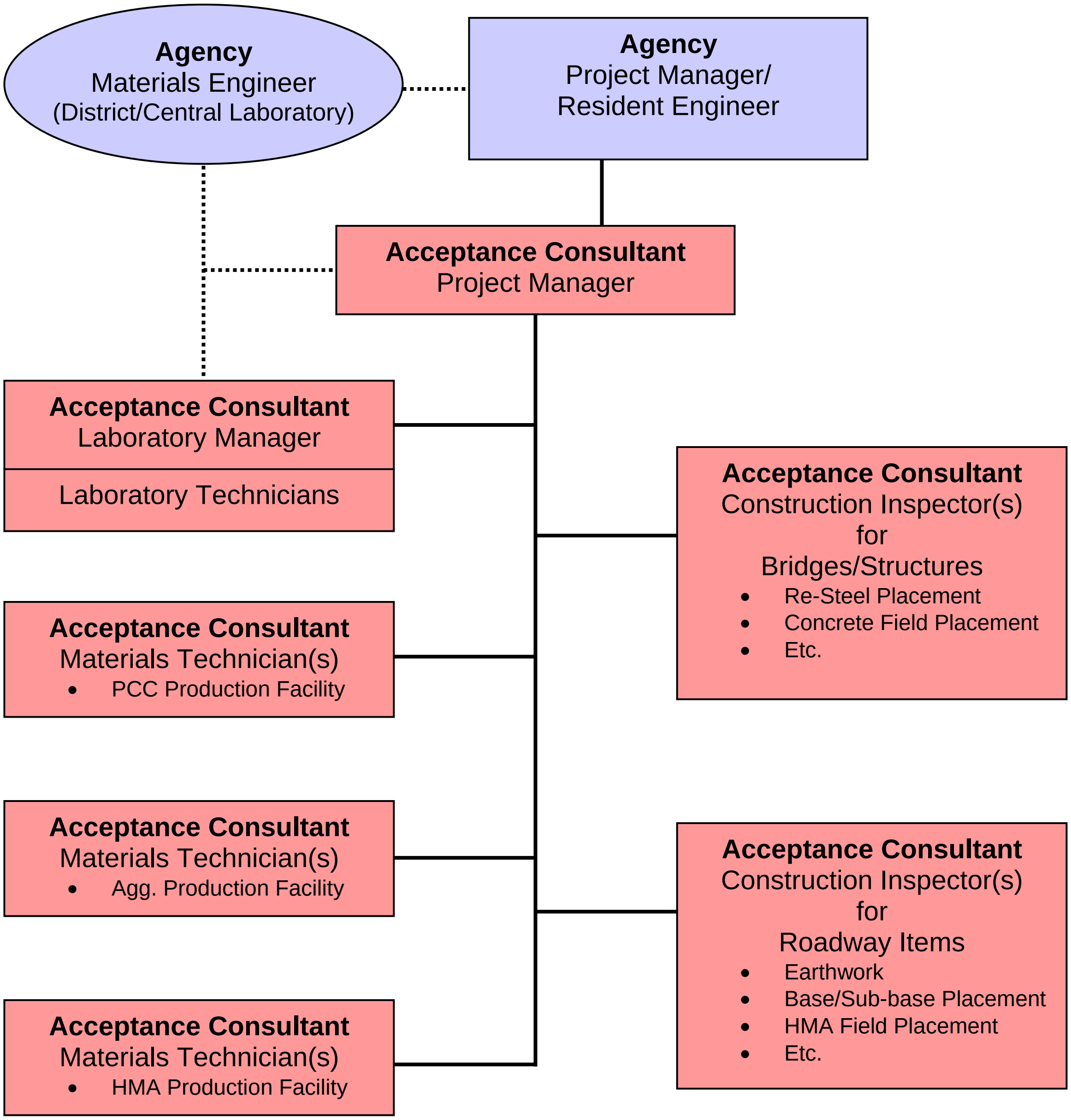
(Optimal Agency Operating Structure for Effective Acceptance)

Transportation Project Acceptance Organization

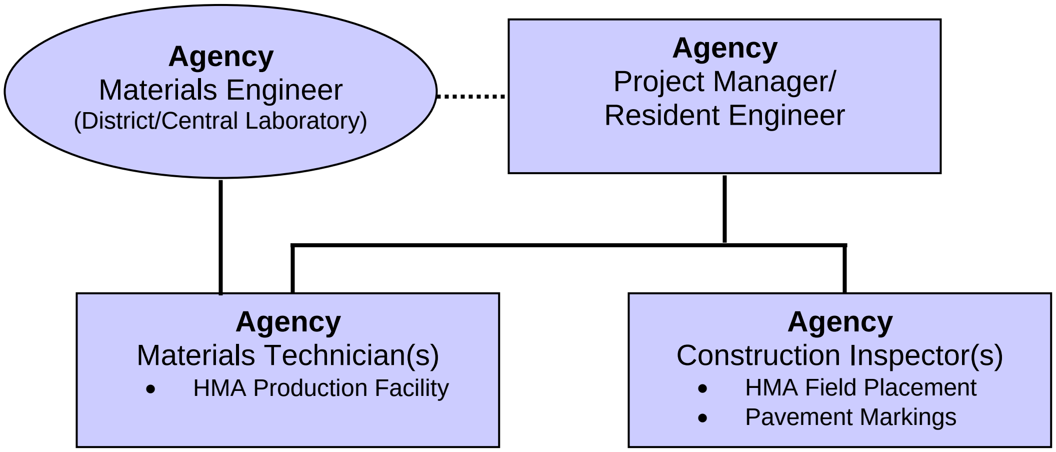
There is no one-size-fits-all Acceptance organization structure that can be applied to each transportation construction project. The agency Acceptance Team organization will vary depending on the size and complexity of the construction project and the individual operations therein. The fact that the contractor is required to have a Quality Control system and sufficient QC personnel does not relieve the agency from providing an adequate number of Acceptance staff.

As discussed previously in this chapter (Section 6.1), Acceptance activities may be performed by either qualified agency Construction and Materials personnel or by qualified personnel of a designated agent (i.e., consultant). Some agencies elect to use consultant personnel to perform some of the Acceptance activities (e.g., inspection, sampling, and testing) on most or all construction projects on a regular basis. Other agencies may choose to only use consultant personnel on very large or complex projects, such as Design-Build, to augment their Construction and Materials staff. Regardless of the type of project on which consultant personnel are used, at least one agency representative (e.g., Project Manager/Resident Engineer) must be assigned to represent the agency to the contractor and to provide direction to the consultant personnel. As stated earlier, agency personnel must ultimately make the final interpretations of all Acceptance information and corresponding decisions on the acceptability of all materials produced and placed by the contractor.

Examples of an agency Acceptance Team for two different types of transportation projects are presented below. The first example shows an Acceptance Team for a major highway construction project where consultant personnel are utilized under the direction of an agency representative. The second example shows an Acceptance staff for an HMA resurfacing project comprised of agency Construction personnel and agency Materials personnel.



(Agency Acceptance Team for Major Highway Construction Project)



(Agency Acceptance Team for HMA Resurfacing Project)

For each transportation construction project, regardless of size and staffing approach, it is recommended that the agency identify in writing all of the personnel that comprise the project Acceptance Team. This should be done with a simple list or table, herein referred to as the ***Project Acceptance Team Organization***. Formal organization charts, similar to the examples above, may also be used to provide a graphic summary of the Acceptance Team personnel. Whichever format is used, the Project Acceptance Team Organization document should include all of the names and relevant information (e.g., qualifications/certifications, phone/fax numbers, email, etc.) for each Acceptance Team position.

The Project Acceptance Team Organization is intended to serve as a tool to communicate the assignment of specific Acceptance responsibilities to everyone on the Acceptance Team. It should be shared with the contractor's personnel (both QC personnel and production personnel) at the start of a project to foster clear lines of communication between the agency and the contractor. It should also be updated on a timely basis to reflect personnel changes that may occur on the Acceptance Team.

Acceptance Personnel Requirements

As discussed above, the agency must provide an adequate Acceptance Team comprised of agency Construction personnel and Materials personnel for each construction project. Staff provided by a designated agent (consultant) may be used in lieu of agency personnel to perform some of the Acceptance activities. Regardless of the Acceptance Team approach, it is essential that a sufficient number of personnel are provided to perform all of the Acceptance activities required for a given project. In addition, all Acceptance personnel should be properly qualified or certified to perform their responsibilities.

Each project Acceptance Team will typically include the following types of Acceptance personnel:

- Project Manager or Resident Engineer
- Production Facility Acceptance Technicians/Inspectors
- Acceptance Laboratory Personnel
- Field Acceptance Technicians/Inspectors

The responsibilities and minimum qualifications typically required for each of these Acceptance Team personnel are briefly described below.

Project Manager or Resident Engineer

As briefly discussed earlier, the agency Acceptance Team for each transportation construction project is led by Construction personnel typically referred to as either the ***Project Manager*** or ***Resident Engineer***. The Project Manager/Resident Engineer (PM/RE) has overall responsibility for managing all Acceptance activities on the project and should, therefore, be thoroughly knowledgeable of all agency Acceptance system requirements. Historically, the agency PM/RE has functioned essentially in the role of counterpart to the contractor's Project Manager, with a primary focus on contract administration activities (i.e., review of contractor submittals, measurement and payment of completed work, monitoring contract time, etc.). Under a Quality Assurance Program and with projects using QA Specifications, this role is ideally balanced with an equal focus by the PM/RE on:

- Monitoring the contractor's Quality Control activities, and
- Directing the agency's Acceptance activities (i.e., sampling, testing, inspection)

This requires an active working relationship between the PM/RE and the contractor's QC Manager. It also requires coordination with personnel from the agency Materials unit (i.e., Materials Engineer, laboratory technicians, production facility technicians/inspectors, field technicians/inspectors) who are involved in performing some of the Acceptance activities. While the PM/RE must still manage contract administration activities, it is extremely important that he or she also assume primary responsibility for coordinating all project Acceptance activities. It is not possible for this to occur if the PM/RE assumes that other agency personnel (such as Materials personnel) will "manage" these activities.

The principal Acceptance duties of each Project Manager/Resident Engineer include:

- Coordinating review and approval of the contractor's QC Plan(s).
- Identifying all Acceptance activities required for the project.
- Managing Acceptance data collection (i.e., sampling, testing, inspection) by Construction and Materials personnel (technicians/inspectors).
- Communicating routinely with the contractor's QC Manager and with all members of the agency Acceptance Team.
- Notifying the contractor of deficiencies identified in Quality Control.
- Performing data analysis to determine product quality and contractor pay.
- Ensuring proper Acceptance documentation and records.

Each agency Project Manager/Resident Engineer should be properly qualified to perform the responsibilities discussed above. While requirements for qualifications of personnel serving as a PM/RE will vary from agency to agency, it is recommended that each PM/RE possess a combination of education and hands-on experience in performing Acceptance activities. It is suggested that the minimum education requirements include formal classroom training and qualification/certification through a comprehensive course on Quality Assurance. The PM/RE should also ideally have relevant experience in applying the requirements of a Quality Assurance Program and QA Specifications on transportation construction projects.

Production Facility Acceptance Technicians/Inspectors

Acceptance activities at production facilities are normally performed by agency Materials technicians or inspectors. As discussed earlier, qualified personnel of a designated agent (i.e., consultant) may also be used to supplement agency personnel in performing Acceptance activities at some production facilities. Each agency should provide a sufficient number of qualified ***Production facility Acceptance technicians/inspectors*** to perform Acceptance activities at the contractor production facilities that are supplying materials to an agency construction project. The number of technicians or inspectors required at each contractor facility will depend upon; the primary material category being produced (i.e., project produced materials, fabricated materials, standard manufactured materials); the average volume of material produced; and the minimum required Acceptance sampling, testing, and inspection frequencies. Acceptance activities performed at producer or fabricator facilities may necessitate that at least one agency Materials technician be present at the facility for some period each day; however the Acceptance activities required at manufacturer facilities are typically on a much less frequent or audit basis, such as monthly, semi-annually, or annually.

The principal duties of each production facility Acceptance technician/inspector include:

- Monitoring adequacy of QC activity at the production facility.
- Performing Acceptance sampling, testing, and inspection at the production facility.
- Preparing and signing standard Acceptance Test/Inspection Report Forms.

- Providing regular feedback to contractor QC technicians/inspectors and the agency PM/RE based on the above Acceptance activities.

A more detailed outline of production facility Acceptance activities is presented in Section 6.7.

Regardless of whether they are employed by the agency or a consultant, all production facility Acceptance technicians/inspectors should be properly qualified to perform the responsibilities discussed above. Formal qualification/certification requirements for Acceptance technicians/inspectors are established by each agency. Ideally, these qualification/certification requirements should be the same as those required by the agency for the contractor's QC technicians/inspectors. This provides appropriate professional standing to the agency Acceptance activities and promotes uniformity in sampling, testing, and inspection by both contractor QC technicians/inspectors and agency Acceptance technicians/inspectors. This in turn can reduce potential disputes associated with sampling, testing, or inspection procedures. Accordingly, most Agencies require all production facility Acceptance technicians/inspectors to be qualified/certified through the same types of national, regional, or individual state programs identified for production facility QC personnel in Chapter 5 (Section 5.2).

Acceptance Laboratory Personnel

The ***Acceptance laboratory personnel*** are normally agency personnel; however, qualified personnel of a designated agent (i.e., consultant) may also be used to supplement agency personnel in performing Acceptance activities at agency laboratories. The Acceptance laboratory personnel at each agency laboratory typically include a laboratory supervisor and laboratory technicians. The number of laboratory technicians provided in each agency laboratory should be sufficient to handle the Acceptance sampling and testing needs of the various active agency construction projects which they support.

The principal duties of the Acceptance laboratory personnel include:

- Obtaining Acceptance samples of material from the construction project site or from production facilities.
- Performing laboratory testing on Acceptance samples.
- Preparing and signing standard Acceptance Test Report Forms.
- Providing feedback to contractor QC laboratory personnel and agency Materials technicians/inspectors based on Acceptance testing results.
- Identifying materials which do not conform to the requirements of the relevant specifications or QC Plan and discussing with the agency PM/RE.

All Acceptance laboratory personnel should be properly qualified to perform the responsibilities discussed above. Acceptance laboratory personnel should be qualified/certified for the individual materials items that they sample and test within the three primary material categories (i.e., project produced materials, fabricated materials, standard manufactured materials). Qualification/certification requirements for Acceptance laboratory personnel are established by each agency. Acceptance laboratory technicians are normally required by the agency to be qualified/certified through the same types of programs discussed above for production facility Acceptance technicians/inspectors.

Field Acceptance Technicians/Inspectors

Acceptance activities during placement or installation of materials at the construction project site should be performed by experienced and properly qualified ***field Acceptance technicians/inspectors***. These Acceptance personnel are generally from the agency's Construction unit or may be from a designated agent (i.e., consultant) under contract with the agency. Qualified field Acceptance technicians/inspectors should be provided to perform Acceptance activities for each major work item category addressed by the project QA Specifications (e.g., earthwork, sub-base and base material, pavements, geotechnical Items, structural concrete). The number of Acceptance personnel required will depend on the quantity of materials being placed or installed for each active work item. In all cases, the number of Acceptance technicians/inspectors should be sufficient to provide timely Acceptance inspection and testing for each work item at the required frequencies.

The principal duties of each field Acceptance technician/inspector include:

- Monitoring adequacy of field QC activity for each active work item.
- Performing Acceptance sampling, testing, and inspection of field placement operations.
- Preparing and signing standard Acceptance Test/Inspection Report Forms.
- Providing regular feedback to contractor QC technicians/inspectors and the agency PM/RE based on the above Acceptance activities.

A more detailed outline of field Acceptance activities is presented in Section 6.8.

Whether they are employed by the agency or a consultant, all field Acceptance technicians/inspectors should be properly qualified to perform the responsibilities discussed above. Field Acceptance technicians/inspectors should be qualified to perform all Acceptance testing or inspection duties required for each major work item for which they are responsible. Testing performed by field Acceptance technicians/inspectors is normally only for project produced materials (i.e., earthwork, geotechnical items, sub-base and base courses, Hot-Mix Asphalt, Portland Cement Concrete, structural steel coatings, and pavement markings). Field inspection is required during placement of these project produced materials as well as for the installation of fabricated materials or standard manufactured materials. Field Acceptance technicians/inspectors can be qualified to perform testing and inspection for multiple work items.

Formal qualification/certification requirements for field Acceptance technicians/inspectors are established by each agency. Ideally, these qualification/certification requirements should be the same as those required by the agency for the contractor’s QC technicians/inspectors. Accordingly, it is recommended that Agencies require all field Acceptance technicians/inspectors to be qualified/certified through the same types of national, regional, or individual state programs identified for field QC personnel in Chapter 5 (Section 5.2).

6.3 - Quality Control Plan Review and Approval

Responsibility for QC Plan Review and Approval

As discussed in Chapter 5, agency QA Specifications normally identify particular work item categories (e.g., earthwork, pavements, structural concrete, etc.) for which the contractor is required to have a Quality Control Plan. The QA Specifications also identify the specific minimum required QC Plan contents and may require a prescribed QC Plan format. While the preparation and full implementation of each QC Plan is the responsibility of the contractor, each QC Plan should be reviewed and approved (or accepted) by the agency. As discussed further below, it is important that agency personnel responsible for reviewing and accepting the QC Plan fully understand the specific submittal requirements and ensure that they are met.

QC Plan Review Objectives

QC Plan <u>review</u> by the agency is intended to serve two primary objectives:

(1) To determine that the contractor has sufficient personnel, facilities, and procedures to perform effective Quality Control.

(2) To determine that the QC Plan adequately addresses project-specific details in the contract plans and specifications.

The QC Plan is intended to serve as an extension of the project specifications. Therefore, it is important that the review of QC Plans by agency personnel addresses the project-specific details and that it not become a routine process.

The intent of QC Plan review is not for the agency to take on the role of writing the QC Plan for the contractor. As stated previously, the contractor must take ownership for authoring a QC Plan that:

(A) Follows the prescribed agency format.

(B) Contains sufficient detailed content addressing the project specific QC personnel and activities.

If the contractor submits a QC Plan that reasonably meets these requirements, the agency's review will normally result in only minor comments. If, on the other hand, the QC Plan is deficient in either format or content, the agency should ensure that specific detailed review comments are documented and forwarded to the contractor requesting that appropriate revisions be made to the QC Plan.

Purpose of QC Plan Approval

In order to eliminate potential misunderstanding or misinterpretation of the agency's approval action, some Agencies elect to indicate that the QC Plan is "Accepted" rather than "Approved." In addition, agencies may include exculpatory language in the contract specifications indicating that although approval (or acceptance) of the QC Plan is provided, the agency will not be responsible for and makes no assurance with respect to the product quality ultimately achieved by the contractor.

Agency approval of the contractor's QC Plan is not intended to assign responsibility to the agency for the implementation or effectiveness of the QC Plan. Authorship and ownership for development of a QC Plan and corresponding implementation of effective Quality Control practices lies entirely with the contractor. The purpose of agency approval of the QC Plan is to formally document that the agency has reviewed the QC Plan and has confirmed that it reasonably meets the two review objectives above. The QC Plan review and approval process provides a formal communication channel for the agency to determine that the contractor is prepared to provide adequate Quality Control. It provides no guarantee that the contractor will be successful in providing a Quality product.

QC Plan Review and Approval Process

Agency review and approval of each QC Plan should occur sufficiently prior to the start of any production or placement operations related to the relevant work item. As explained in Chapter 5 (Section 5.4), the specific requirements for QC Plan format, content, and time of submittal prior to start of construction activity will vary from agency to agency.

Agency personnel reviewing a QC Plan should expect a document prepared in a professional-looking format. The agency's adoption of a standard QC Plan format is beneficial to both the agency and the contractor and is therefore encouraged. Establishing a standard format, including at least an outline of the major topics or headings required to be addressed as well as stylistic elements (e.g., font type, point size, margins, headers and footers, page numbering, etc.) will avoid unnecessary expenditure of valuable time by both parties in resolving such items every time a QC Plan is submitted. A standard format can provide a more efficient QC Plan development and review process as it serves as an outline to guide contractor and agency personnel in assuring that all required information is included in the QC Plan. It also facilitates periodic reference to specific QC requirements by contractor and agency personnel during construction from project to project.

Agency personnel reviewing QC Plans should ensure that each of the major content items outlined in Chapter 5 (Section 5.4) is thoroughly addressed. Because every project is different, and because each contractor may have a different approach to the same work item, individual QC Plans should never be identical. The agency should bear in mind that one of the benefits of requiring contractors to submit QC Plans for review is that it allows specific quality issues to be addressed before the project begins, eliminating the uncertainty of how these situations will be handled by the contractor during construction. The agency has every right to expect that the QC Plan specify, to the greatest degree possible, procedures that will be implemented for corrective action and how the effectiveness of each action will be measured. If a QC Plan submitted does not satisfactorily address these issues, the agency should require additional clarification and revision. Additionally, if the QC Plan contains other relevant contractor QC Plans (e.g., in an appendix), the agency should cross-check the QC Plans to ensure that there are no conflicts between them. The agency should not accept QC Plans from the contractor that are incomplete, or that refer to other QC Plans that are not included.

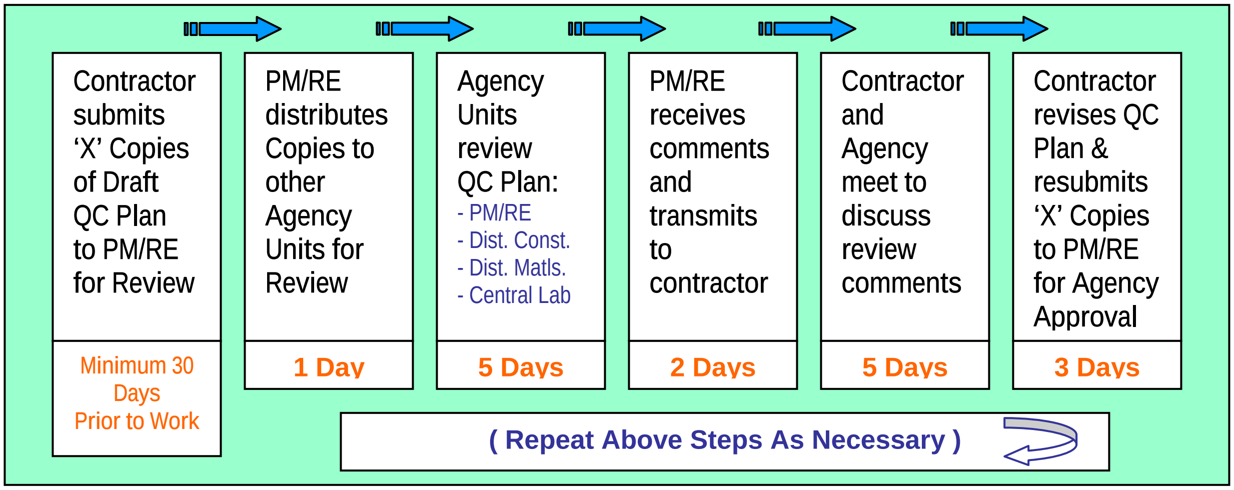
The agency personnel involved in the QC Plan review and approval process should include, as a minimum, those personnel directly responsible for Acceptance activities on the project (i.e., Project Manager/Resident Engineer, field technicians/inspectors, Materials Engineer, production facility technicians/inspectors). In addition to the project Acceptance Team, agency procedures may require other Construction personnel or Materials personnel further up the agency organization structure (i.e., District/Regional Office personnel, Central Office personnel) to be involved in the QC Plan review and approval process. As discussed in Section 6.2 above, all agency Acceptance related activities on individual construction projects are ideally performed by (or under the direction of) the Project Manager/Resident Engineer. Accordingly, agencies are encouraged to place responsibility for coordinating the review and final approval of the QC Plan in the hands of the Project Manager/Resident Engineer.

Regardless of the QC Plan review and approval structure within the agency, the specific procedures and assignment of responsibility should be clearly documented and shared with all agency personnel involved in the process. The minimum specific information recommended to be provided includes:

- The number of copies of the QC Plan to be submitted by the contractor (one per reviewer suggested).
- All agency units/personnel that are required to review the QC Plan.
- The time (number of days) allotted for agency review and return of comments.

It is strongly recommended that a review meeting between the agency and contractor be held after initial submittal of the QC Plan to discuss the agency's specific review comments. This can help to clarify or resolve comments and facilitate a timely review process.

A flow chart or similar diagram outlining the QC Plan review and approval process may be useful in documenting and communicating this information. An example of a flow chart outlining an agency process for QC Plan review and approval is presented below.



6.4 - Monitoring Contractor QC Activity

Agency Role in Monitoring Contractor QC

As briefly discussed above (Section 6.1), there are three general Acceptance activities performed by the agency to measure the quality of all materials produced and placed by the contractor. The first of these agency activities is ***monitoring*** the adequacy of contractor ***Quality Control activity***.

The purpose of agency monitoring of contractor QC is to confirm that Quality Control activities for each work item are being performed in reasonable compliance with the approved QC Plan for that Item. The agency role is not to try to perform QC responsibilities for the contractor or to provide constant direction to the contractor on how to perform Quality Control.

The focus, therefore, of agency monitoring of QC is on the adequacy of actual Quality Control personnel and the effectiveness of the QC procedures being implemented by the contractor. It is not intended to evaluate the quality of the product being produced and placed. In short, agency monitoring of QC activity serves as an audit tool for the agency to ensure that the contractual requirement for the contractor to provide effective Quality Control is being satisfactorily met.

Scope of Agency Monitoring Activities

Agency monitoring of contractor QC includes the following general activities:

- Periodic (e.g., daily, weekly, etc.) visual observation of QC inspection, sampling, and testing.
- Review of QC records/documents to ensure that they are being prepared and maintained properly.
- Providing feedback to contractor personnel to confirm that QC activity appears adequate or to bring deficiencies in QC to the contractor’s attention.

Monitoring Documentation and Feedback

Agency Acceptance personnel should document their monitoring findings (positive or negative) on the adequacy of Quality Control. It is recommended that some type of standard ***Monitoring Report Form*** (MRF) be developed and used to record the agency’s findings from monitoring of contractor QC. The agency may elect to develop separate MRFs for production facility QC monitoring and field placement QC monitoring for individual major work item categories. It is often helpful for the MRFs to provide specific references to the applicable section of the contractor’s QC Plan for each QC activity being monitored. The format of the MRFs need not be overly lengthy, but should ideally include as a minimum an outline or checkbox listing of required Quality Control items (i.e., QC personnel, QC procedures, QC documentation, etc.) along with space for noting specific observations and findings on the adequacy of the individual items reviewed.

To make effective use of the agency's monitoring of Quality Control activity, agency personnel should provide timely feedback to the contractor's QC personnel on findings of their QC inspection activities. Accordingly, the agency should submit copies of all MRFs to the contractor and discuss the specific findings (both positive and negative) with the QC personnel responsible for the particular operation. This is to ensure that the agency monitoring information is used to either confirm with the contractor that QC activity is being performed in reasonable compliance with the approved QC Plan, or to point out where QC activity is found to be deficient and require that the contractor take appropriate corrective action.

Agency Action for Inadequate Quality Control

If inadequate contractor QC is identified and documented by the agency, the contractor should take immediate action to address the deficiency. The agency's response in the event the contractor fails to take corrective action to Quality Control activity, after being notified by the agency of identified inadequacies, should be in accordance with applicable provisions in the QA Specifications. The specifications may indicate that the agency can direct or request the contractor to suspend operations for the corresponding work item until satisfactory corrective measures are taken. Other action that the specifications may provide for includes withholding payment to the contractor for the work item involved and/or withholding payment for contractor QC activity when payment for QC activity is included in the contract as a separate payment item.

The agency's Project Manager/Resident Engineer should be aware of the specific contract provisions, and when necessary, apply them to ensure that effective contractor QC, which is a contractual requirement that the agency is paying for, is being provided.

6.5 - Acceptance Inspection Activities

Purpose of Agency Acceptance Inspection

The second general Acceptance activity performed by the agency to measure the quality of materials produced and placed by the contractor is ***Acceptance inspection*** to identify visually deficient work. This activity should not be confused with monitoring of QC activity described above (Section 6.4). The purpose of agency Acceptance inspection is to provide the agency with its own information, independent of the contractor's formal QC inspection activities, to <u>visually assess the quality</u> of materials and workmanship for reasonable compliance with the project plans and specifications. The agency Acceptance role is <u>not</u> to duplicate all of the contractor's QC inspection activities. Agency Acceptance inspection should primarily focus on the <u>quality of the product</u> produced and placed, but should <u>not</u> ignore the <u>methods</u> used by the contractor for production and placement.

Scope of Agency Acceptance Inspection

Like contractor QC inspection, agency Acceptance inspection should utilize both visual observation and check measurements. However, while the contractor QC inspection is focused on four broad inspection components (i.e., equipment, materials, environmental conditions, product workmanship), the agency Acceptance inspection is intended to focus on only two of these, namely:

- Materials
- Product Workmanship

This does not mean that the agency is not concerned about the other two inspection components (i.e., equipment, environmental conditions). The agency expects the contractor's QC inspection activities will include these two inspection components and should allow the QC personnel to take primary ownership for them. In the event the agency Acceptance personnel find that the contractor's QC personnel are not adequately performing inspection related to equipment or environmental conditions, these findings should be documented and communicated to the contractor as part of the agency's monitoring of QC activity as previously described (Section 6.4).

Agency Acceptance inspection of ***materials*** and ***product workmanship*** will include periodic visual inspections and checks of source documentation (i.e., Certificates of Compliance) at both the site of material production as well as the site of installation or placement. These Acceptance inspection activities are used to ensure that all products are produced to meet the agency's material quality requirements and are placed in acceptable conformance to the plan dimensions, lines, grades, and tolerances contained in the applicable specifications.

At material production facilities, the Acceptance inspection should ensure proper quality of the component materials (e.g., aggregates, RAP, PG binder, etc.) as well as the quality of the complete product when prepared for shipment (HMA, PCC, etc.) to the project.

Acceptance inspection of materials and product workmanship in the field should occur during and after placement or installation of the product. It should include inspection of the quality of the component materials at the time of placement or installation (e.g., embankment visual classification and lift thickness, epoxy coated rebar type and condition, etc.) as well as the quality of the finished product (e.g., HMA mat segregation, PCC cracking or surface defects, etc.).

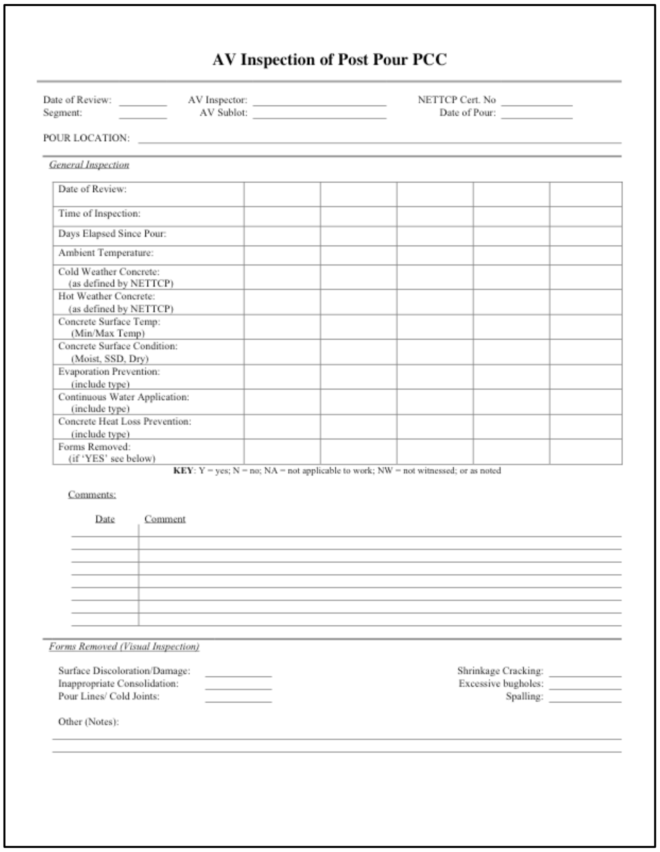
Approach to Acceptance Inspection

Agency Acceptance inspection is recommended to be performed periodically (preferably a minimum of once per day/production or placement operation). It is suggested that random techniques be utilized to determine specific locations for the agency's detailed visual observations and check measurements. This approach is predicated upon the fact that the contractor's QC inspection activity is intended to provide a first line of inspection to prevent deficiencies in materials or workmanship from occurring. Therefore, the agency should not find it necessary to inspect every bit of material produced and placed, but rather should inspect a random representation of all of the materials and finished workmanship.

However, the identification of non-conforming materials and/or workmanship need not rely solely on randomly determined points of observation. All materials used in the final product and/or the finished workmanship of each work item are "fair game" for agency Acceptance inspection. If obvious deficiencies in materials or product workmanship are discovered at locations other than those randomly pre-selected for inspection, the agency inspection personnel should document such findings as part of the Acceptance inspection.

Acceptance Inspection Documentation and Feedback

All inspection activities performed by Acceptance technicians/inspectors should be documented on standard ***Inspection Report Forms*** (IRFs) on a daily basis. It is recommended that separate IRFs be developed and used for production facility inspection and field placement inspection for each major work item category. Inspection Report Forms should address the two primary components of Acceptance inspection (i.e., materials and product workmanship) discussed above. The format of the IRFs should ideally include an outline or checkbox listing of key inspection items along with space for noting specific observations, measurements, or reviews of manufacturers' Certificates of Compliance.



AV Inspection of Post Pour PCC

Date of Review: ________ AV Inspector: ________________ NETTCP Cert. No __________
Segment: ________ AV Sublot: ________________ Date of Pour: __________

POUR LOCATION: ________________________________

General Inspection

Date of Review:					
Time of Inspection:					
Days Elapsed Since Pour:					
Ambient Temperature:					
Cold Weather Concrete: (as defined by NETTCP)					
Hot Weather Concrete: (as defined by NETTCP)					
Concrete Surface Temp: (Min/Max Temp)					
Concrete Surface Condition: (Moist, SSD, Dry)					
Evaporation Prevention: (include type)					
Continuous Water Application: (include type)					
Concrete Heat Loss Prevention: (include type)					
Forms Removed: (if 'YES' see below)					

KEY: Y = yes; N = no; NA = not applicable to work; NW = not witnessed; or as noted

Comments:

Date Comment

Forms Removed (Visual Inspection)

Surface Discoloration/Damage: __________
Inappropriate Consolidation: __________
Pour Lines/ Cold Joints: __________

Shrinkage Cracking: __________
Excessive bugholes: __________
Spalling: __________

Other (Notes):

6.6 - Acceptance Sampling and Testing Requirements

Purpose of Acceptance Sampling and Testing

The third general Acceptance activity used by the agency to measure the finished quality of all materials produced and placed by the contractor is ***Acceptance sampling and testing***. Like Acceptance inspection, the purpose of Acceptance sampling and testing is to provide the agency with its own data (independent of the contractor's QC sampling and testing) to <u>measure the quality</u> of the final product. The role of agency Acceptance sampling and testing is <u>not</u> to provide data for Quality Control or to otherwise direct or control the contractor's production and placement operations. As explained in Chapter 5, the contractor's QC sampling and testing is intended to serve that function. Acceptance sampling and testing is focused only on the <u>measured quality of the product</u> and is not intended to assess the processes used by the contractor for materials production and placement.

Scope of Acceptance Sampling and Testing

The agency must ensure that Acceptance sampling and testing occurs at both the production facilities supplying material to the project and at the field location of product installation or placement. Acceptance sampling and testing at production facilities includes manufactured, fabricated, or project produced materials. Construction materials that require Acceptance sampling and testing during field placement will normally only include project produced materials.

Acceptance sampling and testing is not intended to duplicate all of the contractor's QC sampling and testing activities. The agency's measurement of material quality is accomplished by sampling and testing only those key Quality Characteristics that the agency will use for its final Acceptance determination. As is explained in Chapter 4, Quality Characteristics for each work item are selected for Acceptance sampling and testing that are demonstrated to relate to long-term performance of the finished product.

Acceptance sampling and testing should be conducted only by Acceptance technicians or inspectors who are properly qualified to perform the specific sampling and testing methods required. As briefly explained in Chapter 2, all Acceptance sampling and testing must be:

- Performed by agency personnel (or personnel of a designated agent).
- Performed independent of the contractor's QC sampling and testing.

To maintain the proper balance and boundaries between contractor Quality Control and agency Acceptance, the agency should always obtain its own Acceptance samples. Split samples from QC should not be used as agency Acceptance samples. Obtaining separate QC and Acceptance samples (i.e., independently obtained) is not just recommended, but is required by some transportation agencies. For example, on all federal-aid highway projects, it is a requirement (23 CFR 637.205(d)) that all Acceptance sampling and testing be performed by agency personnel or qualified personnel of the agency's designated agent.

In order to be considered independent of the contractor, Acceptance samples must contain independent information reflecting all sources of variability associated with the material, process, sampling, and testing in the test results. This means that the actual sampling and testing of the Acceptance samples must be performed by the agency. However, contractor personnel are permitted to <u>assist</u> the agency personnel in independently obtaining the Acceptance samples when the following requirements are adhered to:

- The Acceptance sample location and time has been randomly selected by the agency and is only given to the contractor immediately prior to sampling.
- The contractor's personnel only provide labor to assist in physically obtaining the Acceptance sample (e.g., operating coring rig and removing core).
- Both the agency technician/inspector and contractor technician/inspector are qualified to sample the material being sampled.
- The agency technician/inspector is present to direct and monitor the taking of the Acceptance sample.
- The agency technician/inspector immediately takes possession of the Acceptance sample.

Approach to Acceptance Sampling and Testing

As explained in Chapter 2, an agency may take one of the following two approaches in establishing its system of Acceptance sampling and testing to make a final determination of product Acceptance:

- Use agency Acceptance testing only for the acceptance determination.
- Include validated contractor QC testing in the acceptance determination.

As explained further below (Section 6.9), validation is a process of mathematically comparing two independently obtained sets of test results (agency Acceptance results vs. contractor QC results) to determine whether they came from the same population.

If only agency Acceptance test results are used in the final Acceptance determination, then the agency should obtain one sample per sublot. If the agency specifications permit validated QC test results to be included along with the agency Acceptance test results in the final Acceptance determination, the agency may:

(A) Still obtain one Acceptance sample per sublot (i.e., 100% of all sublots are sampled and tested), or

(B) Obtain one Acceptance sample from only some of the sublots (typically only 25% to 50% of the sublots are sampled and tested).

If a reduced frequency of agency Acceptance sampling is used (i.e., < 100% of all sublots), the individual sublots selected for Acceptance sampling should be on a random basis.

Acceptance sampling and testing needs to be timely. Acceptance samples should be obtained at the required frequencies as material production or placement progresses. Regardless of whether the agency samples and tests all sublots or only some sublots, the Acceptance sampling and testing should be performed on a real-time basis throughout materials production and placement for each work item. Under an Acceptance system using either 100% agency Acceptance samples or a reduced number of Acceptance samples with validated QC samples, some agency Acceptance testing may be required during each day of production or placement. Some QA Specifications (typically only for project produced materials or fabricated materials) require the agency to obtain a minimum of one sample per day, regardless of the quantity of material (number of sublots) produced or placed on a given day.

Frequency of Acceptance Sampling and Testing

Agency Acceptance sampling and testing should be conducted at sufficient frequencies to represent defined quantities of material. The agency must have sufficient data, independent of contractor QC data, to evaluate product quality. As was explained in Chapter 4, the total quantity of material produced and placed for an individual work item is divided into lots and sublots. As discussed in Chapter 5, the contractor is normally required to obtain a minimum of one random QC sample per sublot for QC purposes. However, the frequency of agency Acceptance sampling and testing is dependent upon the Acceptance approach specified by the agency.

If agency results only are used in calculating the level of quality for the final Acceptance determination, then the frequency of Acceptance sampling and testing will generally be higher than if QC results are included in the Acceptance determination. If QC results are permitted to be considered, the agency Acceptance sampling and testing frequency may be reduced. However, even if QC results are permitted in the Acceptance system, the agency must still have sufficient data. If QC results are permitted, but cannot be validated by the agency, only the agency Acceptance test results are normally used. Therefore, the minimum agency Acceptance testing frequency should ensure that the number of Acceptance samples will provide a meaningful mathematical representation. Accordingly, Quality Assurance Specifications should require a minimum of 3 to 4 samples to represent a given lot of material produced or placed. As will be further explained in Chapter 8, more Acceptance data is better, but it is important to ensure that the minimum number of Acceptance test results available is sufficient to properly represent each lot of material.

Agency Quality Assurance Specifications will normally identify the minimum required Acceptance sampling and testing frequency using lot and sublot sizes. A list of web addresses for typical agency QA Specification requirements, including the typical lot and sublot sizes specified by Agencies for Acceptance sampling and testing, is provided in **Appendix E**.

Acceptance Sampling and Testing Methods

Most agency Quality Assurance Specifications will also identify the minimum Quality Characteristics subject to Acceptance sampling and testing, as well as the corresponding sampling locations and test methods to be used. The required methods of sampling and testing will normally be standard AASHTO designated test methods. Where AASHTO standard sampling or test methods do not exist, ASTM test methods are typically specified. While not encouraged, some agencies will specify their own sampling or testing methods, which are usually AASHTO or ASTM methods with some minor variation in the procedure. A list of web addresses for typical agency QA Specification requirements, including the minimum Acceptance sampling and testing requirements (i.e., Quality Characteristics, sampling locations, and testing methods) specified by agencies, are provided in **Appendix E**.

Random Acceptance Sampling and Testing

All agency Acceptance samples should be randomly selected from within individual sublots using a random sampling procedure. Random sampling removes bias, thereby providing a truer picture of the quality of material being produced or placed. The use of a random sampling procedure is not just recommended, but is required by some transportation agencies. For example, on all federal-aid highway projects, it is a requirement (23 CFR 637.205(e)) that all samples used for Acceptance testing be obtained randomly. Agency Acceptance sampling should never be performed at uniform intervals (e.g., start of each sublot) or on a quota basis (e.g., all samples obtained from 1st half of the lot).

Acceptance technicians or inspectors should determine Acceptance sample locations using random numbers generated separately from the Quality Control personnel. Most agencies require that all random sampling locations be determined in accordance with ASTM D3665 or by use of a random number generating function on a calculator or computer. All random Acceptance sample locations should be determined prior to the start of the applicable production or placement operation (typically at the beginning of the day) and documented by agency Acceptance personnel on Standard Test Report Forms. It is recommended that a copy of the completed Random Sampling Report Forms be provided to the contractor's QC Manager/QC Plan Administrator for their information after the corresponding Acceptance sampling and testing has been performed each day.

Selective Acceptance Sampling and Testing

If during Acceptance inspection, agency technicians or inspectors visually identify apparent non-conforming materials that have been produced or placed, non-random samples, referred to as selective Acceptance samples, may be obtained within a sublot to <u>assist</u> in quantifying the actual quality of the material. As was explained in Chapter 4 (Section 4.9), a sublot of material found to contain a significant, visible, obvious deficiency should be isolated from the lot, and either rejected or further evaluated through selective sampling plus additional random sampling. The selective sampling is used first to determine the limits of non-conforming materials within the individual sublot. Additional random samples should then be obtained within the area of deficiency defined through selective sampling, in order to properly quantify the actual quality of the material in question. Since selective sampling is non-random and, therefore biased, the test results of selective Acceptance samples should never be combined for analysis with random Acceptance samples in the Acceptance determination for a given lot.

Acceptance Sample Identification System

It is important that Acceptance technicians or inspectors ensure that all Acceptance samples are clearly and properly identified. Agencies normally establish a particular system for identification of Acceptance samples obtained from all production and placement operations. Specific Acceptance sample identification requirements are usually provided in the agency's QA Program procedures. The importance of establishing and consistently applying an Acceptance sample identification system cannot be overemphasized. Improper labeling of Acceptance samples can result in Acceptance testing data from different lots being combined or can result in selective Acceptance sample data being combined with random Acceptance sample data, thus invalidating analysis of the data for the agency's Acceptance determination.

The information that is necessary for an agency Acceptance sample identification system is essentially the same as described in Chapter 5 for QC sample identification. This typically includes:

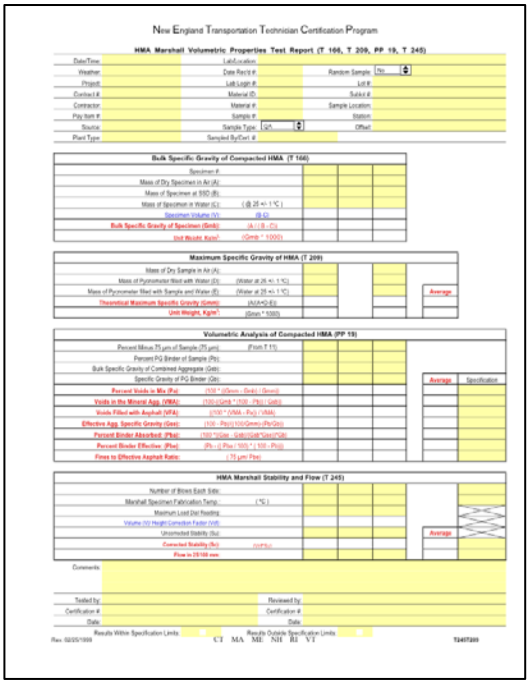
- Project Name or Number
- Material Type (e.g., Ordinary Borrow, 12.5mm HMA, #9 Epoxy Rebar)
- Acceptance Sample Type (e.g., Acceptance Random, Acceptance Selective)
- Lot Number and Sublot Number
- Sample Location (e.g., Median, Shoulder, East Wingwall)
- Station, Offset, Depth
- Sample Date
- Agency Acceptance Technician or Inspector

Acceptance Sample Storage and Retention Procedures

The agency should establish and implement a sound system for storage and retention of Acceptance samples on each project. Specific Acceptance sample storage and retention requirements are usually provided in the agency's QA Program procedures.

Storage practices prior to testing should ensure that all Acceptance samples are kept in a suitable location that protects them from damage and which provides the proper environment for curing the material or maintaining the required material properties. It is recommended practice for all Acceptance samples to be split prior to testing, in accordance with relevant sampling and testing procedures. Agency Quality Assurance Specifications may outline specific procedures for sample splitting. The split sample portion of material not used for initial testing should be retained in the original sample storage device with proper identification. The split sample should be stored in an appropriate Sample Storage Room at the agency laboratory which performed the initial testing for a reasonable period following testing (typically a minimum of 30 to 60 days).

Acceptance Sampling and Testing Documentation and Feedback



New England Transportation Technician Certification Program

HMA Marshall Volumetric Properties Test Report (T 166, T 209, PP 19, T 245)

Date/Time:
Weather:
Project:
Contract #:
Contractor:
Pay Item #:
Source:
Plant Type:
Lab/Location:
Date Rec'd #:
Lab Login #:
Material ID:
Material #:
Sample #:
Sample Type: QA
Sampled By/Cert. #:
Random Sample: No
Lot #:
Sublot #:
Sample Location:
Station:
Offset:

Bulk Specific Gravity of Compacted HMA (T 166)

Specimen #:
Mass of Dry Specimen in Air (A):
Mass of Specimen at SSD (B):
Mass of Specimen in Water (C): (@ 25 +/- 1 °C)
Specimen Volume (V): (B-C)
Bulk Specific Gravity of Specimen (Gmb): (A / (B - C))
Unit Weight, Kg/m³: (Gmb * 1000)

Maximum Specific Gravity of HMA (T 209)

Mass of Dry Sample in Air (A):
Mass of Pycnometer filled with Water (D): (Water at 25 +/- 1 °C)
Mass of Pycnometer filled with Sample and Water (E): (Water at 25 +/- 1 °C)
Theoretical Maximum Specific Gravity (Gmm): (A/(A+D-E))
Unit Weight, Kg/m³: (Gmm * 1000)
Average

Volumetric Analysis of Compacted HMA (PP 19)

Percent Minus 75 µm of Sample (75 µm): (From T 11)
Percent PG Binder of Sample (Pb):
Bulk Specific Gravity of Combined Aggregate (Gsb):
Specific Gravity of PG Binder (Gb):
Percent Voids in Mix (Pa): (100 * ((Gmm - Gmb) / Gmm))
Voids in the Mineral Agg. (VMA): (100-((Gmb * (100 - Pb)) / Gsb))
Voids Filled with Asphalt (VFA): ((100 * (VMA - Pa)) / VMA)
Effective Agg. Specific Gravity (Gse): (100 - Pb)/((100/Gmm)-(Pb/Gb))
Percent Binder Absorbed: (Pba): (100 *((Gse - Gsb)/(Gsb*Gse))*Gb)
Percent Binder Effective: (Pbe): (Pb - ((Pba / 100) * (100 - Pb)))
Fines to Effective Asphalt Ratio: (75 µm/ Pbe)
Average
Specification

HMA Marshall Stability and Flow (T 245)

Number of Blows Each Side:
Marshall Specimen Fabrication Temp.: (°C)
Maximum Load Dial Reading:
Volume (V) Height Correction Factor (Vcf):
Uncorrected Stability (Su):
Corrected Stability (Sc): (Vcf*Su)
Flow in 25/100 mm:
Average

Comments:

Tested by:
Certification #:
Date:
Reviewed by:
Certification #:
Date:

Results Within Specification Limits: ☐
Results Outside Specification Limits: ☐

Rev. 02/25/1999
CT MA ME NH RI VT
T245T209

All Acceptance sampling and testing performed by agency Acceptance technicians or inspectors should be documented on standard ***Test Report Forms*** (TRFs) on a daily basis. It is recommended that separate TRFs be developed for each sampling or testing activity or group of related tests conducted at the production facility or field placement location for each major work item category.

The Test Report Forms should use the correct sampling or test method nomenclature and should be designed to follow the line by line steps of the sampling or testing procedure with entry lines or boxes for recording each measured or calculated value. The TRFs should also include space for providing comments, and should provide for the name and relevant qualification/certification number of the Acceptance technician or inspector performing the sampling or testing. Examples of Standard Test Report Forms are contained in **Appendix G**.

Further guidelines for documenting and maintaining appropriate Acceptance sampling and testing records are presented below in Section 6.11, Acceptance Records.

6.7 - Acceptance Activities at Production Facilities

As explained throughout this chapter, there are many activities that should be performed by agency Acceptance personnel to ensure material quality and product workmanship. The total number of qualified production facility Acceptance technicians/inspectors present at each production facility should be based on the agency's ability to effectively carry out the minimum required Acceptance activities (i.e., monitoring contractor QC, Acceptance inspection, Acceptance sampling and testing).

An overall agency Acceptance system must adequately address all production facilities (i.e., manufacturers, fabricators, and producers) for manufactured and fabricated materials as well as project produced materials which are being supplied to a given transportation construction project. With this in mind, there are some general activities that should occur on a regular basis in the performance of agency Acceptance that are not specific to an individual production facility. These general Acceptance activities are summarized below in terms of the phases of the production process (pre-production, during production, post-production). This summary does not take into account every agency's individual requirements, nor does it attempt to dictate when and where specific Acceptance activities and procedures are appropriate.

Pre-Production Acceptance Activities

- Arrive at appropriate time in order to set up any Acceptance equipment required for the day.
- Alert Quality Control personnel of your presence.
- Verify with QC personnel that the production job is still scheduled and not delayed.
- Verify anticipated production totals with QC personnel (needed to determine sublot sizes and/or required number of random samples).
- Turn on any equipment required for sampling and testing (warm-up, calibrate, prepare and/or maintain as necessary to meet test procedure requirements).
- Begin filling out required records of daily information, sometimes referred to as a ***Acceptance Production Facility Diary***, which should include time arrived at facility, weather information (precipitation, temperature), the presence of QC personnel or other agency personnel at the facility (names and times present), as well as any significant production delays or cancellations and the causes for delays or cancellations.

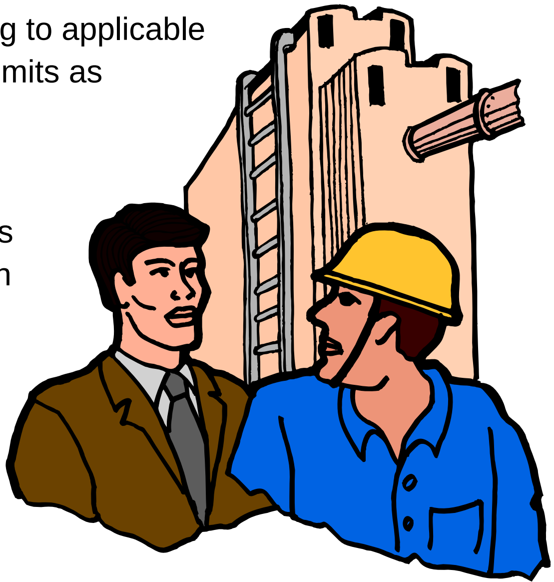
- Select random numbers and determine random Acceptance sample locations (in accordance with agency requirements).

Acceptance Activities During Production

- Monitor Quality Control activities (i.e., QC inspection, sampling, testing, use of control charts, etc.) periodically during production to ensure adequate QC procedures are being followed per the approved QC Plan.

- Discuss need for corrective action to Quality Control activities with QC personnel.
- Perform Acceptance visual inspection of material components and complete product during production.
- Identify materials that do not conform to the requirements of the relevant specifications or QC Plan.
- Prepare and sign QC Monitoring Report Forms and standard Acceptance Inspection Report Forms.
- Obtain Acceptance samples of material at the production facility using random locations determined during pre-production.
- Label all Acceptance samples with required information (e.g., sublot, date, etc.) and store samples in an orderly manner for duration prescribed by the agency.
- Perform required random Acceptance testing at frequencies required by the QA Specifications.
- Perform any selective sampling when required to assist in evaluating questionable quality or to confirm that the product is unacceptable.
- Perform any required re-sampling or re-testing in accordance with agency guidelines or QA Specifications.

- Prepare and sign standard Acceptance Test Report Forms.
- Compare the results of Acceptance testing to applicable Specification Limits and/or Engineering Limits as indicated in the QA Specifications.
- Provide regular feedback to Project Manager/Resident Engineer and Materials Engineer based on Acceptance inspection and testing results.
- Notify QC personnel if suspension of transport of nonconforming materials from the production facility appears to be triggered per the approved QC Plan.



- Communicate with Acceptance personnel in the field in order to convey Acceptance inspection or testing information regarding the product.
- Communicate with QC personnel as needed to provide feedback based on Acceptance activity.
- Perform any daily Acceptance activities at required frequencies and record any information or results gathered from such activities in the ***Acceptance Production Facility Diary***.
- Perform any regular calibration and/or verification of laboratory equipment used for Acceptance in accordance with required frequencies.
- Keep records of all Acceptance activities updated on a regular basis.

Post-Production Acceptance Activities

- Make sure that all information (random numbers, sample locations, results of testing, visual observations, QC monitoring, etc.) has been recorded on proper forms.
- Place all completed QC Monitoring Report Forms, Inspection Report Forms, and Test Report Forms in ***Acceptance Production Facility Record Book***.
- Prepare and forward copies of all completed Report Forms to the Project Manager/Resident Engineer and Materials Engineer.
- Clean up the laboratory facility area and all equipment used for Acceptance testing prior to leaving the production facility.
- Perform any preparatory activity for the next production day.

6.8 - Acceptance Activities in the Field

Field Acceptance activities (like production facility Acceptance activities) consist of sampling, testing, and inspection on a day to day basis, as well as other related activities, to ensure material quality and product workmanship. The number of qualified field Acceptance technicians/inspectors present at the project site should be adequate to effectively perform the minimum required Acceptance activities (i.e., monitoring contractor QC, Acceptance inspection, Acceptance sampling and testing).

The general activities that occur on a daily basis in the performance of field Acceptance that are not specific to a particular manufactured/fabricated product or project produced material are summarized below in terms of the phases of placement or installation of the product (pre-placement, during placement, and post-placement).

Pre-Placement Acceptance Activities

- Arrive at appropriate time before scheduled installation in order to set up work for the day and to perform any pre-installation Acceptance inspection activities.

- Alert QC personnel of your presence.
- Verify with QC personnel that the placement job is still scheduled and confirm any anticipated material delivery totals.
- Ensure that all relevant pre-placement installed materials have been inspected and are acceptable prior to delivery and placement of new material.
- When non-acceptable items are discovered, notify contractor QC personnel to provide correction prior to placement of new material.
- Set up or turn on any equipment required for Acceptance sampling and testing (warm-up, calibrate, prepare and/or maintain as necessary to meet test procedure requirements).
- Begin filling out required records of daily information, sometimes referred to as a ***Acceptance Field Diary***, which should include time arrived at the job site, weather information (precipitation, temperature), the presence of QC personnel or other agency personnel at the jobsite (names and times present), as well as any significant installation delays or cancellations and the causes for delays or cancellations.
- Select random numbers and determine random Acceptance sample locations (in accordance with agency requirements).

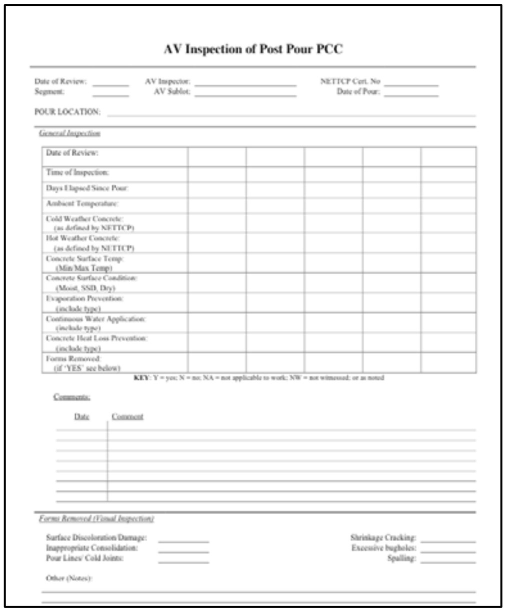
Acceptance Activities During Placement

- Monitor field QC activities (i.e., QC inspection, sampling, testing, use of control charts, etc.) periodically during field placement to ensure adequate QC procedures are being followed per the approved QC Plan.
- Perform visual Acceptance inspection of materials Quality and workmanship.
- Identify field placed materials which do not conform to the requirements of the relevant specifications or QC Plan.
- Discuss the need for corrective action to field QC activities with Quality Control personnel.
- Prepare and sign QC Monitoring Report Forms and standard Acceptance Inspection Report Forms.
- Obtain Acceptance samples of material at the field placement site using random locations determined during pre-placement.
- Label all Acceptance samples with required information (e.g., lot, sublot, date, etc) and store samples in an orderly manner for the duration specified by the agency.
- Perform required Acceptance testing at frequencies as indicated in the Quality Assurance Specifications.
- Perform any selective sampling when required to assist in evaluating questionable Quality or to confirm that the product is unacceptable.

- Perform any required re-sampling or re-testing in accordance with agency guidelines or QA Specifications.

- Prepare and sign standard Acceptance Test Report Forms.
- Compare the results of Acceptance testing to the Specification Limits and/or Engineering Limits as indicated in the agency QA Specifications.
- Provide regular feedback to Project Manager/Resident Engineer and Materials Engineer based on field Acceptance inspection and testing results.
- Identify any visually deficient work as a result of either unacceptable material quality or unacceptable workmanship.
- Notify QC personnel if suspension of field placement of nonconforming materials appears to be triggered per the approved QC Plan.
- Communicate with production facility Acceptance personnel to convey test information regarding the product.
- Communicate with contractor QC personnel the results of testing as needed to provide feedback based on Acceptance activity.

Post-Placement Acceptance Activities



AV Inspection of Post Pour PCC

Date of Review: ______ AV Inspector: ______ NETTCP Cert. No ______
Segment: ______ AV Sublot: ______ Date of Pour: ______

POUR LOCATION: ______

General Inspection

Date of Review:					
Time of Inspection:					
Days Elapsed Since Pour:					
Ambient Temperature:					
Cold Weather Concrete: (as defined by NETTCP)					
Hot Weather Concrete: (as defined by NETTCP)					
Concrete Surface Temp: (Min/Max Temp)					
Concrete Surface Condition: (Moist, SSD, Dry)					
Evaporation Prevention: (include type)					
Continuous Water Application: (include type)					
Concrete Heat Loss Prevention: (include type)					
Forms Removed: (if 'YES' see below)					

KEY: Y = yes; N = no; NA = not applicable to work; NW = not witnessed; or as noted

Comments:

Date	Comment

Forms Removed (Visual Inspection)

Surface Discoloration/Damage: ______
Inappropriate Consolidation: ______
Pour Lines/ Cold Joints: ______
Shrinkage Cracking: ______
Excessive bugholes: ______
Spalling: ______

Other (Notes):

- Place all completed QC Monitoring Report Forms, Inspection Report Forms, and Test Report Forms in ***Acceptance Field Record Book***.
- Make sure all information (random numbers, sample locations, results of testing, visual observations, QC monitoring, etc.) has been recorded on proper forms.
- Prepare and forward copies of completed Report Forms to the Project Manager/ Resident Engineer and Materials Engineer.
- Clean up all equipment used for Acceptance testing prior to leaving the job site.
- Perform any preparatory work for the next field inspection day.

6.9 - Acceptance of Completed Work

Scope of Acceptance Determination

The final step in fulfilling the first agency Acceptance objective (i.e., quality measurement) is to make an Acceptance determination for work completed. The agency's Acceptance determination should be based on the evaluation of:

- Agency Acceptance inspection information.
- Agency Acceptance testing data.
- Validated contractor QC testing data (if allowed by agency).

An assessment of both inspection and testing is needed in order to make a complete Acceptance determination. As explained earlier, visual inspection for Acceptance is just as important as Acceptance sampling and testing. The agency, therefore, should not focus solely on sampling and testing data in the Acceptance determination process.

Timely analysis of Acceptance data is necessary to determine the measured quality level of all materials produced and placed. The process of determining the acceptability of materials Quality and workmanship should occur as work is being completed, not after substantial completion of the project. It is important, therefore, that agency Acceptance personnel evaluate all Acceptance data (Acceptance inspection and Acceptance testing) on a real-time basis. Waiting until significant time has elapsed (e.g., end of the month, end of the project) or until significant quantities of material have been produced or placed before evaluating Acceptance information will not result in an effective Acceptance system. Accordingly, the agency Project Manager/Resident

Engineer must ensure that all Acceptance data is periodically evaluated to provide a current assessment of the quality of materials and workmanship.

While it is important for analysis of Acceptance data to be performed on a real-time basis, it is also necessary to have sufficient data (i.e., number of test results) to provide meaningful analysis. Due to the inherent variability found in any lot of material produced or placed, the test results of a single agency Acceptance sample (or even an individual QC sample) cannot be used to determine the overall quality of the lot. Instead, multiple test values throughout the lot (i.e., sublot test results) must be used to characterize the lot of material.

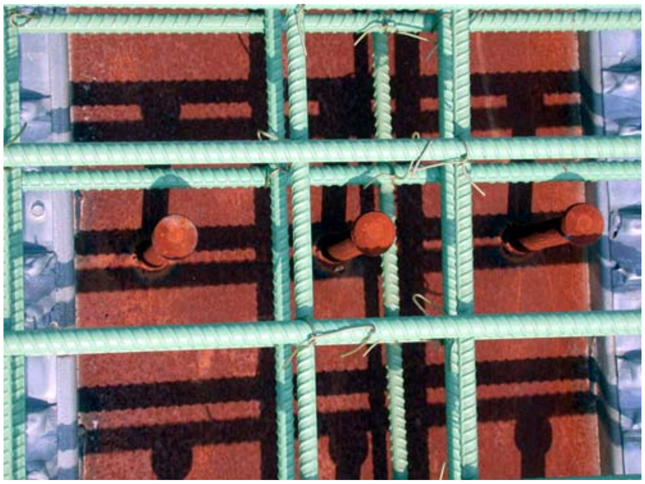
Communicating the results of Acceptance data evaluation to the contractor in a timely manner is desirable as it provides information, in addition to the contractor's QC data, which either confirms that each product is at an acceptable quality level or is deficient. This approach can help avoid untimely identification of non-conforming material that may require costly corrective action or which may lead to unnecessary disputes.

Evaluation of Acceptance Inspection Information

As presented previously (Section 6.5), the agency is responsible for performing Acceptance inspection at both production facilities and field placement locations. The findings of all Acceptance inspection activity (i.e., visual observation and check measurements) should be properly documented and used to determine the acceptability of materials and product workmanship.

Evaluation of Acceptance inspection information is essentially based on a comparison of inspection findings against the materials and workmanship requirements contained in the project plans and specifications. All products produced and placed should consist of material that is uniform in character and should exhibit finished workmanship that is reasonably close to the specified Acceptance value or Acceptance range. The agency

Acceptance evaluation will include an assessment of the materials for correct type (e.g., proper size and epoxy coating of rebar, correct HMA mixture type) and placement condition (e.g., epoxy rebar is clean and free of visible damage, HMA mixture is not segregated). It will also include a determination that all finished lines, grades, cross-sections, and other dimensions are within the required tolerances.



This evaluation can sometimes be subjective and dependent upon the judgment of the agency Acceptance personnel. Accordingly, it is recommended that criteria for Acceptance based on visual inspection be provided in the agency's QA Specifications that is unambiguous and as objective as possible. Some transportation agencies have moved toward implementing a scoring or grading system for materials quality and product workmanship based on visual inspection of individual work items. While the adoption of such an approach may not entirely remove subjectivity in performing visual inspection, it can provide a clear tool that both agency Acceptance personnel and contractor QC personnel can understand for documenting and evaluating the agency's Acceptance inspection findings.

If the agency's evaluation of Acceptance inspection information indicates that the material quality and product workmanship provided for an individual work item reasonably meets all criteria set forth in the project plans and specifications, the agency should conclude that the subject work is accepted.

In the event the Acceptance inspection information identifies deficiencies in either material quality or product workmanship, the agency must determine an appropriate disposition of the material in question. Acceptance personnel should follow the specific procedures outlined in the QA Specifications to determine the disposition of apparently unacceptable material or workmanship when it is identified. Materials or finished product locations exhibiting deficiencies should be isolated and addressed independently of the rest of the sublot and lot within which they are located. If the extent or magnitude of apparent deficiency is in question, the agency or the contractor may utilize sampling and testing (when relevant and possible) to assist in determining the acceptability of the materials or finished product. Dispute resolution procedures may also assist in this process. In all cases, however, the responsibility for making the Acceptance determination lies with the agency.

Evaluation of Testing Data for Acceptance

The agency is responsible for performing Acceptance sampling and testing at both production facilities and field placement locations, as presented earlier in this chapter (Section 6.6). The results of all agency Acceptance sampling and testing should be properly documented and used to measure the quality of the final product.

As previously explained, the agency's final determination of product Acceptance using sampling and testing data may take one of the following two approaches:

- Use only agency Acceptance test results.
- Include validated contractor QC test results.

The desirability of decreasing risks for both the contractor and the agency is a strong incentive to include more test results per lot. The more non-biased information that can be gathered regarding a product, the more likely the assumptions being made about the product will be accurate. Therefore, agencies are encouraged to either increase the frequency of agency Acceptance testing, or include validated contractor QC test results in the Acceptance determination.

When the second approach above is utilized, the agency may select one of the following three allowable options for its acceptance determination:

Option A – Include all validated QC test results + agency Acceptance test results for the lot.

Option B – Include all validated QC test results + correlated contractor splits of the agency Acceptance test results for the lot.

Option C – Include all validated QC test results for the lot only.

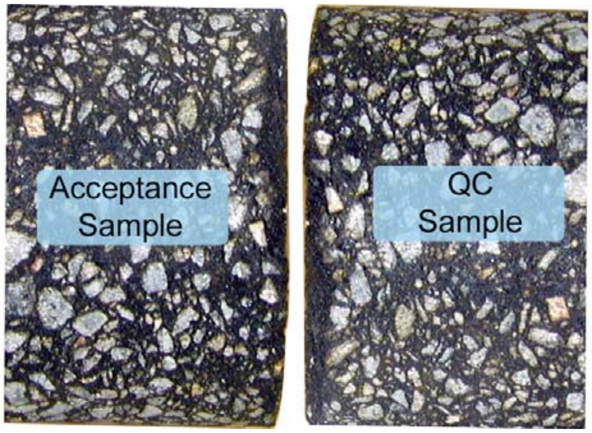
The factors considered by an agency in selecting one option over the other two will not be discussed herein, as they are essentially issues that require consideration by QA Specification writers. However, whichever option is selected by the agency must be clearly identified and explained in the agency's QA Specifications.

If any of the three above options for including contractor QC test results in the acceptance determination are specified, the agency must ensure that:

- The agency's monitoring of contractor QC activity confirms that Quality Control is being adequately performed in accordance with the approved QC Plan.
- Correlation sampling and testing is conducted by contractor QC and agency Acceptance personnel prior to material production.
- All QC test results used are confirmed to be from random QC samples.
- The random QC test results are validated against the Acceptance test results.

Each of these steps is necessary to ensure the validity of all contractor QC test results included in the acceptance determination. Even if the agency elects not to include random QC data in the acceptance determination, the contractor must adhere to the requirements contained in the approved QC Plan in order to provide the appropriate level of Quality Control over all production and placement processes. Correlation sampling and testing and validation procedures are fully presented in Chapter 10. Both of these steps are explained briefly below.

Correlation Sampling and Testing



In order to increase the level of confidence in the contractor's QC, the agency should use ***correlation testing*** to compare and correlate test results for those Quality Characteristics that will be sampled and tested for use in the Acceptance decision. Correlation testing should be performed initially on the project (at the earliest possible time) on split samples. Acceptance personnel test one half of the correlation sample, QC personnel test the other. The results of the correlation testing are then analyzed in order to determine if there is any significant difference between them.

One method of analysis of correlation samples is to compare results to precision statements listed in the AASHTO or ASTM procedure being conducted. When the results are within the allowable tolerances, it may be assumed that there is no difference in either the test equipment or the procedure. Some agencies, however, have established more stringent comparative requirements. Another method used to verify multiple split-sample results (that is, pairs of samples) is known as the ***paired t-test***. Evaluation of correlation split sample test results using the paired t-test is used to indicate the degree of difference in the means of two sets of paired data (in order to determine the probability that both sets of data came from the same population). This method is described in detail in Chapter 10. When the results of the paired t-test indicate a significant difference between results, the source of the difference (the testing personnel, equipment, or procedures) must be identified and eliminated in order to avoid discrepancies between contractor QC testing and agency Acceptance testing.

Validation of QC Data

A ***validation*** analysis is used to indicate the degree of difference in the variances and the means of two sets of data (agency Acceptance data vs. contractor QC data) independently obtained from the same material lot. Validation determines the probability that both sets of data came from the same population (i.e., lot) through the use of an ***F-test*** in addition to the t-test. If the results of the validation process indicate that the independent sets of samples (Acceptance vs. QC) are likely to have come from the same population, then the contractor's QC test results are determined to be validated and may be included with the agency's Acceptance test results in the agency's Acceptance determination. If the results of the validation process indicate the two sample sets came from different populations then only the agency's Acceptance test results are used in the Acceptance determination. More information on validation and the F-test and t-test can be found in Chapter 10. Additionally, **Appendix H** of this manual contains the *AASHTO Implementation Manual for Quality Assurance* documentation which provides more detailed examples of the application of the F-test and t-test.

As stated in the *AASHTO Implementation Manual*, for the validation analysis to be meaningful, both sets of test results (QC and Acceptance) must be from samples that were:

- Obtained in a random manner.
- Sampled over the same time period.
- Sampled and tested using the same sampling and testing procedures.

The ability of the validation procedure to properly identify differences between two sets of test results also depends upon the number of test results that are being compared. The greater the number of test results, the greater the ability of the procedure to identify valid differences. For this reason it is recommended to use a larger amount of agency Acceptance testing early in a project. This way, more data will be available to make a determination whether the contractor QC test results are consistent with the agency Acceptance tests.

Evaluating Test Results with Quality Level Analysis

The evaluation of the overall quality of a lot of material produced or placed should not be focused on individual samples (n = 1). Rather, the test results from multiple sublots are used to evaluate lot quality for an individual Quality Characteristic. Quality Assurance Specifications will indicate the specific Quality Measure to be used to evaluate multiple agency Acceptance test results (and validated QC test results if permitted). The Quality Measure typically specified is the Percent Within Limits (PWL), which is determined using a ***Quality Level Analysis*** (QLA) procedure. QLA is a mathematical tool that looks at the average (mean) of all test results in conjunction with the variability of the test results against the Target and Specification Limits for an individual Quality Characteristic. The QLA procedure is presented in Chapter 8. As was briefly explained in Chapter 4, the Specification Limits are statistical limits that are used with the QLA procedure. Specification Limits are intended only to assess multiple test results, not individual test results.

Acceptable Lot Quality

The specific requirements for Acceptance based on QLA evaluation of test results are established by each agency in their QA Specifications. However, the target level of quality established for Acceptance warranting full (100%) payment for an individual Quality Characteristic is typically set at 90 or 95 PWL. This value is referred to as the ***Acceptable Quality Level*** (AQL). QLA evaluation that results in a PWL greater than the AQL (e.g., 96 to 100 PWL) is likewise accepted and should, depending upon the QA Specification provisions, receive above 100% payment.

Lot Quality Requiring Rejection

It is important that the agency Project Manager/Resident Engineer be completely familiar with the specification requirements for determining product Acceptance using QLA. QA Specifications normally stipulate a bottom threshold level of material quality which must be met. This value is referred to as the ***Rejectable Quality Level*** (RQL). Material that is below the AQL (e.g., 90 PWL) and at or above the RQL (e.g., 60 PWL) is usually accepted, but receives less than 100% pay. Quality levels below the RQL (e.g., 60 PWL) typically result in rejection of the material by the agency. Such material will usually be identified for removal, corrective action (if possible), or a reduced payment for the corresponding lot.

Agency QA Specifications usually require termination of the lot when the QLA indicates a PWL below the RQL. Terminating a lot of material allows the contractor to make adjustments to the process of production or placement and bring the process back into control. Once the contractor has demonstrated that the process is capable of producing material at the Acceptable Quality Level, a new lot of material is established. The terminated lot will still require corrective action or be penalized, but these penalties are not carried forward into the new lot. Most QA Specifications allow the contractor to submit a written request to permit a lot containing material below the RQL to remain in place at a reduced price. Such requests usually require that the contractor provide an engineering analysis showing expected effects on long-term product performance. The agency will then determine whether or not the material may remain in place with an appropriate price reduction or must be removed.

Lot Quality Requiring Suspension

Many QA Specifications also prescribe a running assessment of the quality level for a lot of material throughout production or placement. Such specifications will typically define a minimum quality level for provisional acceptance before the lot is completed and the corresponding final Acceptance determination for the lot has been made. Material in the lot is considered acceptable as long as the QLA indicates that the material is somewhere between the AQL (e.g., 90 PWL) and a ***Suspension Quality Level*** (SQL). When the QLA evaluation of Acceptance test results yields a quality level below the SQL (e.g., 70 PWL), most QA Specifications require suspension of material production or placement until corrective action and subsequent testing confirms that the PWL has been returned above the SQL (e.g., 70 PWL).

Provisional determination of lot quality assumes that the quality levels are monitored throughout the process of material production and placement. The QLA should ideally be performed on a daily basis after a sufficient number of test results are available (n > 4 or 5). Furthermore, the frequency of the “check” of the QLA should be indicated in the QA Specifications to avoid differing opinions by the contractor and the agency as to the current level of lot quality. The final QLA evaluation for the determination of lot Acceptance must include all valid test results for the lot.

Determining Acceptance with Engineering Limits

Assessment of individual test results (n = 1) should be addressed through the use of ***Engineering Limits***. As mentioned above and briefly explained in Chapter 4, agency QA Specifications may also include Engineering Limits (sometimes referred to as Suspension Limits) that individual Acceptance (or QC) test results must be evaluated against for Acceptance. The rationale for using Engineering Limits is to identify material that has a measured value that is beyond the expected range of acceptable inherent variability.

If an individual Acceptance (or QC) test result is outside of the Engineering Limits, it should not be automatically interpreted as an indication that the material produced or placed is unacceptable. QA Specifications may require additional Acceptance testing and QC testing in order to determine the actual quality of the sublot represented by the nonconforming test result. The final acceptance determination should be based on the supplemental sampling and testing. Material in the affected sublot may be required to be re-worked (if possible), barred from placement (if located during production), or removed (if already placed in the field).

6.10 - Determination of Contractor Pay

Mechanisms Used to Determine Contractor Pay

As mentioned earlier (Section 6.1), the second of the two primary objectives of the agency Acceptance system is to determine the payment the contractor should receive based on the agency's determination of Acceptance. Quality Assurance Specifications for each work item (e.g., HMA, PCC, soils) normally include provisions for determining payment based on the measured quality of materials produced and placed. In addition, payment may be linked to the adequacy of the contractor's Quality Control system. The three principal mechanisms which are typically used to determine contractor pay as a function of quality include:

- The monitored sufficiency of QC activity.
- The inspected quality of materials and workmanship.
- The tested quality of materials.

Typical approaches used by Agencies for each of these payment mechanisms are briefly discussed below. However, the agency Project Manager/Resident Engineer should be fully familiar with the particular agency specification requirements for determination of contractor pay based on Acceptance activity information.

Measurement and Payment for QC Activities

As fully discussed in Chapter 5, proper implementation of Quality Assurance requires the contractor to provide an effective Quality Control system, including:

- Preparing and implementing one or more QC Plans.
- Visual QC inspection.
- QC sampling and testing.
- Developing and using control charts.
- Maintaining a QC Records System.

Most agency QA Specifications identify each of these QC activities as a contractual requirement which the agency is paying for and which must be fulfilled by the contractor.

The adequacy of each of these QC activities should be monitored and documented by agency Acceptance personnel throughout the duration of a construction project. QA Specifications normally include one of the following two approaches for measurement and payment of contractor QC:

- Separate Pay Item (Lump Sum/Unit Price).
- Included in Pay Item for Major Work Item.

Regardless of which of these approaches is used, the agency Project Manager/Resident Engineer should ensure that the contractor's QC activities are routinely monitored and documented by agency personnel. Measurement and payment for the QC activity should be determined for progress payments and final payment in accordance with the specific procedures in the agency's QA Specifications; however, the two above approaches are briefly described below.

With the first approach, the contractor receives progress payments under a Quality Control pay item in proportion to the amount of material produced and placed for the related work item (e.g., HMA, PCC, soils, etc.) as long as all QC activity is determined by the agency to be satisfactory. However, if the agency's monitoring of contractor QC finds and documents deficiencies in one or more of the above QC activities, the QA Specifications may contain provisions indicating that payment under the pay item for QC is to be adjusted using one of the following options:

- Payment for the QC item is temporarily withheld.
- Reduced payment is made for the QC item.
- No payment is made for the QC item.

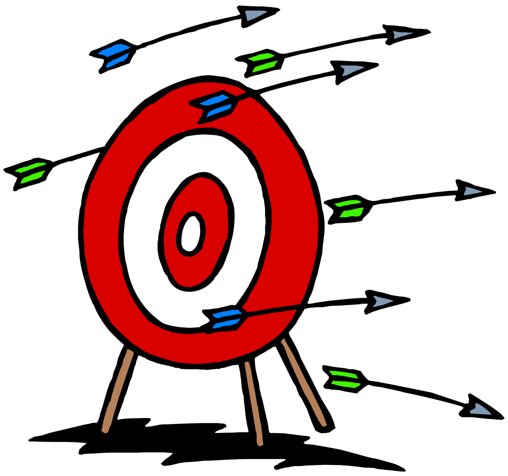
When payment for QC activity is incidental to the Contract Pay Item for a major Work Item, the QA Specifications should clearly establish the procedures for determining pay adjustments to the work item related to the agency's documented QC monitoring findings. In the event that any or all of the contractor's QC activities are deficient, specification provisions may require that the agency either:

- Temporarily withhold payment for the work item.
- Apply a reduced payment (e.g., xx%) for the work item.

Payment based on Acceptance Inspection

The second mechanism typically applied in the determination of contractor pay is the agency's independently obtained Acceptance inspection information. As discussed previously (Section 6.9), the Acceptance inspection findings on the quality of materials and product workmanship should be properly documented and periodically evaluated (i.e., by sublot or other defined quantity of material placed) as part of the agency's

Acceptance determination. If the Acceptance inspection information indicates that a quantity of material produced or placed for a work item meets all applicable requirements for visual material quality and workmanship, the corresponding quantity of material is determined “Accepted.” The accepted work item quantity normally receives payment at the full bid item price (i.e., 100% pay), provided that the results of Acceptance sampling and testing (discussed below) also indicate the material is at or above the Acceptable Quality Level (AQL).



However, if the agency’s Acceptance inspection information for some quantity of a work item identifies deficiencies in the material quality or product workmanship, the QA Specifications will normally prescribe appropriate procedures for determining payment. If the deficiency is of a magnitude to require complete rejection of the material (i.e., removal), specifications will typically provide for no pay (i.e., 0% pay) for the rejected material. Agency specifications may also include provisions for performing sampling and testing and/or an engineering analysis (when relevant and possible) to quantify the magnitude of deficiency identified with the inspected material quality or workmanship. In such cases, the determination of pay for the corresponding material quantity may be negotiated by the contractor and the agency.

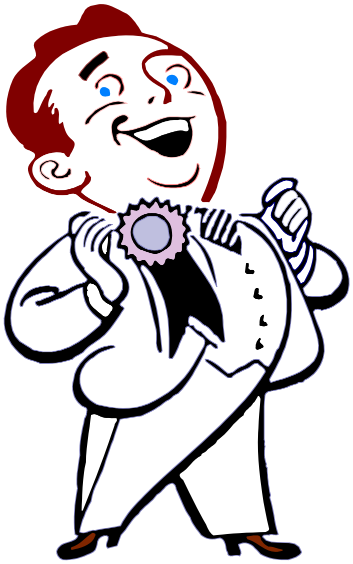
If the deficiency does not warrant complete rejection, the agency may apply some type of scoring or grading system (as mentioned in Section 6.9) to arrive at a qualitative measurement of the material quality or workmanship. The results of such an assessment are then used to determine payment. The agency specifications may assign a specific reduced pay amount as a percentage of the contract bid item price based on the score or grade range assigned by the agency Acceptance personnel.

Payment Based on Sampling and Testing

The third mechanism included in QA Specifications which is used to determine contractor pay for a work item produced and placed is the tested quality of the material. As previously explained, Acceptance sampling and testing is performed by agency personnel at sufficient frequencies to provide a meaningful mathematical representation of the material in a given lot. The agency Acceptance test results (and validated contractor QC test results if permitted) for individual Quality Characteristics are evaluated for determination of Acceptance using a Quality Level Analysis (QLA) procedure which determines the Percent Within Limits (PWL) for the lot. Based on the calculated PWL value for the lot, most QA Specifications typically provide for the following:

- Full payment (i.e., 100%).
- Reduced payment or disincentive (e.g., 85-99%).
- Increased payment or incentive (e.g., 101-105%).

In order for the contractor to receive full (100%) payment, the quality level for the lot must be at the AQL (typically 90 PWL or 95 PWL). If the calculated lot quality level is below the full payment value (e.g., 89 PWL), but is at or above the Rejectable Quality Level (typically 60 PWL), then a pay reduction is applied. If the lot quality level exceeds the full payment value (e.g., 96 to 100 PWL), then a pay increase is awarded.



Once the Quality level (i.e., PWL) for the lot is known, a corresponding ***Pay Factor*** can be determined. Pay Factors are derived using either:

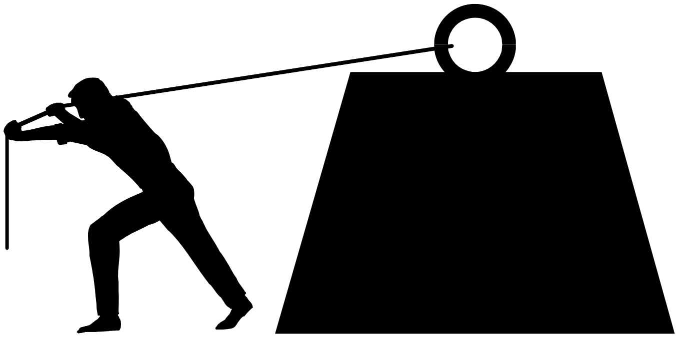
- Pay Factor Tables
- Pay Factor Formulas
- Pay Factor Curves

Because multiple Acceptance Quality Characteristics are used to assess the material quality in each lot, a separate pay factor is determined for each Quality Characteristic. Most Agencies typically combine the individual pay factors for each Quality Characteristic into one ***composite pay factor***.

There are several approaches for combining the individual pay factors for each Quality Characteristic into a composite pay factor, which include the following:

- Use only the minimum individual pay factor.
- Use the average (mean) of the individual pay factors.
- Use the product (i.e., multiply) of the individual pay factors.
- Use the sum (i.e., add) of the individual pay adjustments.

Under the "averaging approach," each Quality Characteristic is typically assigned a weight which is applied to the corresponding pay factor. The individual weighted pay factors are then combined to form the composite pay factor.



The final ***pay adjustment*** for a work item (e.g., HMA, PCC, soils, etc.) is calculated by multiplying the pay factor (or composite pay factor) by the contract unit price and the lot quantity for the work item. Examples of procedures for determining pay factors and pay adjustments are presented in Chapter 10.

6.11 - Acceptance Records

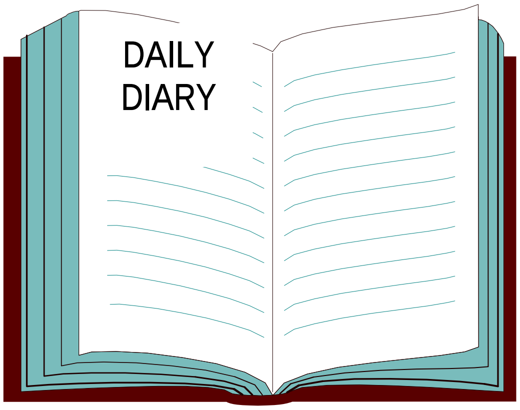
Objective of Agency Acceptance Records System

As discussed previously, all agency Acceptance activities (i.e., monitoring the contractor's QC, Acceptance inspection, Acceptance sampling and testing) conducted at both production facilities and field placement locations must be properly documented. Accordingly, a well-designed and properly maintained ***Acceptance Records System*** is an important part of each agency's Acceptance system.

The primary objective of the Acceptance Records System is to provide a rational process to organize, evaluate, store, and retrieve all Acceptance documentation. The organization of the Acceptance Records System should facilitate the immediate, executive level review of pertinent information such as the results of agency monitoring of QC activity on a daily basis, or a summary of all Acceptance sampling and testing for required Quality Characteristics. It should also provide for the collection and storage of the individual documents (paper or electronic) that record the results of agency monitoring of QC activity, individual Acceptance inspection findings, and Acceptance test results, thus providing a complete record of all information used by the agency in its Acceptance determination for each construction project.

Acceptance records are normally maintained by various agency personnel on the project Acceptance Team in accordance with established procedures outlined in the agency's QA Program. While each transportation agency may have a slightly different approach to collecting, storing, analyzing, or presenting Acceptance information, typical key components that are included in an effective agency Acceptance Records System are discussed below.

Project Daily Diary

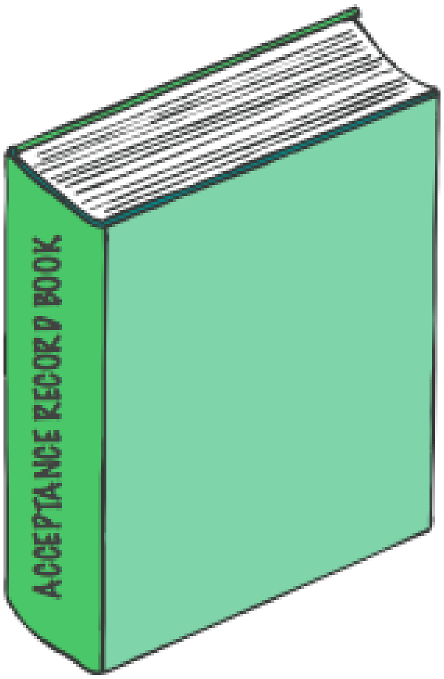


The Project Manager or Resident Engineer on each transportation construction project should maintain a ***Project Daily Diary***. The Project Daily Diary should be used to document all major activities or actions related to the agency Acceptance system that occur at production facilities or field placement locations each day. The Daily Diary is not intended to replicate or supersede individual Inspection Report Forms or Test Report Forms, but rather serves as a summary record of key actions taken by agency Acceptance personnel.

The type of information usually recorded in the Project Daily Diary includes:

- The day’s weather or environmental conditions.
- Summary of production or placement activities completed.
- Any issues of non-quality identified by either contractor QC personnel or members of the agency Acceptance Team.
- Any corrective actions recommended or taken by either QC personnel or agency Acceptance personnel.
- Meetings or discussions held with the contractor’s production personnel, QC personnel, or agency personnel.
- Visitors to the project sites of materials production or field placement.

Acceptance Record Book

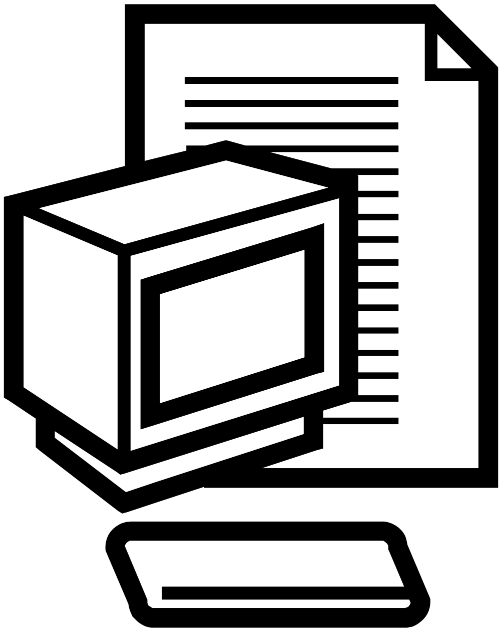


Agency Acceptance personnel should maintain an ***Acceptance Record Book*** for each major work item being produced and placed on the project. The function of the Acceptance Record Book is to store all formal Acceptance documents used or prepared by Acceptance personnel for each production and placement operation for the individual work item. Maintaining the Acceptance Record Book is the responsibility of the Project Manager/Resident Engineer (or Acceptance personnel under the immediate direction of the PM/RE). The PM/RE must maintain a complete record of all Acceptance sampling, testing, inspection, and monitoring activities. Paper records do not need to be maintained if they are in suitable electronic format. However, the original source documentation must be kept whether it is paper or electronic.

Although greater use is made today of computers for recording information, a completely paperless system is often not possible or practical. When paper records comprise some or all of the documentation, agencies are encouraged to retain printed records (originals or copies) of all Acceptance documents in a protected book format, such as a three-ringed binder, or several binders, especially while a project is active. The Acceptance Record Book(s) should be maintained at the PM/RE's office in a location that is readily accessible to all members of the Acceptance Team. A paper folder/file drawer system may similarly be used, typically after the project is completed.

The Acceptance Record Book for each work item should contain the following documents:

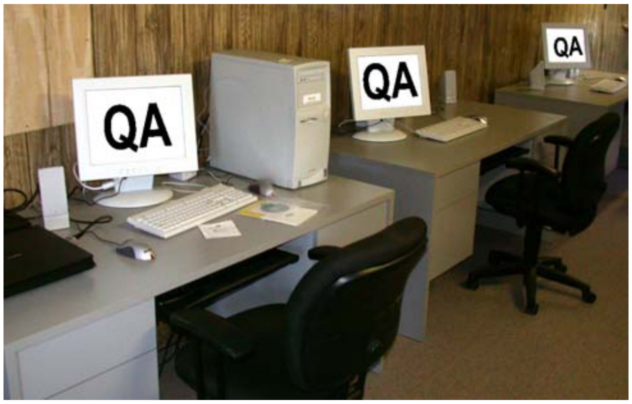
- Signed copy of the contractor’s current approved QC Plan.
- Signed originals or copies of all completed QC Monitoring Report Forms.
- Signed originals or copies of all completed Acceptance Inspection Report Forms.
- Signed originals or copies of all completed random sampling location forms.
- Signed originals or copies of all completed Acceptance Test Report Forms (plus QC Test Report Forms if QC test results are used in Acceptance determination).
- Current copy or printout of all Quality Level Analyses performed.
- Current summaries of all individual Acceptance test results (plus QC test results if included in Acceptance determination) to date (by lot and sublot).
- Summary sheets of material quantities produced or placed (by lot and sublot).



Each unit of the agency Acceptance Team (i.e., PM/RE, production facility Acceptance personnel, District/Central Materials laboratory personnel) involved with a given construction project should retain the original copies of their Acceptance documents in their own Acceptance Record Book or similar system. The Acceptance Record Book(s) maintained by the PM/RE, however, should serve as the “Master Acceptance Record Book” and should include copies of Acceptance documentation prepared by other Acceptance Team members, including those from all offsite production operations as well as from all agency Acceptance laboratories. The agency Project Manager/Resident Engineer should take the lead responsibility for all Acceptance activities on the project and be fully aware of the status of the quality of all materials produced and placed for the project. The Acceptance Record Book for each off-site production operation (e.g., HMA or PCC production, prestressed concrete fabrication) should be maintained by Acceptance personnel at the location of production. Field Acceptance technicians/inspectors will typically submit their Acceptance records to the PM/RE for inclusion in the "Master Acceptance Record Book" at the project site.

All required Acceptance documents should be placed in the Acceptance Record Book(s) in a timely manner. This is to ensure that the records are available on a real-time basis for use by agency personnel in evaluating the measured quality of all materials produced and placed. Agency procedures may specify a maximum time period for completing Acceptance documents and entering them into the Record Book. As a general rule, it is recommended that Acceptance personnel ensure that all required Acceptance records (originals or copies) are placed in the appropriate Acceptance Record Book within 24 to 48 hours after they are completed.

Agency Acceptance Database



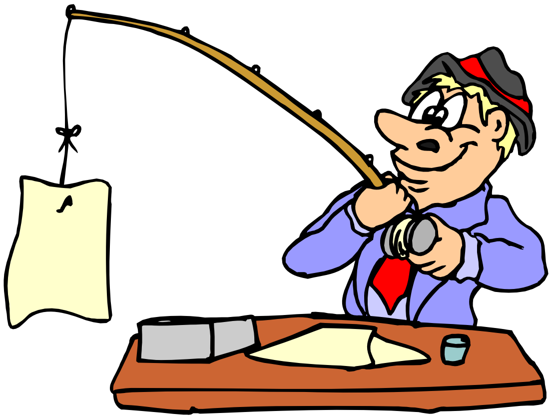
A complete Acceptance Records System should allow for easy access to Acceptance data by the Project Manager/Resident Engineer and immediate staff, as well as other offsite members of the agency Acceptance Team. It should also allow secure access by contractor QC personnel, as needed, for sharing of Acceptance information. Accordingly, most agencies have established some type of ***Acceptance database*** for storage, analysis, and retrieval of Acceptance sampling, testing, and inspection data. Acceptance databases are typically designed to evaluate production or placement quality levels (e.g., Quality Level Analysis), and provide summaries of Acceptance test results or Acceptance inspection information to date.

Acceptance databases can be developed using standard database software or may be custom-made to address the agency's individual needs. Ideally, their design should permit sharing of data between the Project Manager/Resident Engineer, other agency Acceptance Team members, and the contractor. Given these parallel needs, it is generally advantageous to use an Acceptance database that is developed with a standard software platform used by all agency Acceptance Team members, and that can be provided to or reasonably purchased by contractors.

Data security is obviously important to protect original data once entered into the Acceptance database. Access to the Acceptance database can be provided to outside parties (other agency personnel or contractors) on a read-only or similar limited basis. Or instead of providing direct access to the QC database, the agency can share files containing Acceptance data. Data sharing may be accomplished via a Local Area Network (LAN), an Intranet system, or an Internet connection.

Submittal of Acceptance Records to the Contractor

The agency's QA Program procedures or QA Specifications may require that the agency periodically submit copies of some Acceptance records to the contractor for information. Acceptance sampling and testing results are typically shared with the contractor's QC personnel, particularly if the agency permits validated contractor QC test results to be included in the Acceptance determination.



Even if not specifically required by agency procedures or the QA Specifications, agency Acceptance personnel are encouraged to share copies of their Acceptance sampling, testing, and inspection results to the contractor on a regular basis. This helps to ensure that contractor personnel are apprised of the status of agency Acceptance findings, be they positive or negative. Timely submittal of Acceptance records to the contractor will enhance communications and can help avoid potential points of conflict or dispute. As a general rule, it is recommended that agency Acceptance records, particularly Acceptance Test Report Forms and Inspection Report Forms, be submitted to the appropriate QC personnel within one working day after the Acceptance activity and corresponding documentation is completed.

Materials Acceptance Certification

Transportation agency procedures may require that a ***Materials Acceptance Certification*** be prepared upon final agency Acceptance of all materials produced and placed on an individual project. The Materials Acceptance Certification is used by the agency to attest that the materials' quality and product workmanship for all work items on a project meet the Acceptance requirements established by the agency. This document may be used to comply with internal agency procedures or to comply with regulatory requirements associated with sources of project funding. For example, on all federal-aid highway projects, it is a requirement (23 CFR 637.205(d)) that a Materials Acceptance Certification be prepared and submitted by the transportation agency to the FHWA. Such certification documents, when required, are normally prepared by the agency's Materials Engineer or designated Acceptance personnel.

- END OF CHAPTER 6 -

CHAPTER 7

Key Math Terms and Rules

Chapter 7

Key Math Terms and Rules

Chapter Overview

In this Chapter, the following key mathematical terms and rules will be explained:

7.1 - Mean

7.2 - Deviation

7.3 - Range

7.4 - Variance

7.5 - Standard Deviation

7.6 - Precision, Accuracy, and Bias

7.7 - Repeatability and Reproducibility

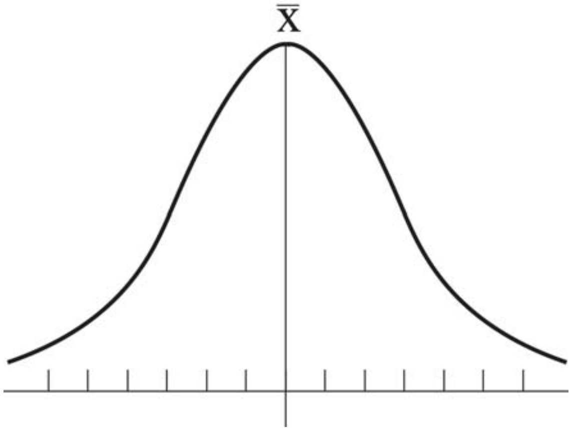
7.8 - Significant Figures

7.9 - Rounding

7.1 - Mean

Definition of Mean

The principal mathematical measure used to describe the central tendency of a distribution of measurements or test values is the ***mean***. The mean coincides with the center or midpoint of a normal distribution curve. Accordingly, the mean is defined as follows:

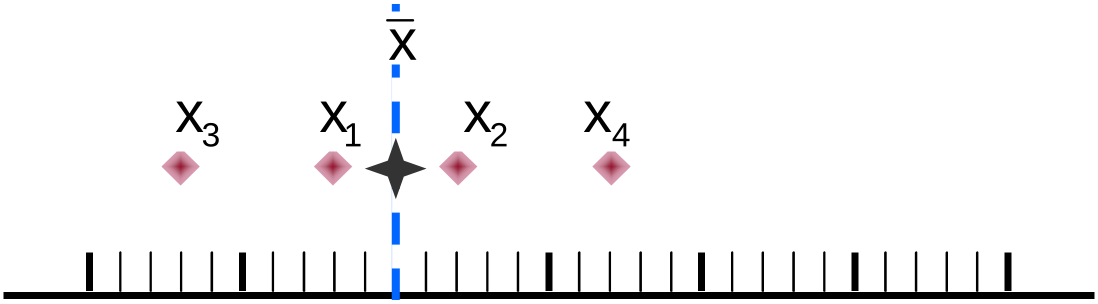


> **Mean** - "The arithmetic average of a set of measurements or test values."

Computing the Mean

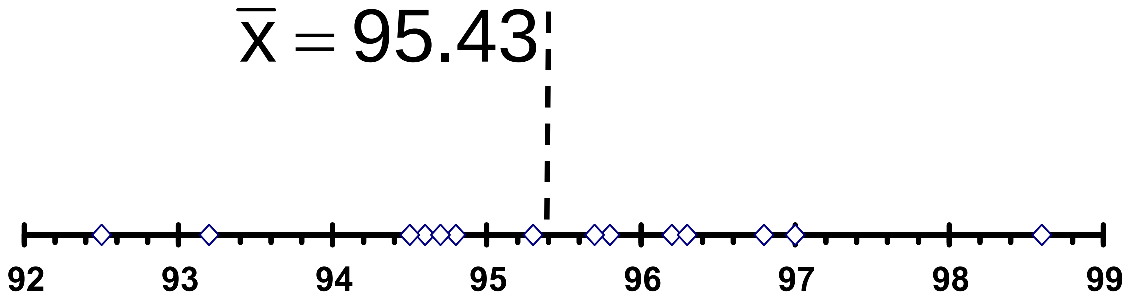
The mean is denoted by an X with a bar over it ($\bar{X}$), and is called "x-bar." The mean ($\bar{X}$) of a statistical sample is computed by adding all of the individual material sample test values (X_i) in the statistical sample and dividing the sum ($\sum$) of those test values by the number of samples (n).

$$\bar{X} = \frac{\sum X_i}{n} = \frac{X_1 + X_2 + X_3 + \ldots X_n}{n}$$



Example 7-A: Fourteen (14) In-Place Density tests were performed on a project. The individual test values for the fourteen samples were recorded and the mean was computed as shown in the table below.

Sample Number	Test Value (x_i)
X_1	95.8
X_2	94.6
X_3	93.2
X_4	97.0
X_5	96.2
X_6	94.8
X_7	95.3
X_8	95.7
X_9	96.8
X_{10}	98.6
X_{11}	92.5
X_{12}	94.5
X_{13}	96.3
X_{14}	94.7
Sum ($\sum$) of test values:	1336
No. of Samples (n):	14
Mean ($\bar{X}$) =	**95.43**

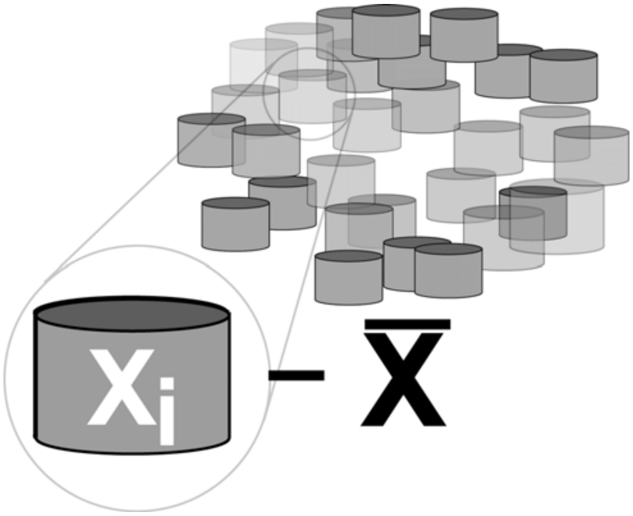


7.2 - Deviation

Definition of Deviation

One simple measure used to express how much an individual sample value varies from the mean of a set of measurements or test values is referred to as ***deviation***. Accordingly, the term deviation is defined as follows:

> **Deviation** - “The difference between an individual value and the mean of a set of measured or tested values.”



Deviation is also sometimes used to express the difference between measured or tested values and target values or intended levels.

Computing Deviation

Deviations for a statistical sample (i.e., multiple samples) are calculated by subtracting the mean ($\bar{X}$) of the statistical sample from the individual sample test values (x_i) in the statistical sample.

$$\text{Deviation} = (x_i - \bar{x})$$

Deviations are used in determining other mathematical measures of the spread of test values, as presented further below.

Example 7-B: The deviation for each of the fourteen In-Place Density samples recorded in Example 7-A is computed as shown in the table below.

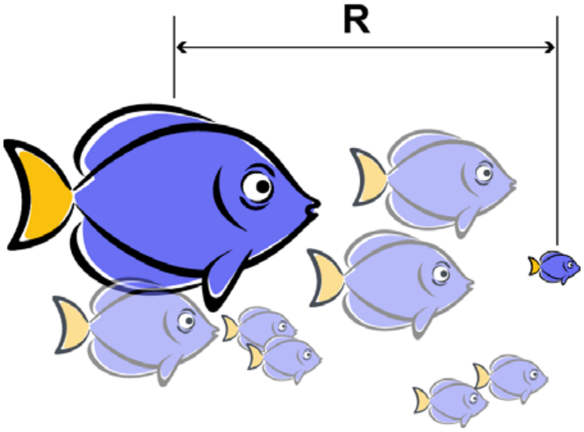
Sample Number	**Test Value (x_i)**	**Mean ($\bar{x}$)**	**Deviation ($x_i - \bar{x}$)**
X_1	95.8	95.43	**0.37**
X_2	94.6	95.43	**-0.83**
X_3	93.2	95.43	**-2.23**
X_4	97.0	95.43	**1.57**
X_5	96.2	95.43	**0.77**
X_6	94.8	95.43	**-0.63**
X_7	95.3	95.43	**-0.13**
X_8	95.7	95.43	**0.27**
X_9	96.8	95.43	**1.37**
X_{10}	98.6	95.43	**3.17**
X_{11}	92.5	95.43	**-2.93**
X_{12}	94.5	95.43	**-0.93**
X_{13}	96.3	95.43	**0.87**
X_{14}	94.7	95.43	**-0.73**

7.3 - Range

Definition of Range

The simplest measure of dispersion (i.e., variability) which can be determined for a set of measurements or test values is the ***range***. The range is defined as follows:

> **Range** - "The difference between the highest individual value and the lowest individual value in a set of measured or tested values."



Computing Range

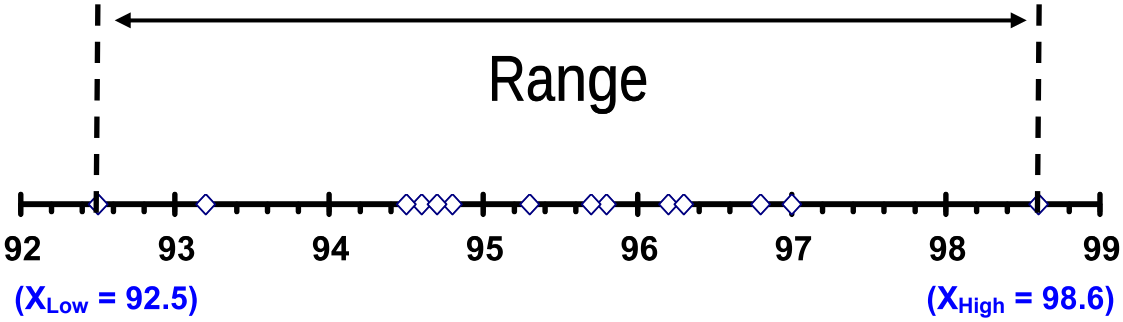
The range is denoted by the term "**R**." The range (R) for a statistical sample (i.e., multiple samples) is computed by subtracting the lowest sample test value (X_{Low}) in the statistical sample from the highest sample value (X_{High}) in the statistical sample.

$$R = (x_{High} - x_{Low})$$

Although it is a single, easy to determine measurement, its primary drawback is that it does not utilize all of the information (i.e., sample values) available in the statistical sample. Since the range only accounts for the two extreme values, it provides no measure of dispersion of the other values in the statistical sample except to indicate that they lie between the extremes. It is typically used in Control Chart applications, which will be discussed in Chapter 9.

Example 7-C: The range for the fourteen (14) In-Place Density samples recorded in Example 7-A is computed as shown in the table below.

Sample Number	Test Value (x_i)
X_1	95.8
X_2	94.6
X_3	93.2
X_4	97.0
X_5	96.2
X_6	94.8
X_7	95.3
X_8	95.7
X_9	96.8
X_{10}	98.6
X_{11}	92.5
X_{12}	94.5
X_{13}	96.3
X_{14}	94.7
Highest Sample Value (x_{High}):	**98.6**
Lowest Sample Value (x_{Low}):	**92.5**
Range (R) =	**6.1**



7.4 - Variance

Definition of Variance

Another mathematical measure of spread or dispersion is the ***variance***. Where the range provides an indicator of the spread of measured or tested values from the highest to the lowest value, the variance looks at the overall deviation of values from the mean. Accordingly, the variance is defined as follows:

> **Variance** - "A measure of dispersion of a set of values from their mean, expressed as a function of the sum of all squared deviations from the mean."

Computing Variance

The variance of a statistical sample is denoted by the term "$\mathbf{s^2}$." The variance (s^2) of a distribution of sample test values is computed by squaring each deviation from the mean $(x_i - \overline{x})^2$, adding these squares, and dividing their sum ($\sum$) by the number of samples (n) minus one.

$$s^2 = \frac{\sum (x_i - \overline{x})^2}{n-1}$$

An alternate version of the formula for variance is as follows:

$$s^2 = \frac{(x_1 - \overline{x})^2 + (x_2 - \overline{x})^2 + \ldots (x_n - \overline{x})^2}{n-1}$$

Thus, the variance provides an idea of how the test results are scattered about the mean. It is used when comparing (validating) contractor and agency sample test results as described in Chapter 10.

Example 7-D: The variance for the fourteen (14) In-Place Density samples recorded in Example 7-A is computed as shown in the table below.

Sample Number	**Test Value (x_i)**	**Deviation** $(x_i - \bar{x})$	**Deviation Squared** $(x_i - \bar{x})^2$
X_1	95.8	0.37	**0.1369**
X_2	94.6	-0.83	**0.6889**
X_3	93.2	-2.23	**4.9729**
X_4	97.0	1.57	**2.4649**
X_5	96.2	0.77	**0.5929**
X_6	94.8	-0.63	**0.3969**
X_7	95.3	-0.13	**0.0169**
X_8	95.7	0.27	**0.0729**
X_9	96.8	1.37	**1.8769**
X_{10}	98.6	3.17	**10.0489**
X_{11}	92.5	-2.93	**8.5849**
X_{12}	94.5	-0.93	**0.8649**
X_{13}	96.3	0.87	**0.7569**
X_{14}	94.7	-0.73	**0.5329**
		Sum (∑) of Deviation Squared:	**32.0086**
		Number of Samples Minus One (n - 1):	**13**
		Variance (s^2) =	**2.4622**

7.5 - Standard Deviation

Definition of Standard Deviation

Another indicator that denotes a measure of spread or variation, and which is derived from the variance, is the ***standard deviation***. The standard deviation provides a measure of the average deviation of the individual sample values from the mean. Accordingly, standard deviation is defined as follows:

> **Standard Deviation** - "A measure of the variability of a set of values which is represented by the principal square root of the variance."

Computing Standard Deviation

The standard deviation of a statistical sample is denoted by the term "**s**." The standard deviation (s) is computed by taking the square root of the variance (s^2) of a distribution of sample test values. The standard deviation has the same units as the original sample test values.

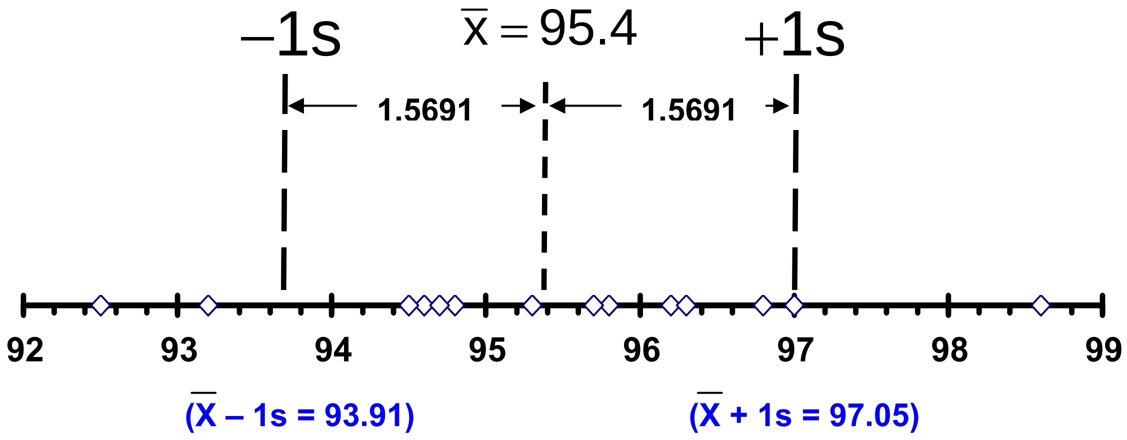
$$\mathbf{S} = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}} \quad \text{or} \quad \sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n}}$$

Typically for transportation construction, the formula used for standard deviation of a statistical sample is used. If the number (n) of random samples that comprise a statistical sample is greater than 30, agencies may use the Population Standard Deviation (σ). The standard deviation of a population is represented by the symbol "**σ**." It should be noted that the math formula for Population Standard Deviation uses an "n" factor in the denominator, whereas the math formula for standard deviation of a statistical sample uses "n – 1" in the denominator.

For the purposes of this manual, the user will normally use the Statistical Sample Standard Deviation (s), which is used for a small number of samples (n < 30). Statistical sample sizes of n < 30 are typically found in transportation construction.

Example 7-E: The standard deviation (s) for the fourteen (14) In-Place Density samples recorded in Example 7-A is computed as shown in the table below. The standard deviation was calculated and plotted on the chart below.

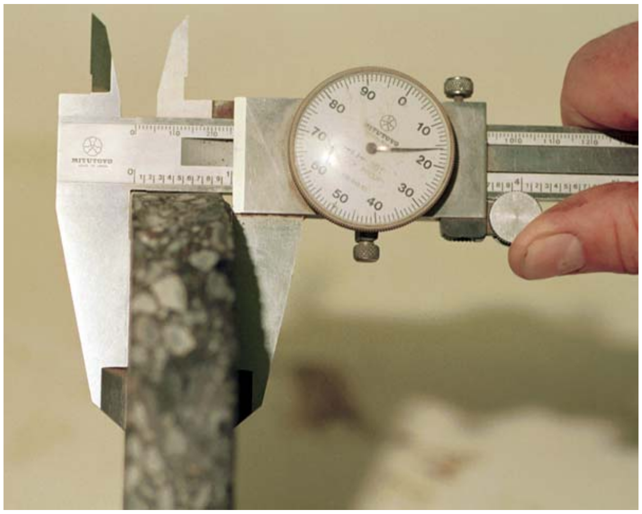
Variance:	**2.4622**
Standard Deviation (s) =	**1.5691**
Mean – s =	**95.48 – 1.5691 = 93.91**
Mean + s =	**95.48 + 1.5691 = 97.05**



7.6 - Precision, Accuracy, and Bias

The actual material sample test values obtained in transportation construction reflect errors of measurement as well as variation in the quality measured. Three key measurement terms that are used to describe the quality of sample test data and which are encountered in AASHTO and ASTM test methods, as well as in Quality Assurance Specifications, are precision, accuracy, and bias. Each of these terms will be explained below.

Definition of Precision



The term ***precision*** refers to the variability of a method of measurement when used to make repeated measurements under carefully controlled conditions. It relates to the degree of refinement or repeatability of a measurement. Accordingly, precision is defined by the *TRB Glossary of Quality Assurance Terms* and AASHTO R 10 as follows:

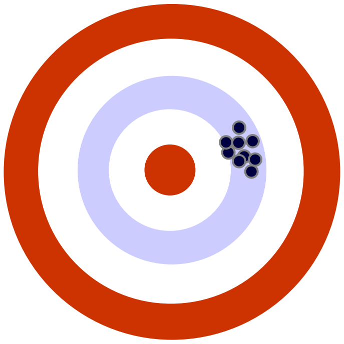
> **Precision** - "(1) The degree of agreement among a randomly selected series of measurements. (2) The degree to which tests or measurements on identical samples tend to produce the same results."

Precision is further defined by ASTM as, "a generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated."

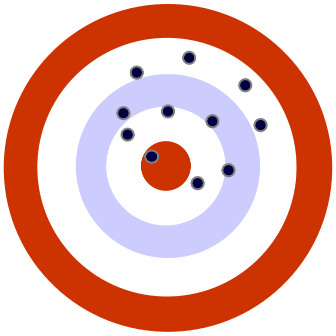
Let's look at some sample test results from a statistical sample which have been plotted on a bulls-eye target. The bulls-eye target has a tight pattern of test results.

When repeated test measurements are found to produce results very close to one another, we have a high level of precision (good precision).

Conversely, when repeated measurements are found to produce results which vary substantially from one another, we have a low level of precision (poor precision).



Good Precision



Poor Precision

Definition of Accuracy

The term ***accuracy*** refers to the absence of bias in a measurement. It represents the degree of conformity of the measurement to the true value of the Quality Characteristic being measured. Accordingly, accuracy is defined by the *TRB Glossary of Quality Assurance Terms* and AASHTO R 10 as follows:

> **Accuracy** - "The degree to which a measurement, or the mean of a distribution of measurements, tends to coincide with the true population mean."

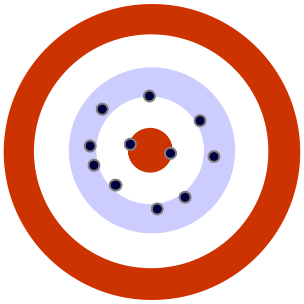
When the *true* population mean is not known (as with a statistical sample), the degree of agreement between the observed measurements and an accepted reference standard may be used to quantify the accuracy of the measurements.

Accuracy is further defined by ASTM as, “a generic concept of exactness related to the closeness of agreement between the average of one or more test results and an accepted reference value.”

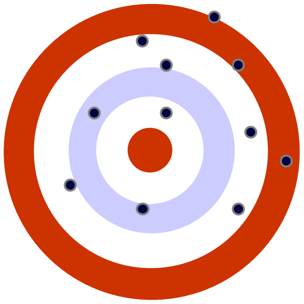
Although often used interchangeably, the terms accuracy and precision do not mean the same thing. In an engineering sense, accuracy denotes nearness to the truth or some value accepted as the truth, while precision relates to the degree of refinement or repeatability of a measurement.

Let’s look at a set of sample test results from another statistical sample which has been plotted on a bulls-eye target. The bulls-eye target indicates test results that are scattered and, yet, are uniformly grouped around the center.

When repeated test measurements are found to produce results very grouped around the center of the target or reference value, we have a high level of accuracy (good accuracy). Conversely, when repeated measurements are found to produce results which vary substantially from the target or reference value, we have a low level of accuracy (poor accuracy).



Good Accuracy



Poor Accuracy

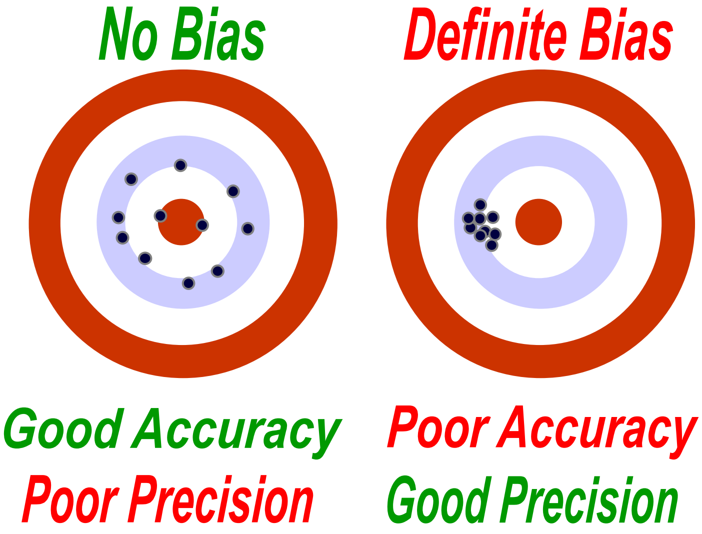
Definition of Bias

The term ***bias*** refers to an error, constant in direction, common to each of a set of test values, which cannot be eliminated by any process of averaging. It indicates a consistent lack of conformity of the measurements to the true value of the Quality Characteristic being measured. Accordingly, bias is defined by the *TRB Glossary of Quality Assurance Terms* and AASHTO R 10 as follows:

> **Bias** - "An error, constant in direction, that causes a measurement, or the mean of a distribution of measurements, to be offset from the true population mean."

Bias is further defined by ASTM as, "a generic concept related to a consistent or systematic difference between a set of test results from the process and an accepted reference value of the property being measured."

Now, let's compare sample test results from two separate statistical samples which have been plotted on separate bulls-eye targets. The first bulls-eye target indicates test results that are scattered and, yet, are very close to the center. The other target has a tight pattern of test results, but all of the results are grouped away from the center. The test results on the first bulls-eye represent a higher level of accuracy (good accuracy) while the results on the second bulls-eye indicate higher precision (good precision) with definite Bias.



An instrument with bias, but good precision can often be adjusted physically or mathematically to provide reliable single measurements. An instrument which produces scattered results, but good accuracy of results, can be used if enough measurements are made to provide a valid average.

Example 7-F: As an example, consider the measurement of the temperature of boiling water (100˚C) at standard atmospheric pressure by two thermometers.
Five separate readings were taken for each thermometer and the mean of the recorded values was determined. The results for each thermometer are shown in the table below.

Thermometer No. 1	**Thermometer No. 2**
101.2	100.6
101.1	99.2
101.2	98.9
101.1	101.0
101.2	100.3
Mean = 101.16˚ C	**Mean = 100.00˚ C**

Thermometer No. 1 shows very little fluctuation, but is off the known boiling point (100˚ C) on average by 1.2˚ C. It has good precision, but definite bias.

Thermometer No. 2 has a mean value equal to the known boiling point, but shows quite a bit of fluctuation between individual readings. It has accuracy within approximately ±1˚ C, but less precision than Thermometer No. 1.

While it might be preferable to use neither thermometer, Thermometer No. 1 could be employed if 1.2˚ C were subtracted from the mean of the recorded measurements. Thermometer No. 2 could be used if enough measurements were made to provide a valid mean.

Engineering and scientific instruments should be calibrated and compared against reference standards periodically to assure that measurements are accurate. If such checks are not performed, the accuracy is uncertain, no matter what the precision. Calibration of an instrument removes fixed error, leaving only random error for concern.

7.7 - Repeatability and Reproducibility

Definition of Repeatability

The term ***repeatability*** refers to the range within which repeated measurements are made by the same operator on the same testing apparatus. It is used to designate the level of test precision under a single operator. Accordingly, Repeatability is defined by the *TRB Glossary of Quality Assurance Terms* and AASHTO R 10 as follows:

> **Repeatability** - "The degree of variation among the test results obtained by the same operator repeating a test on the same material."

The term repeatability is used to designate test precision under a single operator.

Repeatability is further defined by ASTM as, "the closeness of agreement between test results obtained under repeatability conditions, that is, preferred conditions under which test results are obtained with the same test method in the same laboratory, by the same operator with the same equipment, in the shortest practical period of time, using test units or test specimens taken at random, from a single quantity of material that is as nearly homogeneous as possible."

Definition of Reproducibility

The term ***reproducibility*** refers to the consistency of the pattern of variation in testing. It measures the human influence or human error in the execution of a test. Accordingly, reproducibility is defined by the *TRB Glossary of Quality Assurance Terms* and AASHTO R 10 as follows:

> **Reproducibility** - "The degree of variation among the test results obtained by different operators performing the same test on the same material."

It measures the human influence or human error in the execution of a test. The term reproducibility is used to designate inter-laboratory test precision.

Reproducibility is further defined by ASTM as, "a generic term for a measure of precision applicable to the variability between single test results obtained in different laboratories using test specimens taken at random from a single sample of material."

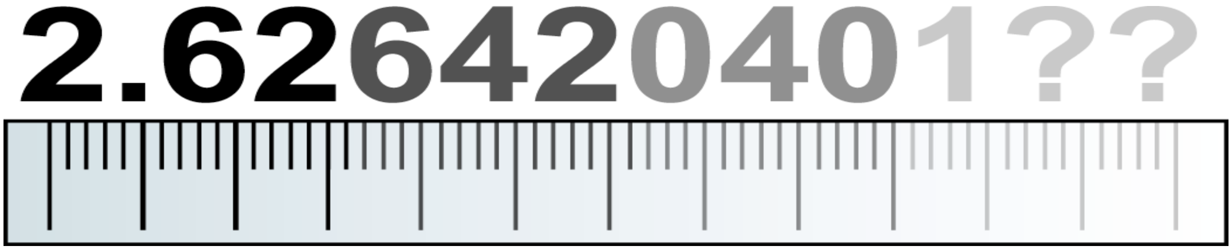
Repeatability and reproducibility are both dependent upon good precision and good accuracy in sampling and testing. When a material sample is obtained or a test is being performed, the following facts should be kept in mind:

- *Precision* depends on the preparations for testing, on the testing equipment, and on the care used in testing.
- *Accuracy* depends on the freedom from bias, on the number of increments or locations from which material samples are taken, and in some cases on the size of the sample.
- *Exactness* is approached and repeatability and reproducibility are improved as both the precision and accuracy are improved.

Mathematics has certain rules and procedures for making measurements and performing calculations that are well established. So do standardized test procedures. Sometimes these agree, but occasionally, they do not. Engineers and technicians must be familiar with both, but must follow standard test procedures in order to obtain valid, comparable results.

7.8 - Significant Figures

Significant Digits and Significant Figures



All measurements have some degree of uncertainty. How great the uncertainty is depends on both the accuracy of the measuring device and the skill of its operator. On a triple-beam platform balance, the mass of a sample substance can be measured to the nearest 0.1 g; mass differences less than this cannot be detected on this balance. We might therefore indicate the mass of a dime measured on this balance as 2.2 ± 0.1 g; the ± 0.1 (read plus or minus 0.1) is a measure of the accuracy of the numerical quantity.

It is important to have some indication of how accurately any measurement is made. The ± notation is one way to accomplish this. It is common to drop the ± notation with the understanding that there is uncertainty of at least one unit in the last digit of the measured quantity; that is, measured quantities are reported in such a way that only the last digit is uncertain. All of the digits, including the uncertain one, are called ***significant digits*** or, more commonly, ***significant figures***. For example, the number 2.2 has two significant figures, while the number 2.2405 has five significant figures.

The AASHTO standard that addresses significant digits or significant figures is **AASHTO R 11**, which is titled *Indicating Which Places of Figures are to be Considered Significant in Specified Limiting Values*. This standard is equivalent to **ASTM E 29**, which is titled, *Standard Practice for Using Significant Digits In Test Data to Determine Conformance with Specifications*. The terms significant digit and significant figure are used interchangeably. Accordingly, these terms are taken to mean the same thing in all subsequent discussion herein.

Definition of Significant Digit (or Significant Figure)

In recording a measured or calculated value, an indication of the accuracy attained is represented by the number of digits (i.e., significant digits or significant figures) recorded. Accordingly, the term significant digit is defined in AASHTO R 11 (ASTM E29) as follows:

> **Significant Digit** - “Any of the digits 0 through 9, excepting leading zeros and some trailing zeros, which is used with its place value to denote a numerical quantity to some desired approximation.”

The American Heritage Dictionary defines significant digits as follows:

> **Significant Digits** - “The digits of the decimal form of a number beginning with the leftmost nonzero digit and extending to the right to include all digits warranted by the accuracy of measuring devices used to obtain the numbers. Also called ***significant figures***.”

The number of significant figures in a calculated or measured value includes all positive (certain) digits plus one digit which is estimated. The significant figures in a measured or calculated value include each digit that is known (e.g., in the number 3.295, the 3, 2, and 9 are absolute quantities) and one digit whose accuracy is not exact (i.e., the 5, being the last digit). The last digit could have been estimated from a gauge or scale reading, rounded, or read from a vernier or other means. The number of significant figures in this example is considered to be four. As another example, a mass recorded as 100.53 grams is said to have five significant figures.

In order to be consistent with the theory of errors, it is essential that data be recorded with the correct number of significant figures. If a significant figure is dropped off in recording a value, the time spent in acquiring certain accuracy has been wasted. On the other hand, if values are recorded with more figures than those which are significant, false accuracy will be implied and time may be wasted in making computations.

Determining When Zero is a Significant Figure

The digit zero may either indicate a specific value or indicate place only. Rules contained in AASHTO R 11 for determining whether or not zeros are considered significant figures are as follows:

- Zeros leading the first nonzero digit of a number indicate order of magnitude only and are not significant figures. For example, the number 0.0034 has two significant figures (3 and 4).
- Zeros trailing the last nonzero digit for numbers represented with a decimal point are significant figures. For example, the numbers 1270. and 32.00 each have four significant figures.
- The significance of trailing zeros for numbers represented without use of a decimal point can only be identified from knowledge of the source value. For example, modulus strength stated as 140,000 Pa may have as few as two or as many as six significant figures.

Decimal Places versus Significant Figures

The number of significant figures is often confused with the number of ***decimal places***. Decimal places may have to be used to maintain the correct number of significant figures, but in themselves they do not indicate significant figures. Some examples of reported values and their corresponding significant figures and decimal places are as follows:

Reported Value	Significant Figures	Decimal Places
24	Two	None
2.4	Two	One
0.0024	Two	Four
365	Three	None
36.5	Three	One
0.0240	Three	Four
7636	Four	None
76.36	Four	Two
24.00	Four	Two

Rules for Significant Figures in Calculations

Mathematical rules exist for handling significant figures in different situations involving calculations. Transportation inspectors and technicians should follow the agency specification requirements (e.g., AASHTO, ASTM, state agency, FAA, FHWA or other) for providing the correct number of significant figures in their reported values for the particular test involved. Likewise, if an inspector or technician is utilizing a look-up table during computations or in following a prescribed procedure, then they must use the correct number of significant figures to properly approach the subject table. In all other cases, there are rules that can be used for adding or subtracting, for multiplication or division, and for the number of digits to use during an intermediate calculation. AASHTO has provided ***Standard Rules*** for retaining significant figures with addition, subtraction, multiplication and division, as presented below.

Significant Figures Retained with Addition or Subtraction

Standard rules for retaining significant figures when adding or subtracting are provided in AASHTO R 11. The rule when adding or subtracting test data is that the result shall contain no significant digits beyond the least place of the last significant digit of any datum. In short, when performing addition or subtraction, the number of significant figures reported in the sum or difference is determined by the least precise input. AASHTO R 11 provides the following examples:

(1) 11.24 + 9.3 + 6.32 = 26.9, since the last significant digit of 9.3 is the first following the decimal place, 26.9 is obtained by rounding the exact sum, 26.86, to this decimal place.

(2) 926 - 923.4 = 3

(3) 140,000 + 91,460 = 230,000 when the first value was recorded to the nearest ten thousand, 231,000 when the first value was recorded to the nearest thousand, 231,500 when the first value was recorded to the nearest hundred, 231,460 when the first value was recorded to the nearest ten.

Example 7-G: For each of the following three situations, determine the calculated value and report to the appropriate number of significant figures per AASHTO R 11.

Situation 1		**Situation 2**		**Situation 3**	
Calculation	**No. of Significant Figures**	**Calculation**	**No. of Significant Figures**	**Calculation**	**No. of Significant Figures**
				162 kg	(3)
35.67 kg	(4)	143.903 m	(6)	+ 33.546 kg	(5)
+ 423.938 kg	(6)	- 23.6 m	(3)	- .022 kg	(2)
= **459.61 kg**	**(5)**	= **120.3 m**	**(4)**	= **196 kg**	**(3)**
(NOT 459.608 kg)		(NOT 120.303 m)		(NOT 195.524 kg)	

Significant Figures Retained With Multiplication or Division

The rules differ for multiplication and division. Standard rules for retaining significant figures when multiplying or dividing are provided in AASHTO R 11. The rule when multiplying or dividing is that the result shall contain no more significant digits than the value with the smaller number of significant digits. AASHTO R 11 provides the following examples:

(1) 11.38 x 4.3 = 49, since the factor 4.3 has two significant digits.

(2) (926 - 923.4) / 4.3 = 0.60

Example 7-H: For each of the following three situations, determine the calculated value and report to the appropriate number of significant figures per AASHTO R 11.

Situation 1		Situation 2		Situation 3	
Calculation	No. of Significant Figures	Calculation	No. of Significant Figures	Calculation	No. of Significant Figures
19231 kg	(5)	61.2 m	(3)	0.3257 kg	(4)
X 0.0003 kg	(1)	X 5.3872 m	(5)	÷ 1.25 kg	(3)
= **6 kg^2**	**(1)**	= **330 m^2**	**(3)**	= **0.261 kg^2**	**(3)**
(NOT 5.7693033 kg)		(NOT 329.69664 m)		(NOT 0.26056 kg)	

Alternate Rule for Multiplication and Division

Besides the AASHTO Standard Rule, there is an ***Alternate Rule*** for retaining significant figures with multiplication and division. This Alternate Rule states that one should always use one more significant figure than suggested by the Standard Rule.

This Alternate Rule protects against the loss of valuable information. The "extra" significant digit that the Alternate Rule calls for ensures that it never discards valuable information. Thus, the Alternate Rule is more accurate and completely safe for data. The Alternate Rule is considered to be superior to the Standard Rule and, therefore, is recommended for use.

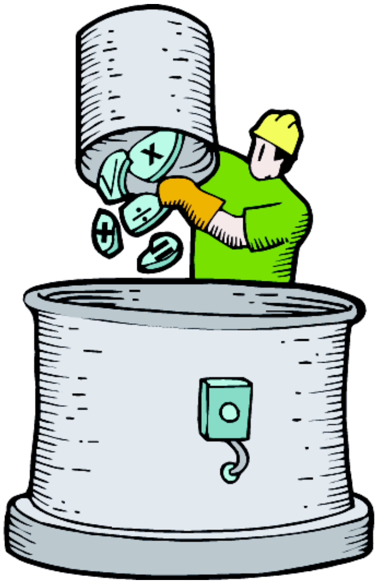
For example, when performing multiplication or division using the Alternate Rule, the number of significant figures reported in the product or quotient is determined by the least precise input plus one additional significant digit. Consider the following example.

Example 7-I: Using the same three situations presented in Example 7H, report the calculated values to the correct number of significant figures using the Alternate Rule.

Situation 1		**Situation 2**		**Situation 3**	
Calculation	**No. of Significant Figures**	**Calculation**	**No. of Significant Figures**	**Calculation**	**No. of Significant Figures**
19231 kg	(5)	61.2 m	(3)	0.3257 kg	(4)
X 0.0003 kg	(1)	X 5.3872 m	(5)	÷ 1.25 kg	(3)
= **5.8 kg^2**	**(2)**	= **329.7 m^2**	**(4)**	= **0.2606 kg^2**	**(4)**
(NOT 5.7693033 kg)		(NOT 329.69664 m)		(NOT 0.26056 kg)	

Note that 0.0003 has only one significant digit. Even though it carries four decimal places and appears to have that level of accuracy, the important consideration in multiplication and division is in preserving accuracy in the calculation. It is important to note that the three in 0.0003 is not absolute, it's an approximation. In multiplication and division, the important number in the decimal 0.0003 is three and the ten thousandths place functions more as units rather than a measure of accuracy. In that example we are multiplying by a number that could be anywhere from 0.0002500001 to 0.0003499999. To carry the calculated result to more than two significant figures would imply a level of accuracy that doesn't exist.

Significant Figures with Mixed Operations



The rules for determining significant figures to be retained with mixed operations involving addition, subtraction, multiplication, and/or division, are beyond the scope of this manual. AASHTO covers this topic to a certain extent in the section called "precision" or "precision and bias" included in many test methods. The reader is directed to the AASHTO Test Methods if more detail is desired.

Significant Figures Retained In Intermediate Calculations

Standard Rules for retaining significant figures during intermediate calculations are provided in AASHTO R 11. The rule when calculating a test result from test data is to avoid rounding of intermediate quantities. As far as is practicable with the calculating device or form used, carry out calculations with the test data exactly and <u>round only the final result</u>. AASHTO R 11 provides the following examples of intermediate calculations:

a. $\sqrt{12} = 3.4641016$

b. $23.59 + 8.32579 = 31.91579$

c. $1 / 30 = 0.0333333333333….$

All of these are examples of intermediate calculations, not final results, so they are not rounded. Most calculations are typically done on a calculator or spreadsheet and any infinite series such as 1 / 3 will be rounded to the default used by the spreadsheet or calculator.

Reporting Final Calculated Value in Meaningful Manner

The correct decision in reporting a calculated value depends on what future use is to be made of the value. If it is to be combined with other data, the rules should be the same as those presented above for intermediate computed values. If the reported value is the final calculated value, the number of significant figures retained should be based on this value.

In engineering work, it is generally agreed that a digit is significant if there is a 50-50 chance that the same digit would be obtained when new data are used for making similar calculations.

7.9 - Rounding

Definition of Rounding

When reporting a value to the required number of significant figures, ***rounding*** of the measured or calculated values is usually necessary. Rounding applies where it is the intent that a limited number of digits in an observed value or a calculated value are to be considered significant. Accordingly, rounding is defined as follows:

> **Rounding** - “The process of dropping one or more digits so that the reported value contains only those digits which are significant or necessary in subsequent computations.”

When rounding, the last digit to be retained is increased (rounding up), or left unchanged (rounding down) after measurement or calculation. Rules for rounding are contained in AASHTO R 11 (ASTM E 29). As stated in AASHTO R 11, there are two commonly accepted methods of rounding data, identified as the ***Absolute Method*** and the ***Rounding Method***. The method of rounding required will normally be specified by the individual AASHTO Test Methods and by the Transportation Agency construction specifications. Each of these methods is explained below.

Absolute Method

The Absolute Method for rounding values is described in AASHTO R 11 as follows:

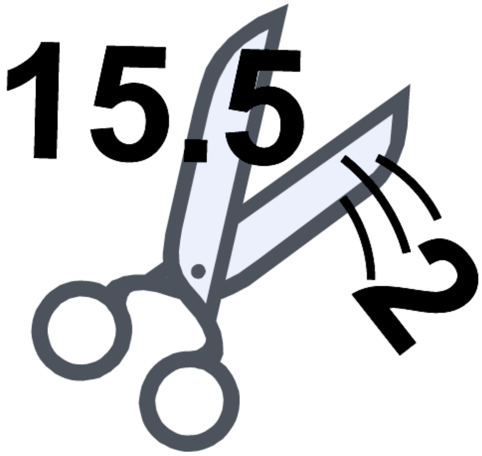
Where Applicable – The Absolute Method applies where it is the intent that all digits in an observed value or a calculated value are to be considered significant for purposes of determining conformance with specifications. Under these conditions, the specified limits are referred to as absolute limits.

How Applied – With the Absolute Method, an observed value or a calculated value is not to be rounded, but is to be compared directly with the specified limiting value. Conformance or nonconformance with the specification is based on this comparison.

Rounding Method

The Rounding Method for rounding values is described in AASHTO R 11 as follows:

Where applicable – The Rounding Method applies where it is the intent that a limited number of digits in an observed value or a calculated value are to be considered significant for purposes of determining conformance with specifications.



How Applied – With the Rounding Method, an observed value or a calculated value should be rounded …to the nearest unit in the designated place of figures stated in the standard, as, for example, “to the nearest kPa”, to the nearest 10 ohms,” “to the nearest 0.1 percent,” etc. The rounded value should then be compared with the specified limit, and conformance or nonconformance with the specification based on this comparison.

AASHTO Rounding Procedures

In order to understand the procedures for rounding required by AASHTO R 11, let's review the following ***rounding rules*** contained therein:

AASHTO R 11 - ROUNDING RULE A

Digit Following Last Digit to Be Retained < 5:

- If the digit following the last digit to be retained is a 0,1,2,3, or 4, then strike out that digit and all following digits. For example:

  53.43 ⇨ reported to three significant figures = **53.4**

  28.69248539 ⇨ reported to five significant figures = **28.692**

AASHTO R 11 - ROUNDING RULE B

Digit Following Last Digit to Be Retained > 5:

- If the digit following the last digit to be retained is a 6, 7, 8, or 9, then increase the last digit to be retained by 1 and strike out all the following digits. For example:

  53.67 ⇨ reported to three significant figures = **53.7**

  28.69248539 ⇨ reported to three significant figures = **28.7**

AASHTO R 11 - ROUNDING RULE C

Digit Following Last Digit to Be Retained = 5 (Digits Right > 0):

- If the digit following the last digit to be retained is 5 and there are digits other than zero to the right of that 5, increase the last digit to be retained by 1 and strike out all the following digits. For example:

53.652 ⇨ reported to three significant figures = **53.7**

28.69248539 ⇨ reported to seven significant figures = **28.69249**

AASHTO R 11 - ROUNDING RULE D

Digit Following Last Digit to Be Retained = 5 (Digits Right = 0):

- If the digit following the last digit to be kept is 5 and there are no digits other than zeros beyond that 5, increase the last digit to be retained by 1 if it is odd or leave it unchanged if it is even or zero. For example:

53.650 ⇨ reported to three significant figures = **53.6**

28.692475 ⇨ reported to seven significant figures = **28.69248**

28.69248500 ⇨ reported to seven significant figures = **28.69248**

Example 7-J: Using the calculated values and required number of significant figures given below, report the appropriate rounded value per AASHTO R 11 Rounding Rule D.

Calculated Value	Significant Figures Reported	Rounded Value
15.675	4	15.68
234.5	3	234
419.500	3	420
11.2345000	5	11.234
65.55	3	65.6
43.0205	5	43.020

AASHTO R 11 - ROUNDING RULE E

Direct Rounding:

- The rounded-off value should be obtained in one step by direct rounding off of the most precise value available and not in two or more steps of successive rounding. For example:

  89490 ⇨ rounded to nearest 1000 in one step = **89000**

  Incorrect:

  (**89490** ⇨ rounded to nearest 100 = 89500 ⇨ rounded to nearest 1000 = **90000**)

Exceptions to Rules for Significant Figures and Rounding

While the mathematical rules of significant figures and rounding have been established in AASHTO R 11, they are not always followed. For example, AASHTO Method of Test T 176, *Plastic Fines in Graded Aggregates and Soils by the Use of the Sand Equivalent Test,* prescribes a method for rounding and significant figures in conflict with the AASHTO R 11 rules.

In this procedure, readings and calculated values are always rounded up to two significant figures. The rounded numbers are then used to calculate the Sand Equivalent, which is the ratio of the rounded sand reading to the rounded clay reading multiplied by 100.

For example, using a clay reading of 7.94 and a sand reading of 3.21, the Sand Equivalent is calculated as follows:

(3.21 ⇨ rounded up = 3.3)
(7.94 ⇨ rounded up = 8.0)

$$\frac{3.3}{8.0} \times 100 = 41.250...$$

Rounded to 41.3 and reported as **42**

$$\text{Not}: \frac{3.21}{7.94} \times 100 = 40.428...$$

Rounded to 40.0 and reported as **40**

It is extremely important that engineers and technicians understand the rules of rounding.

Rounding by Calculators or Computers

It should be recognized however, that calculators and computers do not always adhere to the rounding rules found in AASHTO R 11. For example, if the number being rounded ends with a 5, two possibilities exist when following AASHTO R 11. In this mathematically sound approach, numbers are rounded up or down depending on whether the number to the left of the 5 is odd or even. This procedure avoids the bias that would exist if all numbers ending in 5 were rounded up or all numbers were rounded down.

In some calculators, however, all rounding is up. This does result in some bias, or skewing of data, but the bias may or may not be significant to the calculations at hand. Nonetheless, most agencies perform calculations on calculators or computers and accept the same from contractors.

A comparison of rounding observed or calculated values to four significant figures using AASHTO R 11 and rounding the same values using a calculator or computer that always rounds up is as follows:

Observed or Calculated Value	Rounding per AASHTO R 11	Rounding per Computer
102.25	102.2	102.3
102.35	102.4	102.4
102.45	102.4	102.5
102.55	102.6	102.6

Notwithstanding the use of calculators and computers which may round differently, the determination of proper rounding and the reporting of appropriate significant figures should be in accordance with the Quality Assurance Specifications being used.

Example 7-K: Using the calculated values given below and the rules for rounding, state the final value to 5 significant figures and indicate the rounding rule used.

Calculated Values	Rounded Values	Rounding Rule Used
28.6944999	**28.694**	**Rule A**
28.6554999	**28.655**	**Rule A**
99.9994999	**99.999**	**Rule A**
98.9995000	**99.000**	**Rule D**
98.9999999	**99.000**	**Rule B**
98.8885000	**98.888**	**Rule D**
89.8985001	**89.899**	**Rule C**
89.8915000	**89.892**	**Rule D**
89.8905000	**89.890**	**Rule D**

- END OF CHAPTER 7 -

CHAPTER 8

Mathematical Tools for Quality Assurance

Chapter 8

Mathematical Tools for Quality Assurance

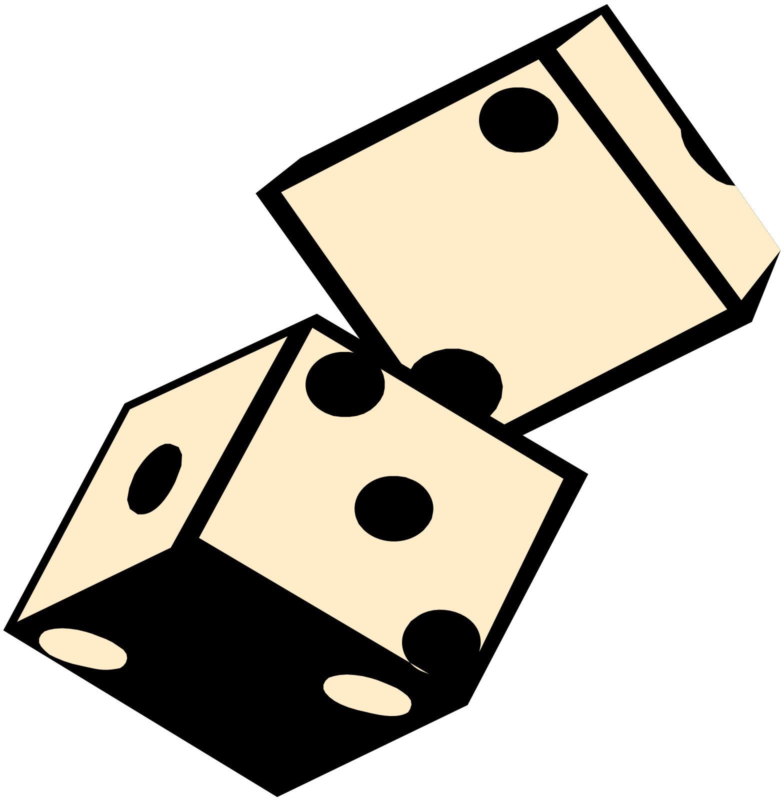
Chapter Overview

In this chapter, the following mathematical tools used in Quality Assurance are presented:

8.1 - Using Random Numbers

Standard Practice for Random Sampling of Construction Materials

As explained in Chapter 4, most Quality Control samples and all Acceptance samples should be selected through random sampling. Each agency should specify the method to be used to randomly determine the location of samples. Such methods may include the use of a spreadsheet provided by the agency, random number generator function on a hand held calculator, or a procedure using random number tables provided by the agency.



Example Applications of Random Numbers

Example 8-A: 2500 tons (2268 Mg) of HMA was produced during one day at a plant. The agency QA Specifications identify a lot size of 10,000 tons (9072 Mg) and a sublot size of 500 tons (454 Mg). The QA Specifications require that one sample be obtained for each sublot from the truck at the plant in order to determine laboratory air voids and asphalt binder content. Using this information, determine the points at which material samples should be taken (to the nearest ton)

(Note: In the following examples, SI (metric) units in parenthesis are hard (approximate) metric conversions of the Imperial (US) units that have been rounded (using AASHTO rules) to the nearest Mg. Subsequent calculations for sample locations in SI are based on the original hard conversion. Solutions for examples therefore should not be construed as precise conversions from Imperial to Metric.)

1) What is the size of each sublot?

The sublot size was defined by the agency as 500 tons (454 Mg). If 2500 tons (2268 Mg) were produced in one day, that day would contain 5 sublots determined as follows:

2500 tons (2268 Mg) / 500 tons (454 Mg) /sublot = **5 sublots**

2) Random numbers should be developed using the state's method. Using the random numbers already provided in the chart below, what is the point at which the random sample within each sublot should be obtained (to the nearest ton (Mg)?

Sublot #	Random #		Sublot Size in tons (Mg)		Sampling Location within Sublot, nearest ton (Mg)
1	**0.3164**	X	500 (454)	=	**158 tons (144 Mg)**
2	**0.7267**	X	500 (454)	=	**363 tons (330 Mg)**
3	**0.7022**	X	500 (454)	=	**351 tons (319 Mg)**
4	**0.1217**	X	500 (454)	=	**61 tons (55 Mg)**
5	**0.1124**	X	500 (454)	=	**56 tons (51 Mg)**

3) What are the sampling locations from the beginning of the lot at which the random samples for each sublot must be obtained?

Example 8-A –Sampling Locations from Beginning of Lot					
Sublot #	**Sampling Location from Start of Sublot**		**Distance from Start of Lot to Start of Sublot**		**Sampling Location from Start of Lot**
1	158 tons (144 Mg)	+	0	=	**158 tons (144 Mg)**
2	363 tons (330 Mg)	+	500 tons (454 Mg)	=	**863 tons (784 Mg)**
3	351 tons (319 Mg)	+	1000 tons (908 Mg)	=	**1351 tons (1227 Mg)**
4	61 tons (55 Mg)	+	1500 tons (1362 Mg)	=	**1561 tons (1417 Mg)**
5	56 tons (51 Mg)	+	2000 tons (1816 Mg)	=	**2056 tons (1867 Mg)**

Example 8-B: A reinforced PCC bridge deck has been placed. The depth of cover over the reinforcing steel must be tested. The agency Quality Assurance Specifications define a lot as the entire bridge deck. In accordance with the Quality Assurance Specifications, each bridge deck lot is to be divided into five sublots based on the total deck length. Actual test locations within each sublot are to be determined using a stratified random sampling procedure. The dimensions of the deck are 350 ft. (107 m) in length by 42 ft. (13 m) wide.

1) What is the size of each sublot for cover measurements?

Since the QA Specification indicated that each deck be divided into five sublots based on length, and the total length of the bridge deck poured was 350 ft. (107 m), the sublot size is calculated as follows:

350 ft. (107 m) / 5 sublots = **70 ft. (21.4 m) / sublot**

2) Assume that random numbers were developed using the state's method. What is the longitudinal location of the random sample for each sublot measured from the beginning of the sublot (to the nearest ft.)?

Sublot #	Random #		Sublot Size, ft. (m)		Sampling Location, ft. (m)
1	**0.5506**	X	70 (21.4)	=	**39** **(12)**
2	**0.4383**	X	70 (21.4)	=	**31** **(9)**
3	**0.9789**	X	70 (21.4)	=	**69** **(21)**
4	**0.2958**	X	70 (21.4)	=	**21** **(6)**
5	**0.5903**	X	70 (21.4)	=	**41** **(13)**

3) What is the longitudinal location of the random sample for each sublot measured from the beginning of the lot (to the nearest ft (m)?

Example 8-B –Longitudinal Sampling Locations from Beginning of Lot					
Sublot #	**Sampling Location from Start of Sublot**		**Distance from Start of Lot to Start of Sublot**		**Sampling Location from Start of Lot**
1	**39 ft. (12 m)**	+	0	=	**39 ft. (12 m)**
2	**31 ft. (9 m)**	+	70 ft. (21.4 m)	=	**101 ft. (30 m)**
3	**69 ft. (21 m)**	+	140 ft. (42.8 m)	=	**209 ft. (64 m)**
4	**21 ft. (6 m)**	+	210 ft. (64.2 m)	=	**231 ft. (70 m)**
5	**41 ft. (13 m)**	+	280 ft. (85.6 m)	=	**321 ft. (99 m)**

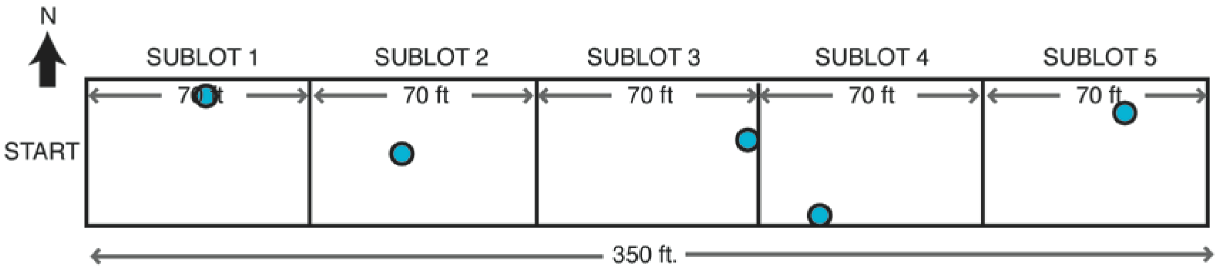
4) Assume that random numbers (given below) were developed using the state's method. Determine the transverse offset location of the random sample for each sublot measured from the right edge (south side) of the 42-ft. wide deck (to the nearest 0.1 ft.).

Sublot #	**Random #**		**Sublot Size, ft. (m)**		**Sampling Location, ft. (m)**
1	**0.9108**	X	42 (13)	=	**38.3** **(**11**.8)**
2	**0.4169**	X	42 (13)	=	**17.5** **(5.4)**
3	**0.4469**	X	42 (13)	=	**18.8** **(5.8)**
4	**0.0056**	X	42 (13)	=	**0.2** **(0.1)**
5	**0.7568**	X	42 (13)	=	**31.8** **(9.8)**

5) Summarize the random sampling location for each sublot.

Example 8-B – Summary of Random Sampling Location for Each Sublot			
Sublot Number	**Longitudinal Sampling Location from Start of Sublot**	**Longitudinal Sampling Location from Start of Lot**	**Transverse Offset Sampling Location from Right Edge**
1	**39 ft. (12 m)**	**39 ft. (12 m)**	**38.3 ft. (11.8 m)**
2	**31 ft. (9 m)**	**101 ft. (30 m)**	**17.5 ft. (5.4 m)**
3	**69 ft. (21 m)**	**209 ft. (64 m)**	**18.8 ft. (5.8 m)**
4	**21 ft. (6 m)**	**231 ft. (70 m)**	**0.2 ft. (0.1 m)**
5	**41 ft. (13 m)**	**321 ft. (99 m)**	**31.8 ft. (9.8 m)**

6) Indicate the approximate location of the random sample for each sublot on the sketch below.



8.2 - Using the Mean

Calculating the Mean

The mean is a powerful mathematical tool in Quality Assurance that can be used to help make a reasonable determination (estimate) of the quality of a given population (lot). As presented in Chapter 7, the mean ($\overline{X}$) is simply the average of all of the individual sample measurements or test results obtained from a population (lot). The mean has an important relationship to the concept of normal distribution, which will be discussed below.

$$\overline{x} = \frac{\sum x_i}{n}$$

Example Applications of the Mean

The following table lists the batting averages for six baseball players over a five month period. While the average (mean) of each player differs from month to month as the table indicates, the overall average (mean) for five months is identical for all six players.

Player	**Babe**	**Honus**	**Ty**	**Eddie**	**Lou**	**Cap**
April	100	200	180	50	0	0
May	150	200	190	415	500	125
June	200	200	200	375	0	125
July	250	200	210	105	450	250
August	300	200	220	55	50	500
Sum (ΣX_i)	1000	1000	1000	1000	1000	1000
Number of samples (n)	5	5	5	5	5	5
Average (Mean) ($\overline{X} = \Sigma X_i / n$)	**200.0**	**200.0**	**200.0**	**200.0**	**200.0**	**200.0**

Example 8-C: Using the Air Void test results and Asphalt Binder Content test results from the five HMA samples randomly located in Example 8-A, calculate the mean for each Quality Characteristic.

Sample	**Air Voids (X_i)**	**Binder Content (X_i)**
Sublot 1	8.2	5.7
Sublot 2	3.9	5.7
Sublot 3	4.7	4.8
Sublot 4	5.4	5.2
Sublot 5	4.1	5.4
Sum (ΣX_i)	26.3	26.8
Number of samples (n)	5	5
Mean ($\overline{X} = \Sigma X_i / n$) =	**5.26**	**5.36**

Example 8-D: Using the test results from the five PCC cover over steel measurements obtained randomly in Example 8-B, calculate the mean value.

Sample	**Cover Measurement, in. (mm)**
Sublot 1	2.13 (54)
Sublot 2	2.64 (67)
Sublot 3	2.24 (57)
Sublot 4	1.89 (48)
Sublot 5	2.32 (59)
Sum (ΣX_i)	11.22 (285)
Number of samples (n)	5
Mean ($\overline{X} = \Sigma X_i / n$) =	**2.244 (57.0)**

8.3 - Range of Data

Calculating the Range

$$R = (x_{High} - x_{Low})$$

The range of data provides a basic spread or the largest expected variation within a set of data. As presented in Chapter 7, the range (**R**) is simply the difference between the highest and lowest individual sample measurements or test results obtained from a population (lot).

Example Applications of the Range

Continuing with the batting average example in Section 8.2, the range of each player's monthly average is presented below.

Player	**Babe**	**Honus**	**Ty**	**Eddie**	**Lou**	**Cap**
April	100	200	180	50	0	0
May	150	200	190	415	500	125
June	200	200	200	375	0	125
July	250	200	210	105	450	250
August	300	200	220	55	50	500
Sum (ΣX_i)	1000	1000	1000	1000	1000	1000
Number of samples (n)	5	5	5	5	5	5
Mean **($\bar{X} = \Sigma X_i / n$)**	200.0	200.0	200.0	200.0	200.0	200.0
High (x_{High})	300	200	220	415	500	500
Low (x_{Low})	100	200	180	50	0	0
Range = ($x_{High} - x_{Low}$)	**200**	**0**	**40**	**365**	**500**	**500**

The player who hits most consistently is Honus (whose monthly range from his overall average is 0). Lou and Cap show the highest range (500) from their monthly averages (means), making them the most inconsistent (despite having some significantly better months than Honus).

As a tool that measures variability, the range value provides additional information (beyond that of just the mean) that can be useful in making informed decisions. Simply using the mean and the range for the players (i.e., without assessing other trends in the data), Honus might be the player selected as the most likely batter to get a hit since Honus has shown the most month-to-month consistency.

Example 8-E: Using the Air Void test results and Asphalt Binder Content test results from the five HMA samples randomly located in Example 8-A, calculate the range for each Quality Characteristic.

Sample	**Air Voids (X_i)**	**Binder Content (X_i)**
Sublot 1	8.2	5.7
Sublot 2	3.9	5.7
Sublot 3	4.7	4.8
Sublot 4	5.4	5.2
Sublot 5	4.1	5.4
Sum (ΣX_i)	26.3	26.8
Number of samples (n)	5	5
Mean ($\overline{X} = \Sigma X_i / n$)	5.26	5.36
High (x_{High})	8.2	5.7
Low (x_{Low})	3.9	4.8
Range ($x_{High} - x_{Low}$) =	**4.3**	**0.9**

Example 8-F: Using the test results from the five PCC cover over steel measurements obtained randomly in Example 8-B, calculate the range value.

Sample	Cover Measurement, in. (mm)
Sublot 1	2.13 (54)
Sublot 2	2.64 (67)
Sublot 3	2.24 (57)
Sublot 4	1.89 (48)
Sublot 5	2.32 (59)
Sum (ΣX_i)	11.22 (285)
Number of samples (n)	5
Mean ($\bar{X} = \Sigma X_i / n$)	**2.244 (57.0)**
High (x_{High})	2.64 (67)
Low (x_{Low})	1.89 (48)
Range ($x_{High} - x_{Low}$) =	**0.75 (19)**

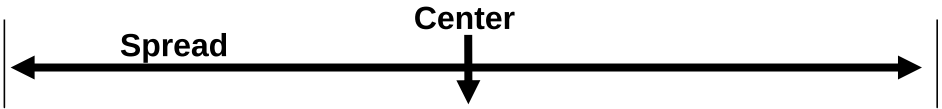
8.4 - Distribution of Sample Data

Frequency Distribution

A ***frequency distribution*** is simply an expression of the frequency of occurrence of data values (or pre-assigned ranges of values) within a set of measurements or test data gathered from a population.

The intervals selected for grouping data (sometimes referred to as bins or classes) are shown on a horizontal axis and the frequencies of occurrence within the selected intervals will be shown on the vertical axis.

Consider the following example. A stockpile of aggregate (call this the lot or population) was sampled and the percentage of the aggregate passing the 1 in. (25 mm) sieve was determined for 126 randomly selected material samples. The results were recorded on a form as samples were tested. Once all the testing was completed, the results were arranged in order of percent passing the 1 in. (25 mm) sieve (lowest to highest) so that the frequency of each occurrence could be established. From this grouping of data, the center (mean) and the spread (range) of the data was determined as shown below.



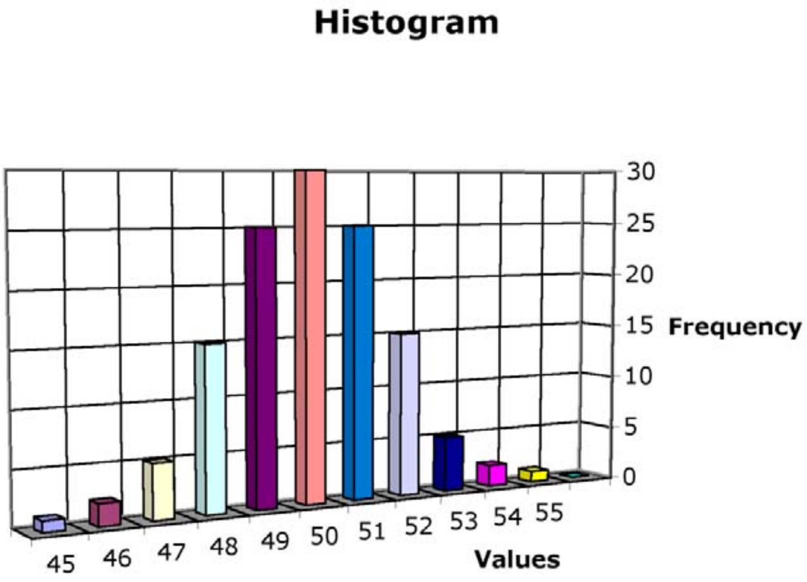
%	45	46	47	48	49	50	51	52	53	54	55	Total
Freq.	1	2	5	15	25	30	25	15	5	2	1	126

The following observations were made from this frequency distribution:

- There were 11 different intervals (the bins or classes) within which all the sample test results were grouped.
- The center (mean) of the test results was 50% passing the 1 in. (25 mm) sieve.
- The spread (range) of the sample test results was from 45 to 55 percent passing the 1 in. (25 mm) sieve.

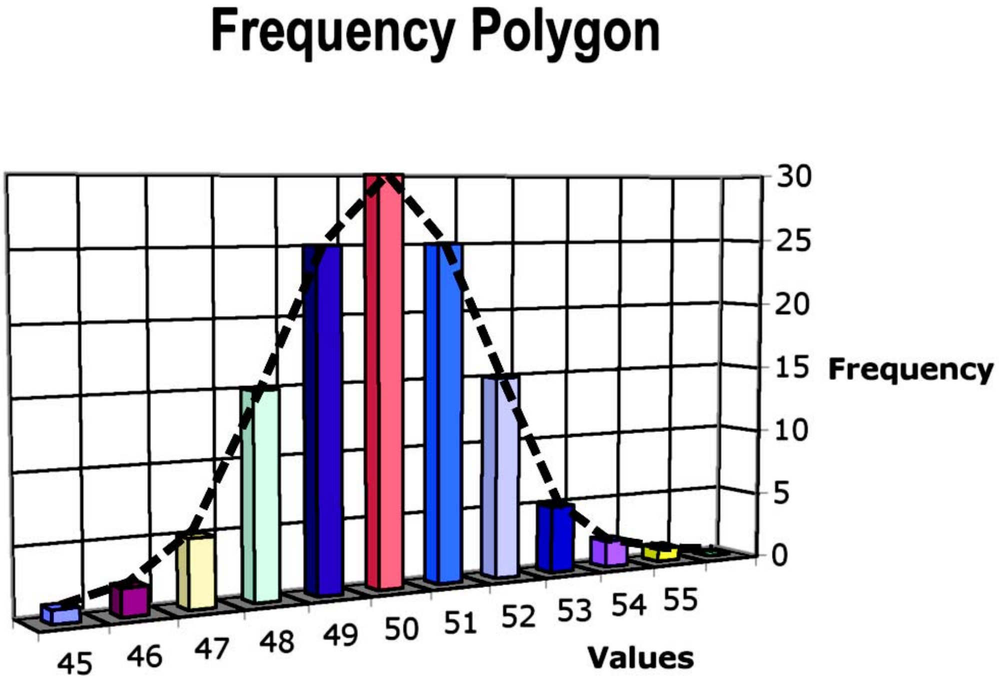
Histogram

A ***histogram*** is a graphical plot of a frequency distribution. A histogram is a particularly informative way of presenting data because it can be used to estimate quickly the center (mean) and find the spread or dispersion (range) and extreme values in the data. A histogram depicts the frequency of occurrence of a measured or tested value as a stack. The histogram below represents the data from the frequency distribution above. The horizontal axis represents the *values* obtained for the percent passing the 1 in. (25 mm) sieve. The height of each stack (represented by the vertical axis) indicates the number of times that a test value occurred (the *frequency*).



Frequency Polygon

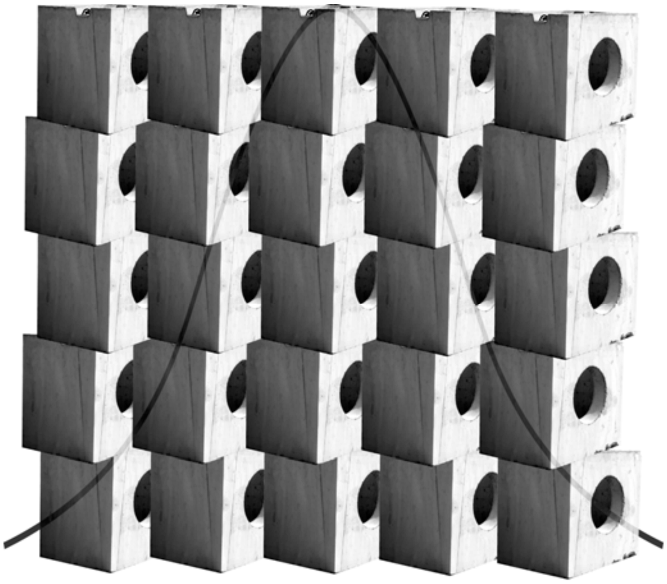
When the midpoints of the stacks of a histogram are connected a bumpy curve is formed. The bumpy curve is called a ***frequency polygon***. The bumpy curve is then generally smoothed out (approximating the original data) in order to arrive at a singular curve that can be used for estimating purposes. The curve that resulted from the gradation results passing the 1 in. (25 mm) sieve has a smooth bell shape. When a population exhibits this type of frequency distribution it is said to be normally distributed. The smooth bell-shaped curve is referred to as a normal distribution curve and will be further discussed below (Section 8.5).



8.5 - Normal Distributions

Normal Distribution Curves Representing Individual Samples

As has been discussed, sampling involves looking at the quality of a *part* (e.g., statistical sample comprised of multiple individual material samples) as evidence of the quality of the *whole* (population or lot). Multiple randomly selected material samples may be used to estimate the properties of an entire lot of construction materials.



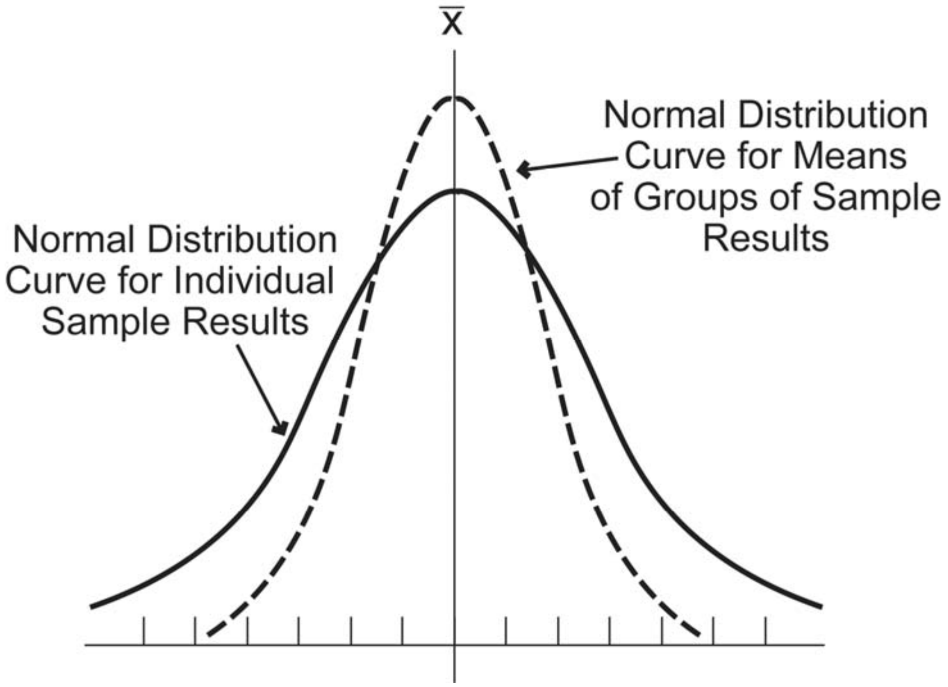
In the previous aggregate stockpile gradation example, a statistical sample of 126 individual material samples was randomly obtained and the frequency distribution for the individual sample test results was plotted. As illustrated in the example, the individual samples representing a population (lot) of construction materials (in terms of the specified Quality Characteristics to be measured) will generally form a frequency distribution close to a ***normal distribution curve***. Examples of Quality Characteristics that have been shown to produce normal distributions include asphalt binder content of HMA, particle distribution for processed aggregates, PCC compressive strength and air content, etc.

In short, the frequency distribution for multiple individual material samples obtained from a lot (of most construction materials) will be represented by a corresponding normal distribution curve. In order to fully describe the normal distribution curve for a given lot, the mean ($\overline{X}$) and the standard deviation (s) for the lot must be known. The mean, will coincide with the center of the normal distribution curve. The standard deviation determines the shape of the normal distribution curve.

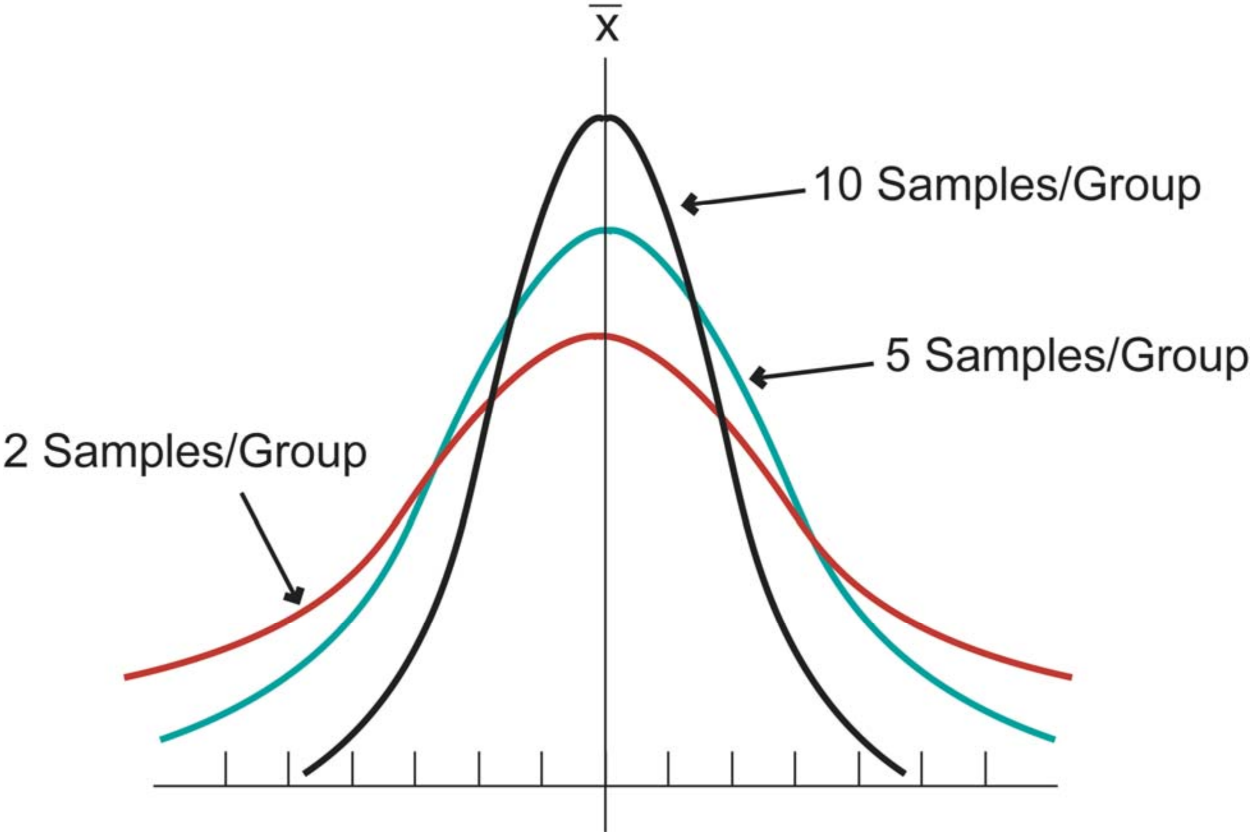
Normal Distribution Curves Representing Sample Group Means

As discussed above, multiple individual material samples obtained from a lot will be represented by a corresponding normal distribution curve. This relationship is useful in measuring the quality of a lot. However, there are other Quality Assurance applications where the distribution of the means of groups of samples (referred to as ***sample means***) may be used, rather than the distribution of individual samples. Particular applications where the distribution of sample means is used include the development of Specification Limits and when establishing control chart limits.

The shape of the distribution of sample means can be derived from the ***Central Limit Theorem***. The Central Limit Theorem states that even if the shape of the population distribution is not normal, the means of sample groups (for groups of n > 1) drawn from the population will approach a normal distribution as the size of the sample groups approaches infinity ($n \Rightarrow \infty$). The normal distribution curve representing sample means will always be narrower than the normal distribution curve representing multiple individual material samples, as shown in the figure below.



For example, let's assume that 100 samples were randomly obtained from a lot and that the samples were then randomly split into groups of 2, 5, and 10 samples/group. If the mean was calculated for each group of samples (i.e., the sample means) and the sample means were then plotted for each set of groups, the corresponding normal distribution curve for each set of sample means would look something like the figure below.



Some significant characteristics of a normal distribution curve for the means of sample groups (i.e., the sample means) include the following:

- Using the sample means removes the influence of extreme individual values.
- The distribution formed by the sample means (e.g., 2 samples/group, 5 samples/group, 10 samples/group) is always narrower than the distribution formed by the individual values.
- The center of the distribution formed by the sample means is the same as the center of the distribution formed by the individual values.
- The more samples used per group, the less the spread of the distribution of the sample means.

8.6 - Using Standard Deviation and Spread of Data

Calculating Standard Deviation

$$s = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n-1}}$$

The standard deviation (s) gives an indication of how closely individual material sample measurements or test values are bunched around the mean. As presented in Chapter 7, the standard deviation of a statistical sample (s) is calculated by taking the square root of the variance (s^2) of all of the individual sample test results obtained from a lot.

This mathematical expression is no more than a way for us to determine what the overall variability is for a lot of material. To put it in other terms, the standard deviation provides a measurement tool to express how many of the test result values lie within a certain distance from the mean value. If the standard deviation is large, the individual sample test results are widely scattered around the mean (i.e., there is greater variability). A smaller standard deviation value indicates that most of the test result values are very close to the mean (i.e., lower variability).

Example Applications of Standard Deviation

Continuing with the baseball batting averages examples used to illustrate the mean in Section 8.2 and range in Section 8.3, let's assume that it is now September. Based on the data provided about the past 5 months, which player has the best chance to make the hits that will help his team make the playoffs?

Evaluation of Team Member's Batting Averages						
Month	**Babe**	**Honus**	**Ty**	**Eddie**	**Lou**	**Cap**
April	100	0	25	0	0	0
May	150	0	190	500	500	0
June	25	200	50	340	0	0
July	200	300	210	105	450	500
August	525	500	525	55	50	500
Sum (ΣX_i)	1000	1000	1000	1000	1000	1000
Number of samples (n)	5	5	5	5	5	5
Mean ($\bar{X} = \Sigma X_i / n$)	200.0	200.0	200.0	200.0	200.0	200.0
High (x_{High})	525	500	525	500	500	500
Low (x_{Low})	25	0	25	0	0	0
Range ($x_{High} - x_{Low}$)	**500**	**500**	**500**	**500**	**500**	**500**

The range of data was previously used in the example in Section 8.3 to determine the most consistent player. However, as we can see from the new data above, all players now show the same average (mean) and the same range. Another measuring tool is needed to determine which player is most likely to get a hit. Standard deviation is that tool, as it is no more than another way to measure variation of data from a group's mean.

Accordingly, the standard deviation for each player's batting average is calculated below.

The standard deviation for the first player's batting average (Babe) over the last five months is calculated below in a step-by-step manner to exemplify the calculation. Batting average standard deviations are reported to the nearest whole number for simplicity's sake.

Calculation of Standard Deviation for Babe's Batting Average

Month	Batting Avg. (X_i)	Overall Mean ($\overline{X}$)	$x_i - \overline{x}$	$(x_i - \overline{x})^2$
April	100	200	-100	10,000
May	150	200	-50	2,500
June	25	200	-175	30,625
July	200	200	0	0
August	525	200	325	105,625
	$\overline{X}$ =	200.0		$\sum(x_i - \overline{x})^2$ = 148,750

n = 5

Mean ($\overline{X}$) = 200.0

$$\sum(x_i - \overline{x})^2 = 148,750$$

$$\frac{\sum(x_i - \overline{x})^2}{n-1} = 37,187.5$$

$$s = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n-1}} = 192.84$$

s = 193

The standard deviations for the rest of the players' batting averages over the last five months were calculated and were recorded as follows:

Standard Deviation for Batting Averages of All Team Members			
Player	**Mean** **($\overline{X}$)**	**Range** ($x_{High} - x_{Low}$)	**Standard Deviation (s)**
Babe	200.0	500	**193**
Honus	200.0	500	**212**
Ty	200.0	500	**199**
Eddie	200.0	500	**212**
Lou	200.0	500	**252**
Cap	200.0	500	**274**

Now that all of the data has been calculated, we can see that Babe exhibits the smallest variation from his mean of 200 (standard deviation = 193). Therefore, simply using the standard deviation for the players (i.e., without assessing other trends in the data), we see that Babe would be the most likely player to get a hit.

Example 8-G: The Air Void test results and Asphalt Binder Content test results from the HMA examples above (means calculated in Example 8-C and ranges calculated in Example 8-E) are presented below. Calculate the standard deviation values for each Quality Characteristic on the following pages.

Sample	**Air Voids (X_i)**	**Binder Content (X_i)**
Sublot 1	8.2	5.7
Sublot 2	3.9	5.7
Sublot 3	4.7	4.8
Sublot 4	5.4	5.2
Sublot 5	4.1	5.4
Sum (ΣX_i)	26.30	26.8
Number of samples (n)	5	5
Mean **($\bar{X} = \Sigma X_i / n$)**	**5.26**	**5.36**
High (x_{High})	8.2	5.7
Low (x_{Low})	3.9	4.8
Range **($x_{High} - x_{Low}$)**	**4.3**	**0.9**

Example 8-G (Continued):

Calculation of Standard Deviation for HMA Air Voids				
Sublot No.	**Air Voids (X_i)**	**Mean ($\bar{X}$)**	$x_i - \bar{x}$	$(x_i - \bar{x})^2$
1	8.2	5.26	2.94	8.6436
2	3.9		-1.36	1.8496
3	4.7		-0.56	0.3136
4	5.4		0.14	0.0196
5	4.1		-1.16	1.3456
	$\bar{x}$ =			$\sum(x_i - \bar{x})^2$ = 12.1720

n = 5

Mean ($\bar{X}$) = 5.26

$\sum(x_i - \bar{x})^2$ = 12.1720

$$\frac{\sum(x_i - \bar{x})^2}{n-1} = 3.0430$$

$$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$$ = 1.7444 (as an intermediate value)

s = 1.7 Percent Air Voids (reported to 1 decimal place as a final value)

Example 8-G (Continued):

Calculation of Standard Deviation for Asphalt Binder Content				
Sublot No.	**Binder Content (X_i)**	**Mean ($\bar{X}$)**	$x_i - \bar{x}$	$(x_i - \bar{x})^2$
1	5.7	5.36	0.34	0.1156
2	5.7		0.34	0.1156
3	4.8		-0.56	0.3136
4	5.2		-0.16	0.0256
5	5.4		0.04	0.0016
	$\bar{x}$ =			$\sum(x_i - \bar{x})^2$ = 0.5720

n = 5

Mean ($\bar{X}$) = 5.36

$\sum(x_i - \bar{x})^2$ = 0.5720

$$\frac{\sum(x_i - \bar{x})^2}{n-1} = 0.1430$$

$$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$$ = 0.3782 (as an intermediate value)

s = 0.4 Percent Asphalt Binder (reported to 1 decimal place as a final value)

Example 8-H: The results from the PCC cover over reinforcing steel measurement examples above (mean calculated in Example 8-D and range calculated in Example 8-F) are presented below. Using this information, calculate the standard deviation (s) on the following page.

Sample	**Cover Measurement, in. (mm)**
Sublot 1	2.13 (54)
Sublot 2	2.64 (67)
Sublot 3	2.24 (57)
Sublot 4	1.89 (48)
Sublot 5	2.32 (59)
Sum (ΣX_i)	11.22 (285)
Number of samples (n)	5
Mean **($\bar{X} = \Sigma X_i / n$)**	**2.244 (57.0)**
High (x_{High})	2.64 (67)
Low (x_{Low})	1.89 (48)
Range **($x_{High} - x_{Low}$)**	**0.75 (19)**

Example 8-H (Continued):

Calculation of Standard Deviation for PCC Cover				
Sublot No.	**Cover Measure (X_i)**	**Mean ($\overline{X}$)**	$x_i - \overline{x}$	$(x_i - \overline{x})^2$
1	2.13 (54)	2.244 (57.0)	-0.114 (-3)	0.012996 (9)
2	2.64 (67)		0.396 (10)	0.156816 (100)
3	2.24 (57)		-0.004 (0)	0.000016 (0)
4	1.89 (48)		-0.354 (-9)	0.125316 (81)
5	2.32 (59)		0.076 (2)	0.005776 (4)
	$\overline{X}$ =			$\sum(x_i - \overline{x})^2$ = 0.30092 (194)

n = 5

Mean ($\overline{X}$) = 2.244 (57.0)

$\sum(x_i - \overline{x})^2$ = 0.30092 (194)

$$\frac{\sum(x_i - \overline{x})^2}{n-1} = 0.07523\ (48.5)$$

$$s = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n-1}}$$ = 0.2743 (6.96) as an intermediate value

s = 0.27 in. (7 mm) Cover

8.7 - Quality Level Analysis

Definition of Quality Level Analysis

The most valid approach to measuring the quality of construction material is through determining the percentage of material contained in a given lot that is within the Specification Limits.

Obviously it is not possible to sample and test every ton of material from a lot of HMA or any other material for Quality Control or Acceptance on projects. We can, however, make a reasonable determination (estimate) of the quality of a lot using several material samples and the concepts of normal distribution and mathematical probability. This procedure is referred to as ***Quality Level Analysis*** (QLA) which is defined as follows:

> **Quality Level Analysis (QLA)** - "A mathematical procedure that provides an estimate of the percentage of a lot that is either within the Specification Limits (Percent Within Limits) or outside of the Specifications (Percent Defective)."

Using Quality Level Analysis to Measure Quality

Quality Level Analysis requires a minimum statistical sample size of n = 3 (3 samples). Using the statistical sample data, we can mathematically calculate:

The average **(*mean*)** of the sample test results.

The amount of variability **(*standard deviation*)** of the sample test results.

Using the mean and standard deviation of the material samples, we can determine the quality level of the statistical sample.

Quality Level Analysis utilizes two ***Quality Index*** **(*Q*)** values. These are the Lower Quality Index denoted by the term "**Q_L**" and the Upper Quality Index represented by the term "**Q_U**."

The Lower Quality Index (Q_L) is computed by subtracting the Lower Specification Limit (LSL) from the mean ($\overline{X}$) of the sample test results, and dividing this difference by the statistical sample standard deviation (s).

$$Q_L = \frac{(\overline{x} - LSL)}{s}$$

The Upper Quality Index (Q_U) is computed by subtracting the mean ($\overline{X}$) of the sample test results from the Upper Specification Limit (USL), and dividing this difference by the statistical sample standard deviation (s).

$$Q_U = \frac{(USL - \overline{x})}{s}$$

Percent Within Limits

The Quality Indices (Q_L and Q_U) obtained with QLA are used to estimate the percent of material in a given lot that is within the Specification Limits. Once Q_L and Q_U are calculated for a statistical sample, a table or spreadsheet is used to determine estimated ***Percent Within Limits*** **(*PWL*)** for the lot. Accordingly, PWL is defined as follows:

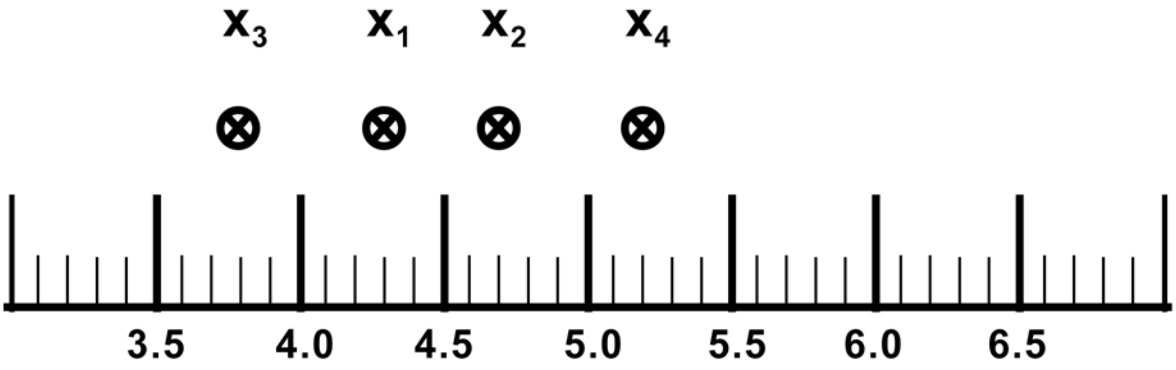
> **Percent Within Limits (PWL)** - "The percentage of the lot falling above the Lower Specification Limit (LSL), beneath the Upper Specification Limit (USL), or between the Upper and Lower Specification Limits."

Graphical Illustration of QLA Procedure

QLA uses the mean and standard deviation to estimate the PWL for the lot. The following example illustrates how the estimated PWL compares to the PWL desired by the QA Specification.

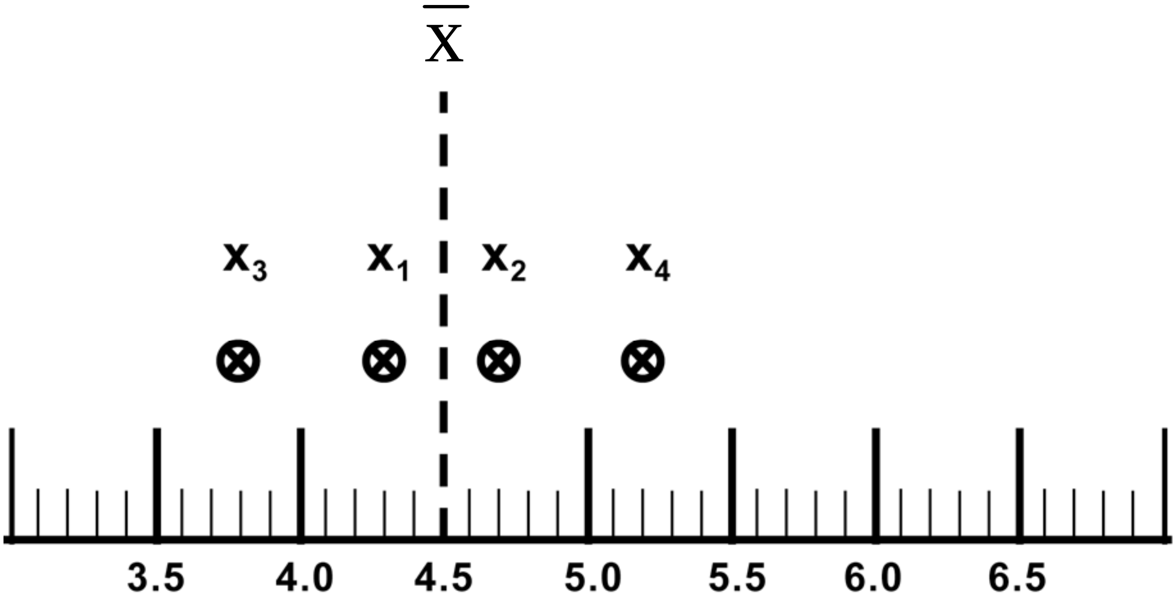
The QA Specification criteria included an upper limit (USL) of 6, a lower limit (LSL) of 4, and a Target Value of 5.

Example 8-I: A lot of PCC is divided into 4 sublots. One material sample is obtained from each sublot and the Air Content is tested on each sample. The test results for this statistical sample of n = 4 samples is plotted below.



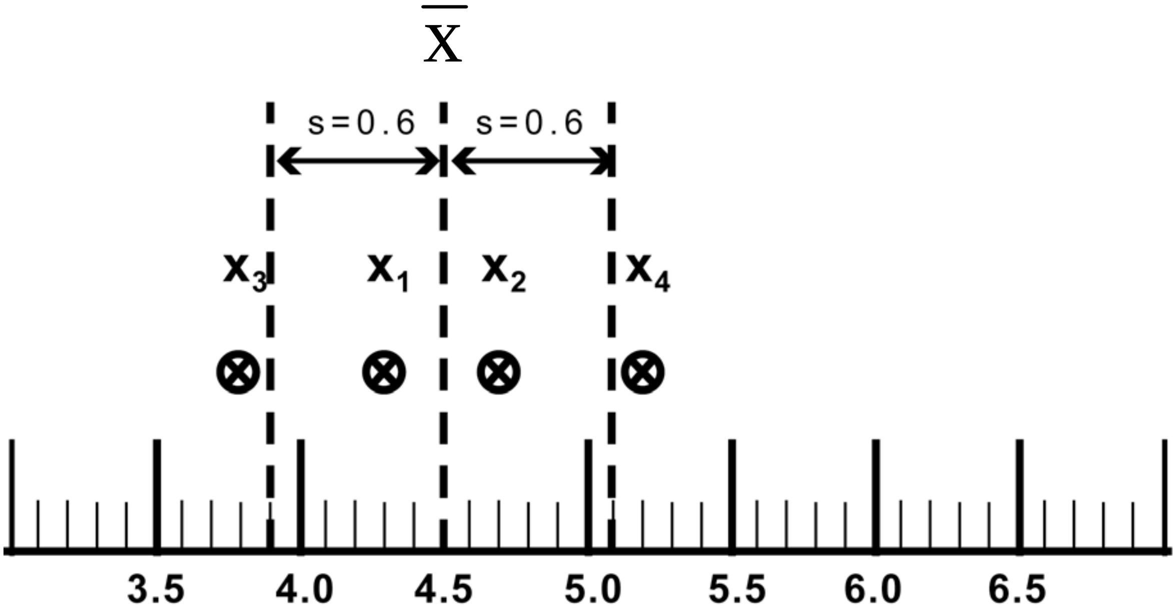
Example 8-I - Individual Air Contents of Four PCC Samples

Example 8-I (Continued): The mean ($\overline{X}$) Air Content of the statistical sample of n = 4 samples is first determined. The statistical sample mean provides us with a good approximation of the average Air Content of the entire lot of PCC. The mean Air Content for the four samples is plotted below.



Example 8-I - Mean Air Content of Four PCC Samples

Example 8-I (Continued): The standard deviation (s) of the statistical sample of n = 4 samples is then determined. The statistical sample standard deviation provides us with an estimate of the overall variability of the entire lot of PCC. The standard deviation for the Air Content of the four samples is shown below.



Example 8-I - Standard Deviation for Air Content of Four PCC Samples

The mean and standard deviation of the statistical sample can be used to mathematically estimate the distribution of the lot of PCC based upon the following known principles:

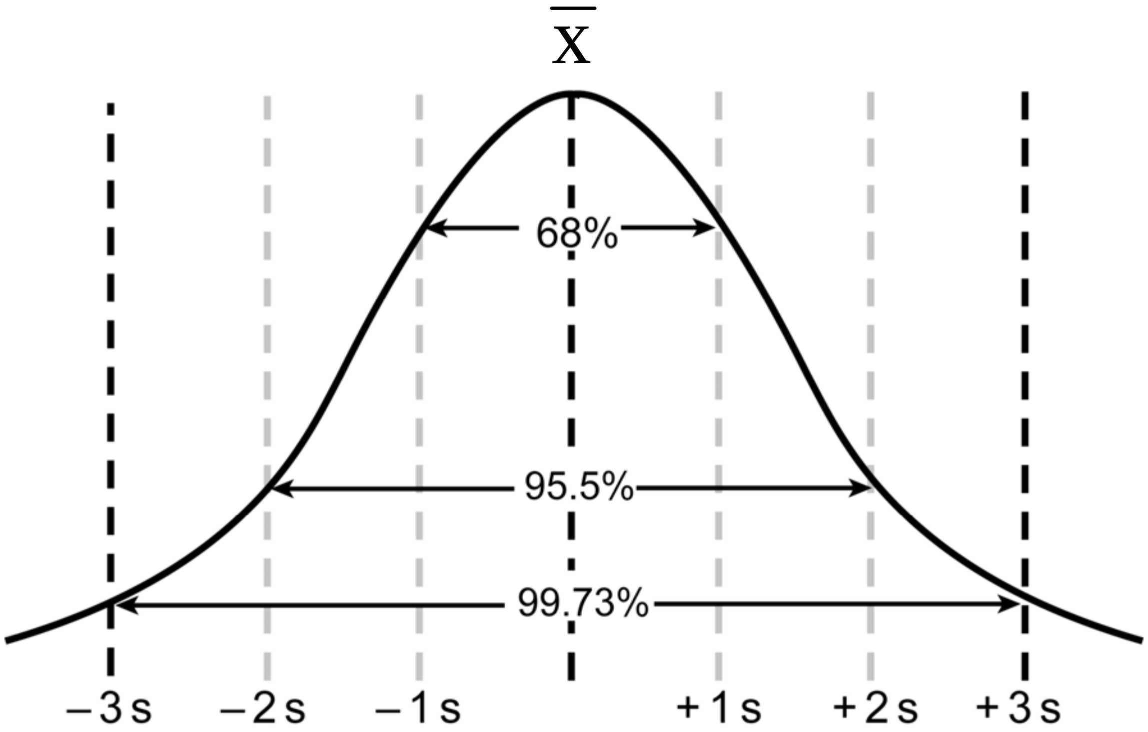
- The midpoint of the normal distribution curve for a statistical sample will coincide with the mean of the statistical sample.

- The normal distribution curve is symmetric about the mean (i.e., 50% of the material sample test values will fall below the mean and 50% above).

- The Empirical Rule states that approximately 68% of all possible samples are clustered about the mean within ± 1 standard deviation.

- The Empirical Rule states that approximately 95.5% of all possible samples are clustered about the mean within ± 2 standard deviations).

- Generally, any material sample obtained from the lot will have a test value between plus or minus three (3) standard deviations of the mean (i.e., the Empirical Rule states that approximately 99.7% of all possible samples are clustered about the mean within ± 3 standard deviations).



Calculating Percent Within Limits

As stated above, the Percent Within Limits for a lot is obtained using the Quality Indices (Q_L and Q_U) derived through Quality Level Analysis.

The percentage of the lot falling below the Upper Specification Limit (USL) is represented by the term "**P_U.**" P_U is determined from a table of areas under a standard curve (non-central distribution) or spreadsheet using the calculated value of Q_U.

The percentage of the lot falling above the Lower Specification Limit (LSL) is represented by the term "**P_L.**" P_L is determined from a table of areas under a standard curve (non-central distribution) or spreadsheet using the calculated value of Q_L.

The Percent Within Limits (PWL) is then computed by adding the estimated percentage of the lot falling below the USL (P_U) to the estimated percentage of the lot falling above the LSL (P_L) and subtracting one hundred (100).

$$\mathbf{PWL = (P_U + P_L) - 100}$$

Tables for estimating the Percent Within Limits (PWL) using the Upper and Lower Quality Indices (Q_U and Q_L) are provided on the following pages. These tables will be used in the examples that follow. The Q values (Q_U or Q_L) are provided in the tables for various statistical sample sizes (n = the number of individual samples in the lot).

For calculated Q_U or Q_L values that fall between the values shown in the tables (shown on the next pages), the user should move up in the table and select the next highest (positive) PWL value for the number of samples in the lot.

For Q_U or Q_L calculated values that are greater than the values contained in the tables (shown on the next pages), then the PWL value (P_U or P_L) will be 100.

If Q_U or Q_L are negative values, P_U or P_L is equal to 100 minus the table value for P_U or P_L. Note that all negative Quality Index values have a PWL of less than 50.

Table for Estimating Percent of Lot Within Limits (PWL)

P_U or P_L, %	n=3	n=4	n=5	n=6	n=7	n=8	n=9
100	1.16	1.49	1.72	1.88	1.99	2.07	2.13
99	--	1.46	1.64	1.75	1.82	1.88	1.91
98	--	1.43	1.58	1.66	1.72	1.75	1.78
97	1.15	1.40	1.52	1.59	1.63	1.66	1.68
96	--	1.37	1.47	1.52	1.56	1.58	1.60
95	1.14	1.34	1.42	1.47	1.49	1.51	1.52
94	--	1.31	1.38	1.41	1.43	1.45	1.46
93	1.13	1.28	1.33	1.36	1.38	1.39	1.40
92	1.12	1.25	1.29	1.31	1.33	1.33	1.34
91	1.11	1.22	1.25	1.27	1.28	1.28	1.29
90	1.1	1.19	1.21	1.23	1.23	1.24	1.24
89	1.09	1.16	1.18	1.18	1.19	1.19	1.19
88	1.07	1.13	1.14	1.14	1.15	1.15	1.15
87	1.06	1.10	1.10	1.10	1.10	1.10	1.10
86	1.04	1.07	1.07	1.07	1.07	1.06	1.06
85	1.03	1.04	1.03	1.03	1.03	1.03	1.02
84	1.01	1.01	1.00	0.99	0.99	0.99	0.99
83	0.99	0.98	0.97	0.96	0.95	0.95	0.95
82	0.97	0.95	0.93	0.92	0.92	0.92	0.91
81	0.95	0.92	0.90	0.89	0.88	0.88	0.88
80	0.93	0.89	0.87	0.86	0.85	0.85	0.84
79	0.91	0.86	0.84	0.82	0.82	0.81	0.81
78	0.88	0.83	0.81	0.79	0.79	0.78	0.78
77	0.86	0.80	0.77	0.76	0.75	0.75	0.74
76	0.83	0.77	0.74	0.73	0.72	0.72	0.71
75	0.81	0.74	0.71	0.70	0.69	0.69	0.68
74	0.78	0.71	0.68	0.67	0.67	0.65	0.65
73	0.75	0.68	0.65	0.64	0.63	0.62	0.62
72	0.73	0.65	0.62	0.61	0.60	0.59	0.59
71	0.7	0.62	0.59	0.58	0.57	0.57	0.56
70	0.67	0.59	0.56	0.55	0.54	0.54	0.53
69	0.64	0.56	0.53	0.52	0.51	0.51	0.50
68	0.61	0.53	0.50	0.49	0.48	0.48	0.48
67	0.58	0.50	0.47	0.46	0.45	0.45	0.45
66	0.55	0.47	0.45	0.43	0.43	0.42	0.42
65	0.51	0.44	0.42	0.40	0.40	0.39	0.39
64	0.48	0.41	0.39	0.38	0.37	0.37	0.36
63	0.45	0.38	0.36	0.35	0.34	0.34	0.34
62	0.41	0.35	0.33	0.32	0.32	0.31	0.31
61	0.38	0.30	0.30	0.30	0.29	0.28	0.28
60	0.34	0.28	0.28	0.25	0.25	0.25	0.25
59	0.31	0.27	0.25	0.23	0.23	0.23	0.23
58	0.3	0.25	0.23	0.20	0.20	0.20	0.20
57	0.25	0.20	0.18	0.18	0.18	0.18	0.18
56	0.2	0.18	0.16	0.15	0.15	0.15	0.15
55	0.18	0.15	0.13	0.13	0.13	0.13	0.13
54	0.15	0.13	0.10	0.10	0.10	0.10	0.10
53	0.1	0.10	0.08	0.08	0.08	0.08	0.08
52	0.08	0.05	0.05	0.05	0.05	0.05	0.05
51	0.05	0.03	0.03	0.03	0.03	0.03	0.03
50	0	0.00	0.00	0.00	0.00	0.00	0.00

Note: If the value of Q_U or Q_L does not correspond to a value in the table, use the next lower Q value. If Q_U or Q_L are negative values, P_U or P_L is equal to 100 minus the table value for P_U or P_L.
Table excerpted from FHWA FP-03, *Standard Specifications for Roads and Bridges on Federal Highway Projects*.

Table for Estimating Percent of Lot Within Limits (PWL)

P_U or P_L, %	n=10 to n=11	n=12 to n=14	n=15 to n=17	n=18 to n=22	n=23 to n=29	n=30 to n=42	n=43 to n=66	n=67 to ∞
100	2.20	2.28	2.34	2.39	2.44	2.48	2.51	2.56
99	1.96	2.01	2.04	2.07	2.09	2.12	2.14	2.16
98	1.81	1.84	1.87	1.89	1.91	1.93	1.94	1.95
97	1.71	1.73	1.75	1.76	1.78	1.79	1.80	1.81
96	1.62	1.64	1.65	1.66	1.67	1.68	1.69	1.70
95	1.54	1.55	1.56	1.57	1.58	1.59	1.59	1.60
94	1.47	1.48	1.49	1.50	1.50	1.51	1.51	1.52
93	1.41	1.41	1.42	1.43	1.43	1.44	1.44	1.44
92	1.35	1.35	1.36	1.36	1.37	1.37	1.37	1.38
91	1.29	1.30	1.30	1.30	1.31	1.31	1.31	1.31
90	1.24	1.25	1.25	1.25	1.25	1.25	1.26	1.26
89	1.19	1.20	1.20	1.20	1.20	1.20	1.20	1.20
88	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
87	1.10	1.11	1.11	1.11	1.11	1.11	1.11	1.11
86	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
85	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
84	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
83	0.95	0.94	0.94	0.94	0.94	0.94	0.94	0.94
82	0.91	0.91	0.91	0.90	0.90	0.90	0.90	0.90
81	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
80	0.84	0.84	0.83	0.83	0.83	0.83	0.83	0.83
79	0.81	0.80	0.80	0.80	0.80	0.80	0.80	0.79
78	0.77	0.77	0.77	0.76	0.76	0.76	0.76	0.76
77	0.74	0.74	0.73	0.73	0.73	0.73	0.73	0.73
76	0.71	0.70	0.70	0.70	0.70	0.70	0.70	0.70
75	0.68	0.67	0.67	0.67	0.67	0.67	0.67	0.66
74	0.65	0.64	0.64	0.64	0.64	0.64	0.64	0.63
73	0.62	0.61	0.61	0.61	0.61	0.61	0.61	0.60
72	0.59	0.58	0.58	0.58	0.58	0.58	0.58	0.57
71	0.56	0.55	0.55	0.55	0.55	0.55	0.55	0.54
70	0.53	0.52	0.52	0.52	0.52	0.52	0.52	0.52
69	0.50	0.50	0.49	0.49	0.49	0.49	0.49	0.49
68	0.47	0.47	0.47	0.46	0.46	0.46	0.46	0.46
67	0.44	0.44	0.44	0.44	0.43	0.43	0.43	0.43
66	0.42	0.41	0.41	0.41	0.41	0.41	0.41	0.40
65	0.39	0.38	0.38	0.38	0.38	0.38	0.38	0.38
64	0.36	0.36	0.36	0.35	0.35	0.35	0.35	0.35
63	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.32
62	0.31	0.30	0.30	0.30	0.30	0.30	0.30	0.30
61	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
60	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
59	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
58	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
57	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
56	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
55	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
54	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
53	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
52	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
51	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: If the value of QU or QL does not correspond to a value in the table, use the next lower Q value. If Q_U or Q_L are negative values, P_U or P_L is equal to 100 minus the table value for P_U or P_L.
Table excerpted from FHWA FP-03, *Standard Specifications for Roads and Bridges on Federal Highway Projects***.**

Example Applications of Quality Level Analysis

Example 8-J: The HMA Air Void test results from the HMA examples above (mean from Example 8-C, range from Example 8-E, and standard deviation from Example 8-G) are presented below. Calculate the PWL for Laboratory Air Voids below. The Upper Specification Limit (USL) is 5.00% and the Lower Specification Limit (LSL) is 3.00%.

Information	HMA Air Voids (P_a)
Number of samples (n)	5
Mean $(\bar{x} = \sum x_i/n)$	**5.26**
High (x_{High})	8.2
Low (x_{Low})	3.9
Range ($x_{High} - x_{Low}$)	**4.3**
Standard Deviation (s)	**1.7444**

$$Q_L = \frac{(\bar{x} - LSL)}{s} \qquad Q_U = \frac{(USL - \bar{x})}{s}$$

$$Q_L = \frac{(5.26 - 3.00)}{1.7444} \qquad Q_U = \frac{(5.00 - 5.26)}{1.7444}$$

$$Q_L = 1.2956 \qquad Q_U = -0.1490$$

$$Q_L = 1.30 \text{ (table has 2 decimals} \qquad Q_U = -0.15 \text{ (table has 2 decimals}$$

Using the above calculated values for Q_U and Q_L, the corresponding values for P_U and P_L were obtained from the n = 5 column of the *Table for Estimating Percent of Lot Within Limits (PWL)*.

For the Q_U of -0.15, find the PWL value for 0.15 with n = 5 (result is 55) and subtract from 100 since all negative Quality Index values have a PWL of less than 50.

P_L = 92 **P_u = 100 – 55** **P_u = 45**

Using P_U and P_L, the PWL is calculated as follows:

$$PWL = (P_U + P_L) - 100$$
$$PWL = (45 + 92) - 100$$
$$\mathbf{PWL = 37}$$

Example 8-K: The HMA Asphalt Binder Content test results from the HMA examples above (mean from Example 8-C, range from Example 8-E, and standard deviation from Example 8-G) are presented below. Calculate the PWL for Asphalt Binder Content below. The Upper Specification Limit (USL) is 5.3% and the Lower Specification Limit (LSL) is 4.7%.

Information	**Asphalt Binder Content (P_b)**
Number of samples (n)	5
Mean $(\bar{x} = \sum x_i/n)$	**5.36**
High (x_{High})	5.7
Low (x_{Low})	4.8
Range ($x_{High} - x_{Low}$)	**0.9**
Standard Deviation (s)	**0.378**

$$Q_L = \frac{(\bar{x} - LSL)}{s} \qquad Q_U = \frac{(USL - \bar{x})}{s}$$

$$Q_L = \frac{(5.36 - 4.7)}{0.378} \qquad Q_U = \frac{(5.3 - 5.36)}{0.378}$$

$$Q_L = 1.746 \qquad Q_U = -0.1587$$

$$Q_L = 1.75 \text{ (table has 2 decimals)} \qquad Q_U = -0.16 \text{ (table has 2 decimal places)}$$

Using the above calculated values for Q_U and Q_L, the corresponding values for P_U and P_L were obtained from the n = 5 column of the *Table for Estimating Percent of Lot Within Limits (PWL)*.

For the Q_U of -0.16, find the PWL value for 0.16 with n = 5 (result is 56), and subtract from 100 because all negative Quality Index values have a PWL of less than 50.

P_L = 100 **P_U = 100-56** **P_U = 44**

Using P_U and P_L, the PWL is calculated as follows:

$$PWL = (P_U + P_L) - 100$$
$$PWL = (44 + 100) - 100$$
$$\mathbf{PWL = 44}$$

Example 8-L: The PCC Cover test results from the PCC examples above (mean from Example 8-D, range from Example 8-F, and standard deviation from Example 8-H) are presented below. Calculate the PWL for PCC Cover below. The Upper Specification Limit (USL) is 3 in. and the Lower Specification Limit (LSL) is 2 in.

Information	PCC Cover, in. (mm)
Number of samples (n)	5
Mean $(\bar{x} = \sum x_i/n)$	**2.244**
High (x_{High})	2.64
Low (x_{Low})	1.89
Range ($x_{High} - x_{Low}$)	**0.75**
Standard Deviation (s)	**0.2743**

$$Q_L = \frac{(\bar{x} - LSL)}{s} \qquad Q_U = \frac{(USL - \bar{x})}{s}$$

$$Q_L = \frac{(2.244 - 2)}{0.2743} \qquad Q_U = \frac{(3 - 2.244)}{0.2743}$$

$$Q_L = 0.8895 \qquad Q_U = 3.6086$$

$$Q_L = 0.89 \text{ (table has 2 decimals)} \qquad Q_U = 3.61 \text{ (table has 2 decimal places)}$$

Using the above calculated values for Q_U and Q_L, the corresponding values for P_U and P_L were obtained from the n = 5 column of the *Table for Estimating Percent of Lot Within Limits (PWL)*.

$P_L = 80$ **$P_U = 100$**

Using P_U and P_L, the PWL is calculated as follows:

$$\mathrm{PWL} = (P_U + P_L) - 100$$
$$\mathrm{PWL} = (100 + 80) - 100$$
$$\mathbf{PWL = 80}$$

- END OF CHAPTER 8 -

CHAPTER 9

Applications for Quality Control

Chapter 9

Applications for Quality Control

Chapter Overview

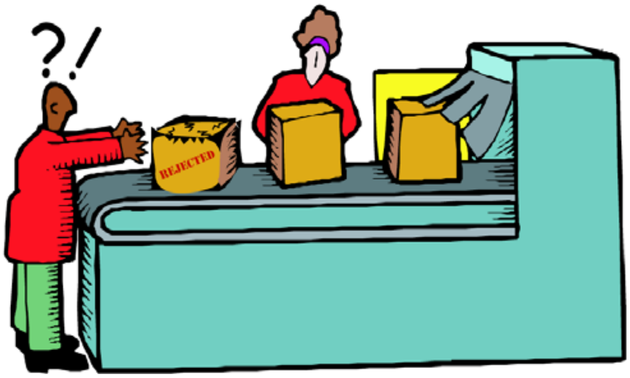
In this chapter, the following mathematical applications for Quality Control are presented:

9.1 - Control Charts

Chance Causes vs. Assignable Causes

Construction materials are subject to a certain degree of variability. This variability stems from two primary sources: ***chance causes*** and ***assignable causes***. They are defined as follows:

> **Chance Cause** - "A source of variation that is inherent in any production process and which cannot be eliminated as it is due to random, expected causes."
>
> **Assignable Cause** - "A source of variation, usually due to error or process change, which can be detected by statistical methods and corrected within economic limits (when assignable causes are identified and removed, the production process is under control)."



Chance causes of variability are inherent to any method of production or placement and must be expected. As stated in Chapter 4, the types of inherent variability that comprise chance causes include: Sampling variability, testing variability, material variability, and construction variability. Assignable causes of variability are those that can be shown (assigned) directly to cause a variation in the process.

Discerning the difference between chance causes and assignable causes can be a challenging process. Control charts do not eliminate variability nor do they point to where the problem lies within the process or even how to correct the problem, but some forms of control charts help distinguish between the inherent chance causes of variability and assignable causes.

Definition of Control Chart

Control charts are useful tools for monitoring and ensuring the quality of a product. A control chart (also called a Statistical Control Chart) is defined as follows:

> **Control Chart** - "A graphical plot of Quality Control measurements or test values used to identify variation in a production or placement process due to either chance causes or assignable causes."

Uses and Benefits of Control Charts

A control chart can be used by a contractor party (i.e., prime contractor, subcontractor, producer, fabricator, manufacturer) as an aid in the Quality Control of a production or placement process. Agencies should also be interested in the proper use of control charts because they must often determine whether or not they are being properly implemented by the contractor. Some of the uses of control charts include:

- Early detection of trouble.
- Establishment of process capability.
- Tool to identify variability of production or placement processes.
- Use as permanent records of quality.
- Use as a basis for modifying Specification Limits.

Some of the benefits of control charts include:

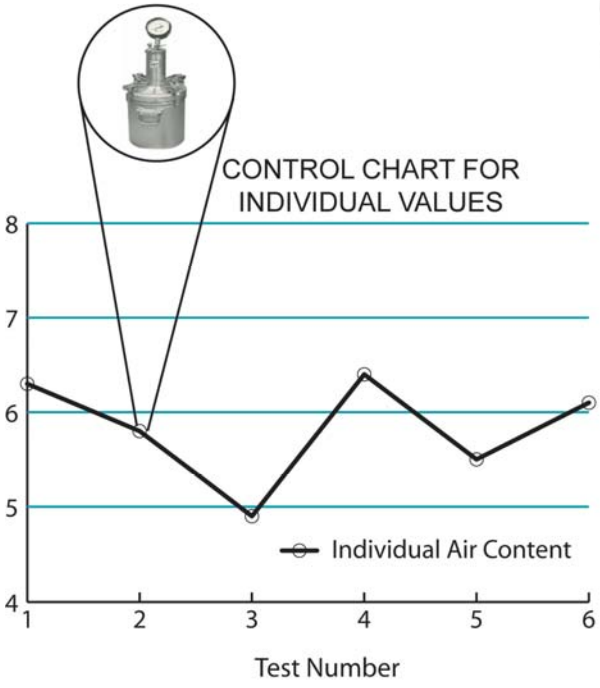
- Decrease in overall product variability.
- Assist in achievement of higher pay adjustments.
- Instill quality awareness.

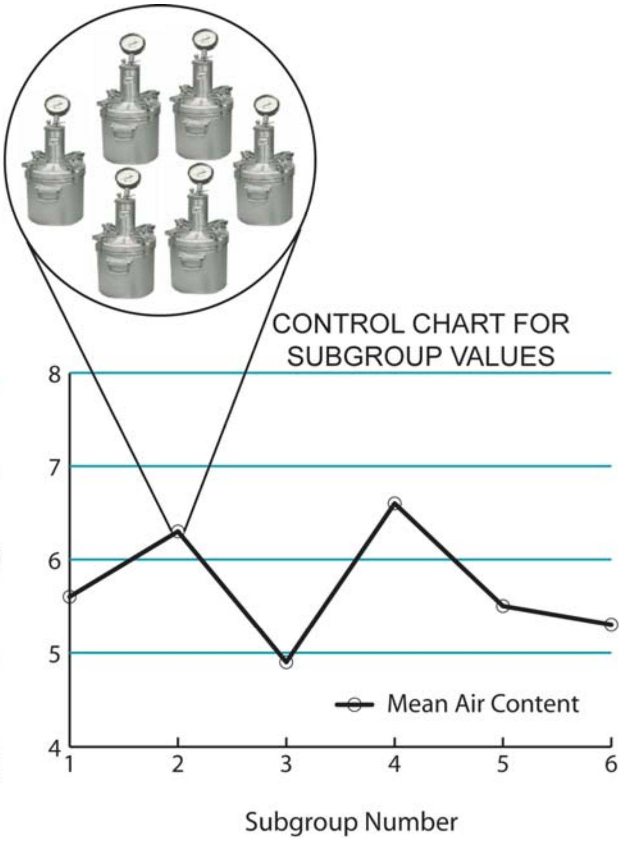
Types of Control Charts

There are two basic forms of control charts:

- Control charts that plot individual measurements or test values.
- Control charts that plot subgroups of measurements of test values.

The first form of control charts are used to record the results of individual Quality Control material samples for a specified period. The second form of control charts plot the results for a subgroup of Quality Control samples for determining if an apparently large variation in a material characteristic is due to a chance cause or an assignable cause.





9.2 - Control Charts Using Individual Values

Definition of Run Chart

The most common form of control chart that uses individual values is referred to as a ***run chart*** (Also called a music bar chart)***.*** A run chart is defined as follows:

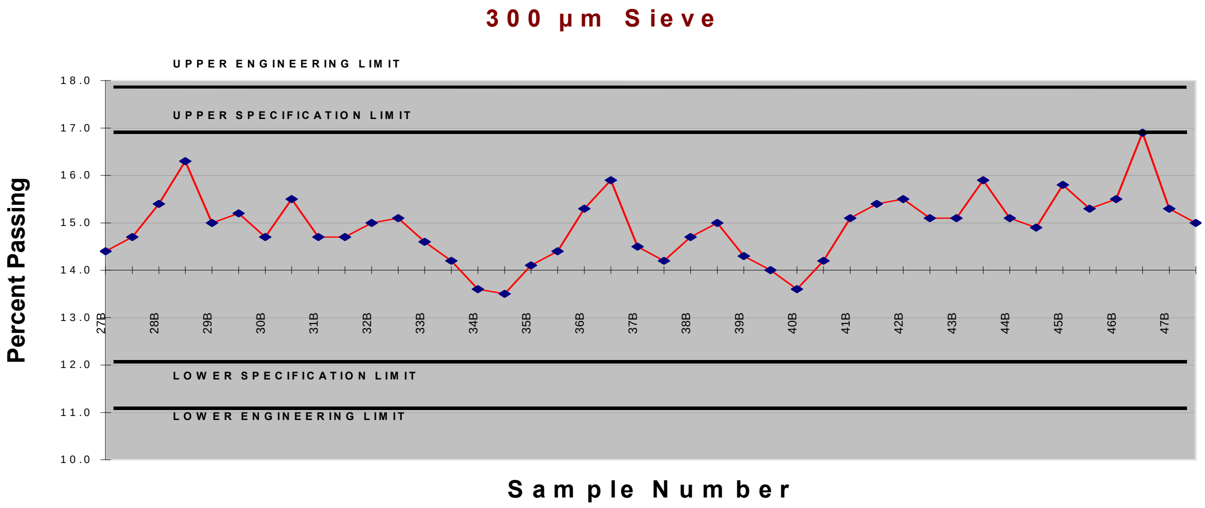
> **Run Chart** - “A control chart that presents individual measurements or test values for a specific Quality Characteristic on a vertical axis and the individual sample numbers (in consecutive order) on a horizontal axis.”

Run charts plot individual material sample values (n = 1) and usually check the measurements or test results against the Specification Limits and/or Engineering Limits. However, run charts may also use statistically derived Control Chart Limits (see section 9.4 below).

Targets and Limits for Run Charts

Targets for run charts are typically established by the contractor party for his or her process for a particular Quality Characteristic within the Specification and/or Engineering Limits. The target should coincide with either a known or assumed mean process capability. For example, based on the development of a specific mix design (HMA, PCC, etc.) a producer would typically utilize the target value from the mix design as the target for the Run Chart. The limits usually used on run charts are either the Specification Limits and/or the Engineering Limits.

Although run charts are simple, they have the disadvantage that they do not provide as good an indication as to whether the process is in control. This type of control chart is a start at Quality Control, but, as will be discussed below (see Section 9.3), there are more powerful charts to use.



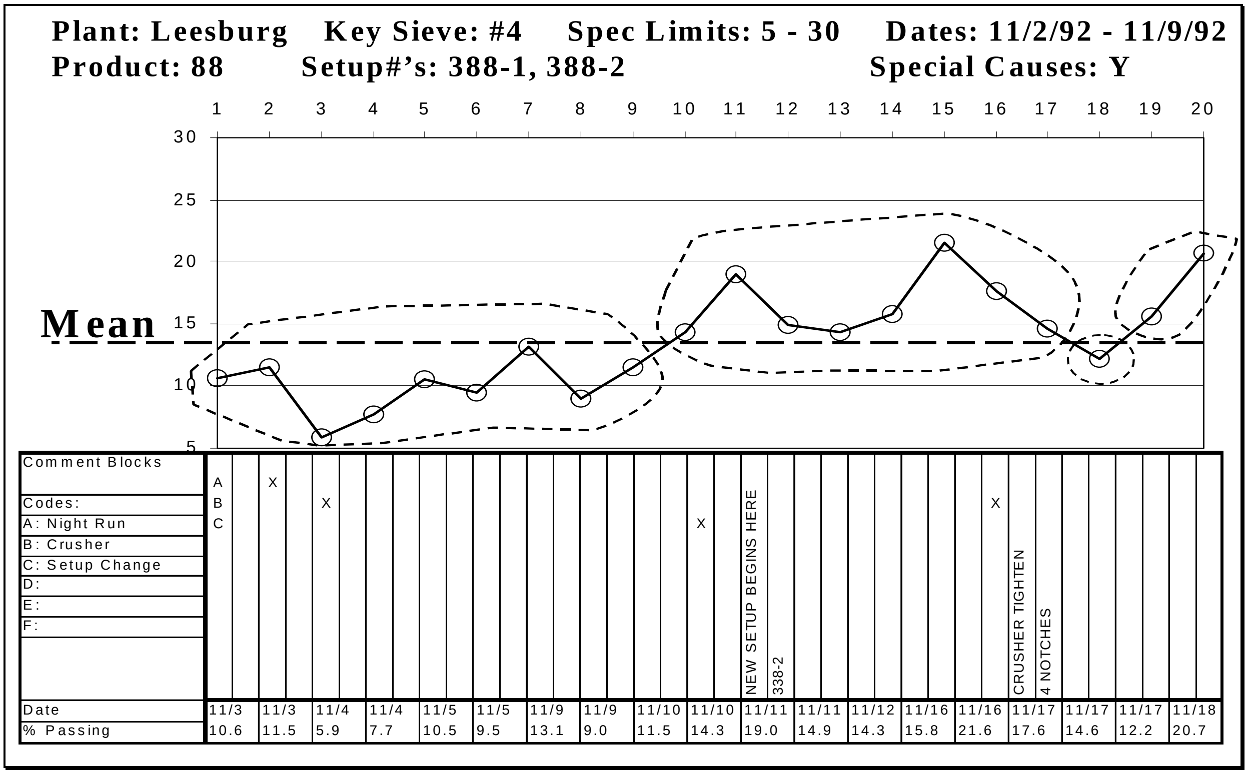
Run Chart Examples

Example 9-A: A typical case study run chart for Luck Stone Corporation as developed from FHWA Demonstration Project 89 - Session VI entitled *“Elements of a QA Program*” is presented below.

The case study presented here is in the form of a run chart used by Luck Stone Corporation at their Leesburg, Virginia plant. The chart is set up for individual tests for a No. 88 stone. The chart uses a combination of Specification Limits (5 to 30% passing) and plant process limits.

For controlling the No. 88 stone, the No. 4 sieve is identified as the key sieve for measuring the effect of the change in the ‘setup.’ Setups are the documentation required (by Luck Stone) to measure every change in the stone control process. The setups contain data on the crusher settings required, the location of various screen sizes, the screen size, and wire cloth screen size. The type of screen, crusher rotation, and the blending gates used are also included in the setup data.

In this case study, evidence is presented to show the impact of setup change on gradation by the shift in trends from one setup (#1-9) to another setup (#10-20). The setup change was necessitated by the material being coarser than desired because of crusher liner wear. As the liners reach their wear limits, the crushing geometry changes, producing a coarser product. The plant technician noticed a ‘run’ of 9 tests (#1-9) being on the coarse side of the target mean, indicating a significant change. (A run is the number of results on the same side of the target mean.) To compensate for this liner wear, the wire cloth screen size was changed from 1/4” cloth to 3/16” cloth, making the product finer. The change was effective as shown by test #10 being slightly above the target mean.

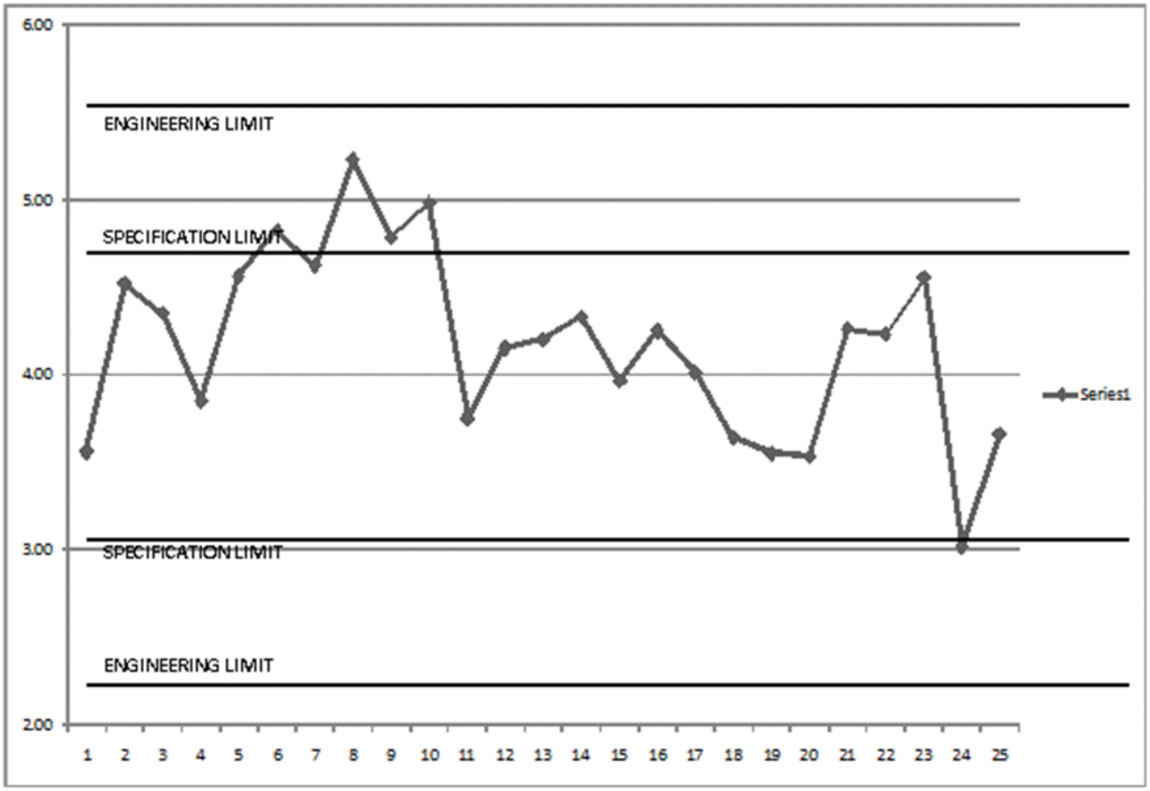


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Date	11/3	11/3	11/4	11/4	11/5	11/5	11/9	11/9	11/10	11/10	11/11	11/11	11/12	11/16	11/16	11/17	11/17	11/17	11/18	
% Passing	10.6	11.5	5.9	7.7	10.5	9.5	13.1	9.0	11.5	14.3	19.0	14.9	14.3	15.8	21.6	17.6	14.6	12.2	20.7	

Example 9-B: An HMA Production facility monitored an HMA mixture's laboratory air voids during production of a lot using a run chart. The lot contained 25 sublots and each sublot's individual sample air void value was plotted on the run chart. Limits used on the run chart were the Specification Limits and Engineering Limits in the agency QA Specifications. These results represent the contractor's QC samples obtained during production of the HMA lot tested by the agency in Example 8-C. Tables summarizing the test result values for the 25 sublots and the run chart plotting these values are shown below.

Sublot	Air Voids (P_a)
1	3.6
2	4.5
3	4.4
4	3.9
5	4.6
6	4.8
7	4.6
8	5.2
9	4.8
10	5.0
11	3.8
12	4.2
13	4.2
14	4.3
15	4.0
16	4.3
17	4.0
18	3.6
19	3.6
20	3.5
21	4.3
22	4.2
23	4.6
24	3.0
25	3.7

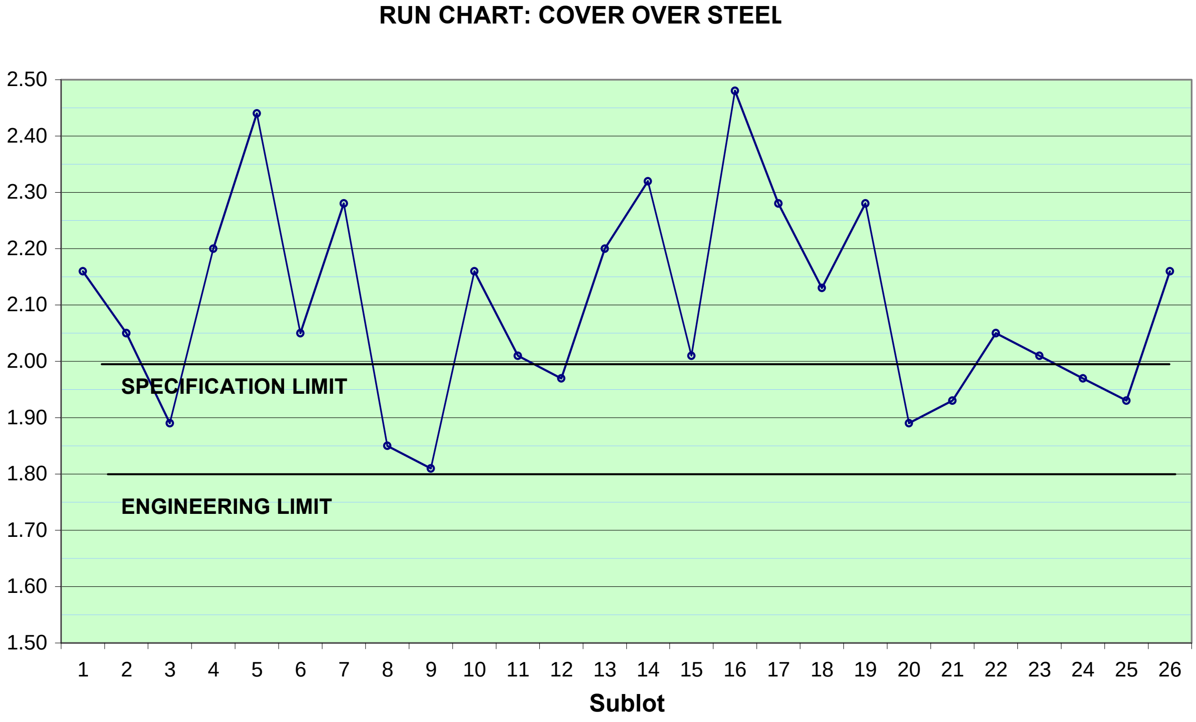
Example 9-B (Continued):



Example 9-C: A contractor measured the PCC cover over reinforcing steel on a bridge deck, and plotted the following results for each sublot on a run chart. Limits used on the run chart were the Specification Limits and Engineering Limits in the agency QA Specifications. These results represent the contractor's QC cover test values obtained for the PCC lot tested by the agency in Example 8-D.

Sublot	Cover, in. (mm)
1	2.16 (55)
2	2.05 (52)
3	1.89 (48)
4	2.20 (56)
5	2.44 (62)
6	2.05 (52)
7	2.28 (58)
8	1.85 (47)
9	1.81 (46)
10	2.16 (55)
11	2.01 (51)
12	1.97 (50)
13	2.20 (56)

Sublot	Cover, in. (mm)
14	2.32 (59)
15	2.01 (51)
16	2.48 (63)
17	2.28 (58)
18	2.13 (54)
19	2.28 (58)
20	1.89 (48)
21	1.93 (49)
22	2.05 (52)
23	2.01 (51)
24	1.97 (50)
25	1.93 (49)
26	2.16 (55)



9.3 - Control Charts Using Subgroups of Data

Subgroups

Unlike run charts, which plot individual sample values, other control charts plot the results of ***subgroups*** comprised of multiple samples (n > 1).

To determine the inherent variability for the production or placement of a given material, the process should be exposed to random sampling for a long period of time. Since duplicate, individual measurements will not always be identical (due to inherent variability), individual results cannot be accurately predicted. However, groups from a constant process tend to be predictable.

Accordingly, control charts that use subgroups of data, rather than individual sample results, are used to make assessments of the consistency of a process. All the values within a subgroup must be logically related. The minimum subgroup size should be n = 2. Typically, subgroup sizes in the range of n = 3 to 5 are used. A subgroup, when working with control charts, is defined as follows:

> **Subgroup** - “A set (n >1) of Quality Control sample values from within a lot, whose mean or range are plotted on a control chart.”

Types of Control Charts Using Subgroups of Data

There are three primary types of control charts using subgroups of data that are typically used for transportation construction material Quality Control:

- $\overline{X}$ Chart (Control Chart for Means, read as “X-Bar Chart”)
- R Chart (Control Chart for Ranges)
- Moving Average Chart

As will be described below, these charts serve a specific function in monitoring and controlling the production or placement of construction materials.

$\overline{X}$ Chart

An X-Bar Chart is a Statistical Control Chart that plots the ***grand mean*** of subgroup means based on n_s, or the number of subgroups, and is defined as follows:

> **X-Bar Chart** - “A control chart that plots the mean ($\overline{X}$) values for subgroups of measurements or test values against statistically derived control limits.

The grand mean ($\overline{\overline{X}}$) is defined as follows:

> **Grand Mean** - “The sum of the means of sets or subgroups of data divided by the total number of sets or subgroups.”

$$\overline{\overline{X}} = \frac{\sum \overline{X}}{n_s}$$

R Chart

An R chart is a Statistical Control Chart that plots the ***mean range*** for the subgroup ranges based on n_s, or the number of subgroups, and is defined as follows:

> **R Chart** - "A control chart that plots the range (R) values for subgroups of measurements or test values against statistically derived control limits."

The mean range ($\overline{R}$) is defined as follows:

> **Mean Range** - "The sum of the ranges of sets or subgroups of data divided by the total number of sets or subgroups."

$$\overline{R} = \frac{\sum R}{n_s}$$

Moving Average Chart

A ***Moving Average Chart*** is defined as follows:

> **Moving Average Chart** - "A control chart that plots a moving average for a predefined number of sample values or subgroup values."

Moving Average Charts mitigate the effect of individual sample "scatter" that can result when plotting individual results (as in run charts). Moving Average Chart plots are therefore more gradual as individual variability has been filtered away. Discernable changes in Moving Average Charts are indicative of significant process changes since it is not simply the individual test value that has changed, but the average test value from several samples.

The Value of Using $\overline{X}$ Charts and R Charts Together

Two of the most useful Statistical Control Charts for the process control of construction materials are the control chart for the means ($\overline{X}$ Chart) and the control chart for the ranges (R Chart). Both charts are necessary in estimating whether a process for a given population is in control. The $\overline{X}$ Chart is used to determine when the center (process mean) changes. The R Chart is used to determine when the spread (process variability) changes.

Control charts that plot subgroups of data for process control are always based on the data means and the range of a subgroup of size n > 1. One of the main reasons is that the distribution of statistical sample means tends to be normally distributed. Therefore, even if the underlying lot (population) from which the samples are taken is not normal, the distribution of statistical sample means will be approximately normal. 3 standard deviations (±) from the statistical sample means are used as the control limits in order to identify when the process is out of control.

In order to gain control of the process (i.e., to assume its predictability), it is necessary to know the behavior between subgroups ($\bar{X}$chart) and also to discover whether or not assignable causes exist within the subgroups or statistical samples. The use of an R Chart for process control prevents the possibility of failing to detect the averaging effects of two extremely opposite test results in the $\bar{X}$ chart. Together, the $\bar{X}$ Chart and R Chart spread a net from which it is difficult for an assignable cause to escape.

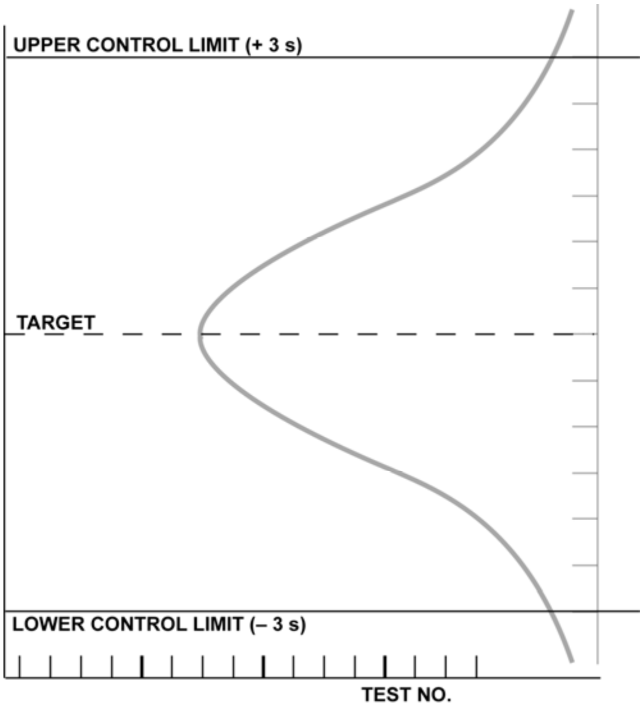
9.4 - Limits for Control Charts Using Subgroups of Data

Definition of Control Chart Limits

The key element in the use of control charts that use subgroups of data is the proper designation of the ***Control Chart Limits*** (also called Action Limits). Limits for control charts that use subgroups of data should not be confused with the Quality Limits used for Acceptance in an agency's QA Specification. Accordingly, Control Chart Limits are defined as follows:

> **Control Chart Limits** - "Statistically derived boundaries applied to a control chart in controlling material production or placement."

Control Chart Limits are expressed as the Upper Control Limit (UCL) and the Lower Control Limit (LCL). When values of the material characteristics fall within these limits, the process is under control. When values fall outside the limits, there is an indication that some assignable cause is present causing the process to be "out of control."



A control chart relies on the fact that we may assume for all practical purposes that the distribution of measurements surrounding the mean value occurs within ± 3 standard deviations of the mean. Therefore, the control chart may be viewed as a normal bell-shaped curve turned on its side. Horizontal lines are then drawn from the center of the curve (normal bell-shaped distribution) and from points on the base at different standard deviation distances from the center. For a normal curve, practically all measured results, (about 1 out of 370 will not) should normally fall between the mean of the population and ± 3 standard deviations from the mean. Lines can be placed on the control chart at points 3 s (3 standard deviations of the lot) and 2 s (2 standard deviations of the lot) representing Action Limits and Warning Limits respectively. A limit of 4 s (4 standard deviations of the lot) would not detect most of the assignable causes acting on the system. On the other hand, if the limits were at 2 s, false indications of assignable causes would be interpreted and much time and money would be spent searching for non-existent problems. Therefore, Upper and Lower Control Chart Limits are normally established at ± 3 standard deviations from the Target Value.

There are two approaches to establishing limits for control charts that use subgroups of data. In the first approach, the mean and the standard deviation of the lot (population) are known through historical QC data. Historical data must not be biased. Remember, historical test data should not be used for these control chart limits unless the data was obtained randomly.

In the second approach, the mean and the standard deviation of the lot (population) are unknown and must be estimated. The recommended process for estimating these Trial Limits is explained below.

Warning Limits

Warning Limits are typically used with Control Chart Limits (Action Limits) and are defined as follows:

> **Warning Limits** - “Boundaries established within the upper and lower Control Chart Limits that plot subgroups of data. They are used to warn of possible problems in the production or placement process that may lead to the process going out of control.”

Warning Limits are established at ±2 standard deviations from the control chart target. Warning Limits are not used with control charts that plot individual sample values (i.e., run charts).

Estimating Limits for Unknown Lot Mean and Standard Deviation

When the population mean and standard deviation are unknown, they must be estimated using past valid data or early production data (with 20+ values) in order to establish the trial limits during the beginning stages of control chart usage.

When using early multiple subgroups of data for development of the Control Chart Limits, be sure to view these as trial control limits. These trial control limits should be computed from data that is free from assignable causes of variation, otherwise the control limits will be set too wide and their full potential will not be realized. To assure that assignable causes are not influencing the location of trial control limits, the initial subgroups and trial limits are plotted on the control charts.

If the subgroups used to compute the trial control limits exceed them, then the trouble causing those extreme points should be investigated. If the investigation results in the identification and correction of assignable causes responsible for those out-of-control points, then those points should be removed and new control limits calculated. If these new trial limits show additional subgroups out of control, the appropriate subgroups should also be investigated. It should be emphasized that points outside the trial control limits should not be removed unless the assignable cause of the variation that is responsible for those out of control points can be corrected. If no assignable cause is found, those subgroups should remain in the control limit calculations.

Calculating Limits for Control Charts that use Subgroups of Data

To determine the limits for control charts that use subgroups of data, the following parameters are required:

- Grand Mean ($\bar{\bar{X}}$) $$\bar{\bar{X}} = \frac{\sum \bar{x}}{n_s}$$
- Mean Range ($\bar{R}$) $$\bar{R} = \frac{\sum R}{n_s}$$
- n_s = number of subgroups
- Control Chart Factors (see Table below)

Control Chart Factors are obtained from standard reference tables. The factors (A_2, D_3, D_4) will depend upon the statistical sample size (n), and are published in standard references (see table below). The factor A_2 incorporates the following items into a single factor to establish the Control Chart Limits:

- A factor to estimate the standard deviation, σ, from the range, R.
- Division by $\sqrt{n}$ to account for $\sigma_{\bar{x}} = (\sigma / \sqrt{n})$.
- Multiplication by 3 to account for 3 standard deviations from the mean.

Control Chart Limits for X-Bar Charts are determined using the formula $\overline{\overline{X}} \pm (A_2 \times \overline{R})$. This formula is an estimate of the formula $\overline{\overline{X}} \pm 3(\sigma / \sqrt{n})$. For the X-Bar Chart, the target value will be the grand mean, which should be compatible with the QA Specification target or the approved Job Mix Formula (JMF) target. For the R chart, the target value is the mean range and the Control Chart Limits are calculated as shown below.

The Control Chart Limits for R charts are defined as $\overline{R} \pm 3\sigma_R$. However, no simple formula gives either the expected mean range ($\overline{R}$), or the standard deviation of all of the subgroup ranges (σ_R). These can however be estimated using the factors D_3 and D_4. Using these factors, the 3-sigma limits can be calculated from an observed $\overline{\mathbf{R}}$ as:

$$\overline{R} + 3\sigma_R = D_4\overline{R}$$

$$\overline{R} - 3\sigma_R = D_3\overline{R}$$

Factors For Developing Control Chart Limits[*]			
Subgroup Size	$\overline{X}$ Chart	Range Chart	Range Chart
	A_2	D_3	D_4
2	1.88	0	3.27
3	1.02	0	2.57
4	0.73	0	2.28
5	0.58	0	2.11
6	0.48	0	2.00
7	0.42	0.08	1.92
8	0.37	0.14	1.86
9	0.34	0.18	1.82
10	0.31	0.22	1.78
11	0.29	0.26	1.74
12	0.27	0.28	1.72
13	0.25	0.31	1.69
14	0.24	0.33	1.67
15	0.22	0.35	1.65
16	0.21	0.36	1.64
17	0.20	0.38	1.62
18	0.19	0.39	1.61
19	0.19	0.40	1.60
20	0.18	0.41	1.59

Subgroup Size - Number of samples in each subgroup
A_2 - Control Chart factor used to calculate Upper and Lower Control Limits for X-Bar Chart
D_3 - Factor used to calculate Lower Control Limit for R Chart
D_4 - Factor used to calculate Upper Control Limit for R Chart

---

[*] Factors for determining from $\overline{R}$ the 3 standard deviation control limits for $\overline{X}$ and R charts from *Statistical Quality Control of Highway Construction - Volume 2*, Table 22-4; Penn. State University (Adapted by NETTCP).

The following equations are used to determine the Upper Control Limits (UCL) and Lower Control Limits (LCL) for both the $\overline{X}$ Chart and R Chart.

The Upper Control Limit (UCL) for the $\overline{X}$ Chart is calculated as follows:

$$UCL_{\overline{X}} = \overline{\overline{X}} + (A_2 \times \overline{R})$$

The Lower Control Limit (LCL) for the $\overline{X}$ Chart is calculated as follows:

$$LCL_{\overline{X}} = \overline{\overline{X}} - (A_2 \times \overline{R})$$

The Upper Control Limit (UCL) for the R Chart is calculated as follows:

$$UCL_R = D_4 \times \overline{R}$$

The Lower Control Limit (LCL) for the R Chart is calculated as follows:

$$LCL_R = D_3 \times \overline{R}$$

Where:

$\overline{\overline{X}}$ = Grand Mean, i.e., the overall mean of the sample means
$\overline{R}$ = Mean range, i.e., the overall mean of the sample ranges
A_2 = Factor from the table above (See page 9-20)
D_3= Factor from the table above (See page 9-20)
D_4= Factor from the table above (See page 9-20)

Control Chart Limits Example

Example 9-D: A contractor obtained QC cores from an HMA pavement each day after the mat had cooled in order to calculate the in-place air voids. Each day's production was defined by the contractor as a subgroup. Each subgroup consisted of five samples (A thru E). Estimate the Control Chart Limits (UCL and LCL) for both an $\overline{X}$ Chart and an R Chart for the lot data below and plot these limits on the $\overline{X}$ Chart and R Chart.

Subgroup Number	**Sample A**	**Sample B**	**Sample C**	**Sample D**	**Sample E**	**Mean ($\overline{X}$)**	**Range (R)**
1	7.0	5.0	9.0	6.0	8.0	7.00	4.0
2	4.0	9.0	7.0	3.0	6.0	5.80	6.0
3	2.0	7.0	5.0	8.0	7.0	5.80	6.0
4	6.0	6.0	9.0	4.0	7.0	6.40	5.0
5	3.0	9.0	7.0	4.0	5.0	5.60	6.0
6	7.0	8.0	5.0	7.0	6.0	6.60	3.0
					$\sum$ =	**37.20**	**30.0**

First, recall the steps for determining the grand mean and mean range:

Step Number 1: Sum the test results for each subgroup and divide by the number of results (n). This yields the mean ($\overline{X}$) for each subgroup (see table above).

Step Number 2: Within each subgroup, subtract the lowest test result value from the greatest test result value. This yields the range (R) for each subgroup (see table above).

Step Number 3: Sum the means ($\overline{X}$) for all subgroups, and divide by the number of subgroups (n_S). This yields the grand mean ($\overline{\overline{X}}$).

Step Number 4: Sum the ranges for all subgroups and divide by the number of subgroups (n_S). This yields the mean range ($\overline{R}$).

Example 9-D (Continued):

Determine the Grand Mean ($\overline{\overline{X}}$) and Mean Range ($\overline{R}$):

$$\overline{\overline{X}} = \frac{\sum \overline{x}}{n_s} \qquad \overline{R} = \frac{\sum R}{n_s}$$

$\overline{\overline{X}}$= 37.20 / 6

$\overline{\overline{X}}$= 6.2

$\overline{R}$ = 30.0 / 6

$\overline{R}$ = 5.0

Calculate the Upper Control Chart Limit (UCL) for the $\overline{X}$ chart:

$$UCL_{\overline{X}} = \overline{\overline{X}} + (A_2 \times \overline{R})$$

We know:

$\overline{\overline{X}}$ = 6.2
$\overline{R}$ = 5.0
A_2 (for n = 5 samples/subgroup) = 0.58

$$UCL_{\overline{X}} = 6.2 + (0.58 \times 5.0)$$
$$UCL_{\overline{X}} = 9.1$$

Example 9-D (Continued):

Calculate the Lower Control Limit (LCL) for the $\overline{X}$ Chart:

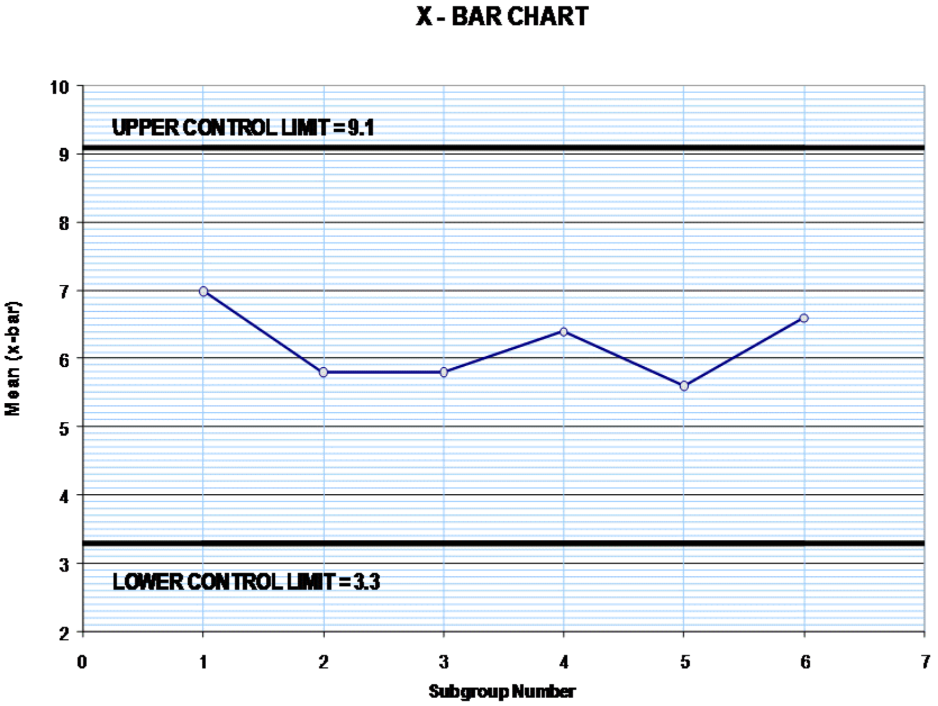
$$\mathbf{LCL}_{\overline{X}} = \overline{\overline{X}} - (A_2 \times \overline{R})$$

We know:

$\overline{\overline{X}} = 6.2$
$\overline{R} = 5.0$
A_2 (for n = 5 samples/subgroup) = 0.58

$$\mathrm{LCL}_{\overline{X}} = 6.2 - (0.58 \times 5.0)$$
$$\mathrm{LCL}_{\overline{X}} = 3.3$$

Plot the Upper and Lower Control Chart Limits for the X-Bar Chart:



Example 9-D (Continued):

Calculate the Upper Control Limit (UCL) for the R Chart:

$$UCL_R = D_4 \times \overline{R}$$

We know:

$\overline{R} = 5.0$
D_4 (for n = 5 samples/subgroup) = 2.11

$$UCL_R = 5 \times 2.11$$
$$UCL_R = 10.55 = 10.6$$

Calculate the Lower Control Limit (LCL) for the R Chart:

$$LCL_R = D_3 \times \overline{R}$$

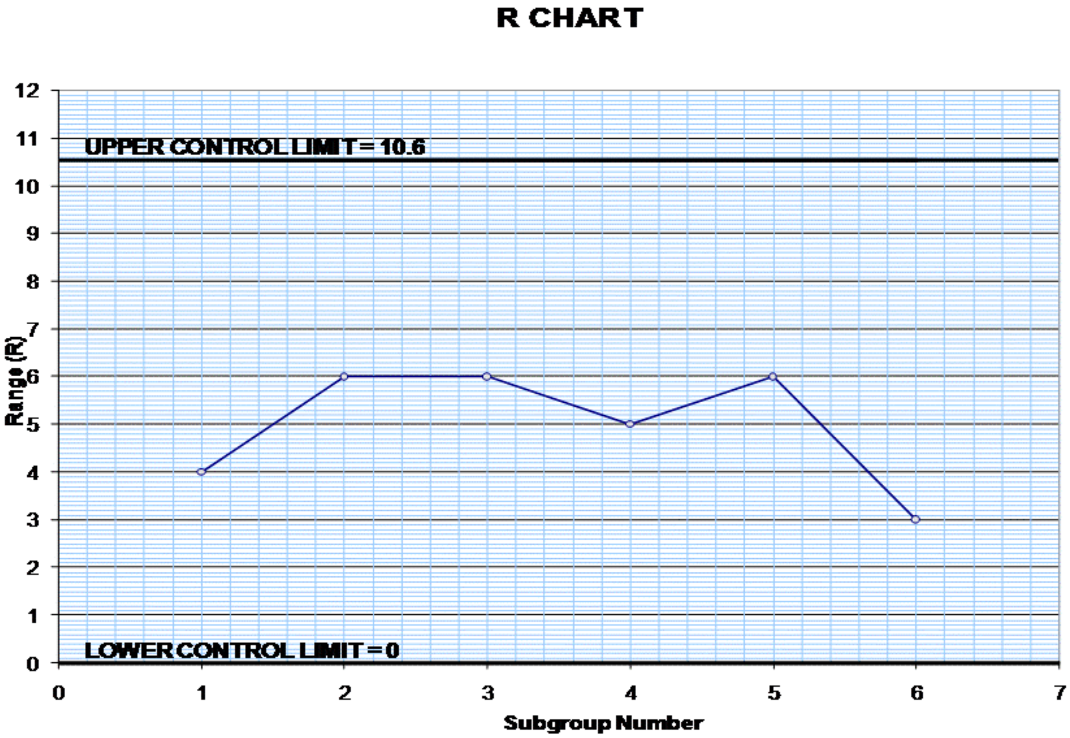
We know:

$\overline{R} = 5.0$
D_3 (for n = 5 samples/subgroup) = 0.00

$$LCL_R = 5.0 \times 0.00$$
$$LCL_R = 0.00$$

Example 9-D (Continued):

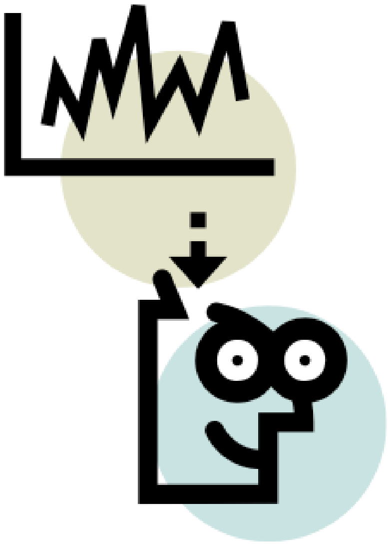
Plot the Upper and Lower Control Chart Limits for the R Chart:



9.5 - Evaluating Control Charts

Troubleshooting for Lack of Control

Statistical control charts can be used to determine where a lack of control exists in a production or placement process. Lack of process control can be identified with the X-Bar Chart and R Chart when the following general trends are observed:



- Change in the X-Bar Chart with the R Chart remaining constant.
- Change in the R Chart, with the X-bar Chart remaining constant.
- Change in both X-Bar Chart and the R Chart.

If a control chart value (control point) becomes very erratic (points which have shown good control suddenly jump out of the Control Chart Limit then jump back inside the Control Chart Limit) then there may be sampling and/or testing errors. If the control chart for the means (X-bar Chart) changes, it is a signal that a subtle change is occurring in the process. If the control chart for the means of the sample range (R Chart) begins to change, it is a signal that a more drastic change is occurring, perhaps worn out equipment or changes in equipment.

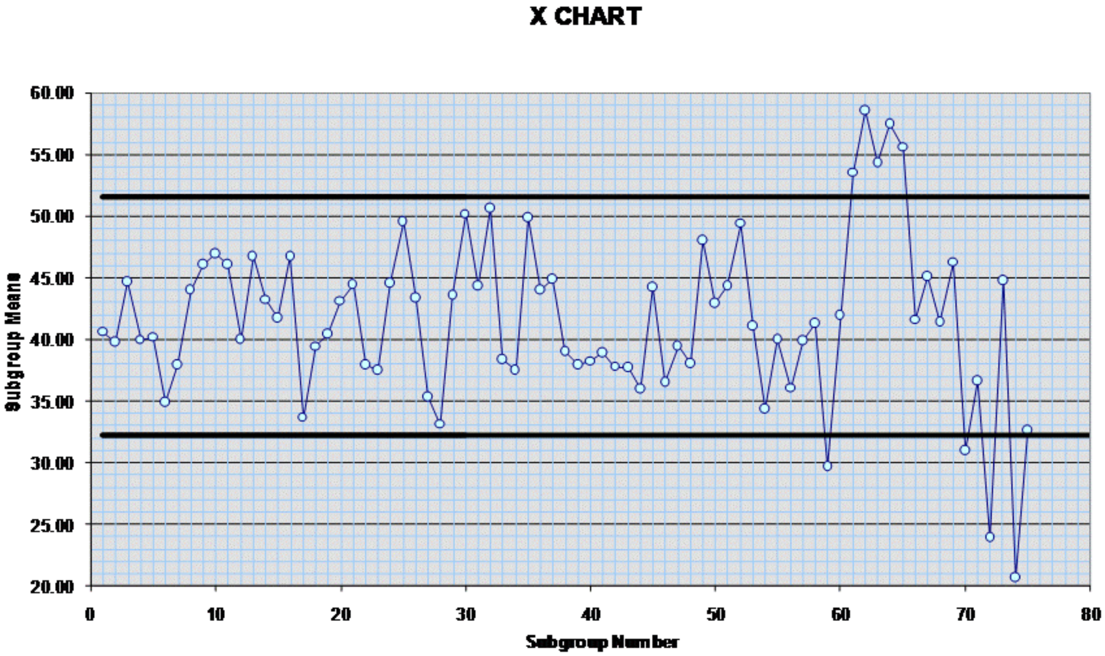
Theory of Extreme Runs – Test for Lack of Control

Control chart limits are set far enough apart (using either 2 or 3 standard deviations from the mean) so that very few points will fall outside of them unless a real change in the process has taken place, that is, unless an assignable cause is acting on the system. For this reason, it is often useful, although not as reliable, to supplement the above mentioned out of control point criteria with evidence given by tests based on a ***Theory of Extreme Runs***.

Successive Points on Same Side of Target

Although there are several different extreme run theories, it is recommended that only one simple Theory of Extreme Runs rule be used in judging if the process is out of control. There is a greater probability of a false indication if we used many rules. To make it simple and practical for a contractor party, the rule may be stated as follows:

> ‘It is to be assumed that grounds exist for suspicion that the population parameter has shifted whenever, in <u>7 successive points</u> on the control chart, all points are on the same side of the central line.’



Single Point Outside of Control Chart Limits

This sequence of extreme runs will occur as a matter of chance (with no change in the population having actually occurred) more frequently than the occurrence of a single point falling outside of the control chart limits. It is for this reason that the Theory of Extreme Runs provides a less reliable basis for identifying lack of control than does a point occurring outside of the control chart limits. In other words, a point that occurs outside the control chart limits is a much more powerful indication that the process is out of control.

In any usage of control charts, an intimate knowledge of the process being controlled is vital to the effective use of the charts. As stated in the *Statistical Quality Control of Highway Construction – Volume 2* (Pennsylvania State University), "the control chart tells <u>when</u> to look for trouble but it cannot, by itself, tell <u>where</u> to look or <u>what</u> cause will be found."

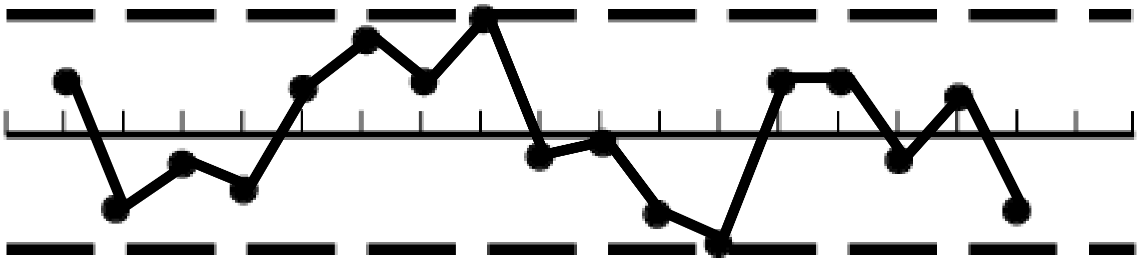
Patterns Observed on Control Charts

There are other patterns that may occur on control charts which may indicate a lack of process control. In the above referenced document from Pennsylvania State University, research is reported on some of the patterns frequently seen on control charts. These patterns are presented below along with some of the potential assignable causes that may be creating the pattern on an X-Bar Chart or R Chart. As noted by Pennsylvania State University:

> "These figures, shown hereinafter, were developed by Bell Telephone Laboratories as an aid in training young inspectors and engineers. The listed causes should be used only as a guide to possible action, not as an authoritative listing of the causes of trouble."

Pattern #1: Recurring Cycles

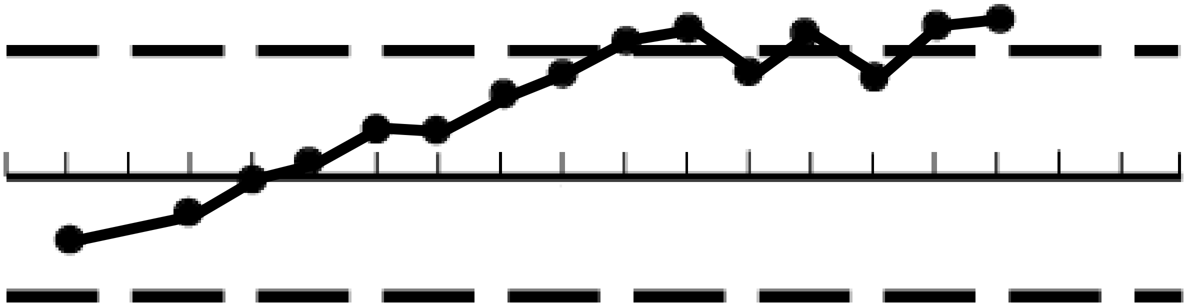
Recurring cycles are formed by repeatable discernable patterns of data. An example of such a pattern is presented below.



Some Causes Affecting $\bar{X}$ Chart	**Some Causes Affecting R Chart**
1. Temperature or other recurring changes in physical environment	1. Scheduled preventive maintenance
2. Worker fatigue	2. Worker fatigue
3. Differences in measuring testing devices which are used in order	3. Worn tools
4. Regular rotation of equipment or operators	
5. Merging subassemblies other processes	

Pattern #2: Pattern Trends

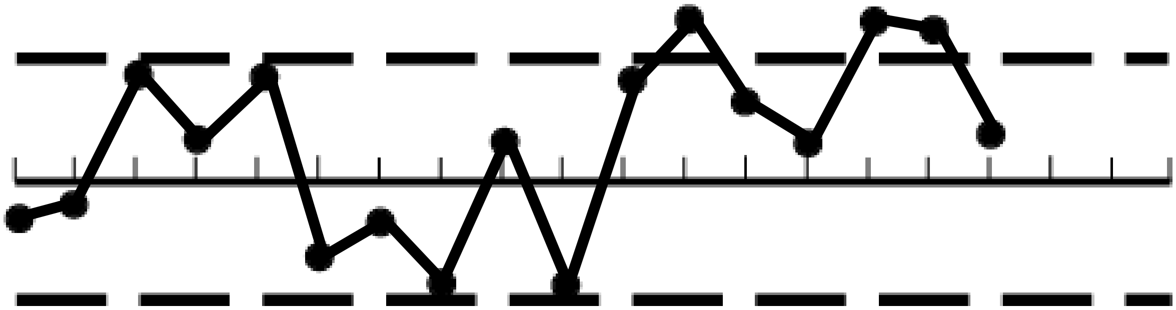
A gradual upward or downward discernable pattern is observed. An example of such a pattern is shown below.



Some Causes Affecting $\bar{X}$ Chart	Some Causes Affecting R Chart
1. Gradual deterioration of equipment which can affect all items	1. Improvement or deterioration of operator skill
2. Worker fatigue	2. Worker fatigue
3. Accumulation of waste products	3. Change in proportions of subprocesses feeding an assembly line
4. Deterioration of environmental conditions	4. Gradual change in homogeneity of incoming material quality

Pattern #3: Jumps In Process Level

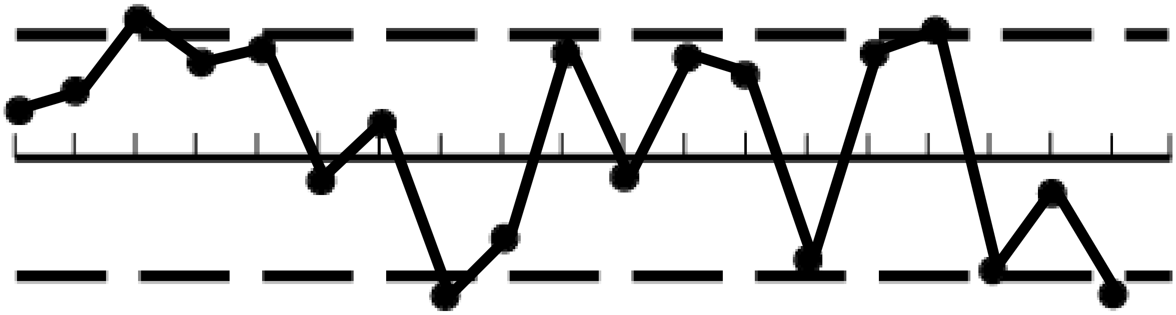
An erratic move in the data appears. An example of such a pattern is presented below.



Some Causes Affecting $\overline{X}$ Chart	Some Causes Affecting R Chart
1. Change in proportions of material or subassemblies coming from different sources	1. Change in material
2. New worker or machine	2. New method
3. Modification of production method or process	3. Change in worker
4. Change in inspection device or method	

Pattern #4: High Proportion of Points Near or Outside Limits

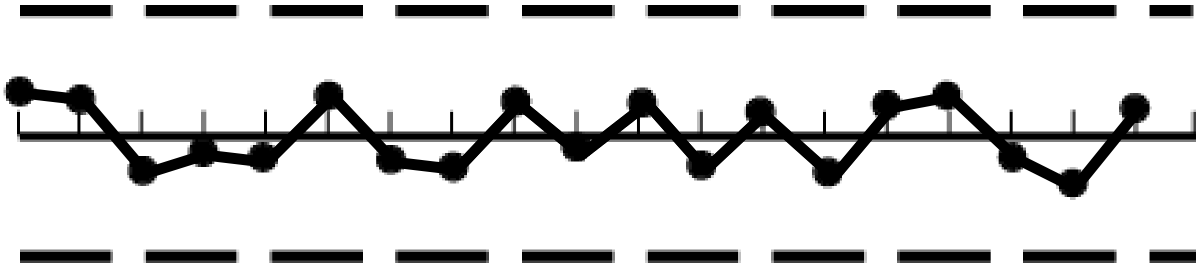
A large number of data points are near or outside the control chart limits. An example of such a pattern is presented below.



Some Causes Affecting $\overline{X}$ Chart	Some Causes Affecting R Chart
1. Over control	1. Mixture of materials of distinctly different quality
2. Large systematic differences in material quality	2. Different workers using a single R chart
3. Large systematic difference in test method or equipment	3. Data from processes under different conditions plotted on same chart
4. Control of two or more processes on same chart	▨

Pattern #5: Stratification or Lack of Variability

The control chart data shows a small band of variability close to the target. If the Control Chart Limits are calculated in accordance with the previously describe sections, then this chart may indicate good control over the process. An example of such a pattern is presented below.



Some Causes Affecting $\overline{X}$ Chart	Some Causes Affecting R Chart
1. Incorrect calculation of control limits	1. Collecting in each sample a number of measurements from widely differing universes

9.6 - Application of QLA for Quality Control

QLA as a Tool for Quality Control

Although Quality Level Analysis (QLA) is normally used with a particular Quality Measure (e.g., PWL) for Acceptance of the product by the agency, it should also be used by the contractor for Quality Control purposes. In fact, some agency QA Specifications require that the contractor either take corrective action or suspend production or placement of materials if the Quality Level falls below a certain threshold level (e.g., 85 PWL).

Even when not specifically required by the QA Specifications, good Quality Control suggests contractors use their QC test results to periodically assess the Quality Level of materials throughout production and placement operations. One manner of assessment includes plotting QLA results at a regular frequency to continuously monitor Quality Levels generated as the project proceeds.

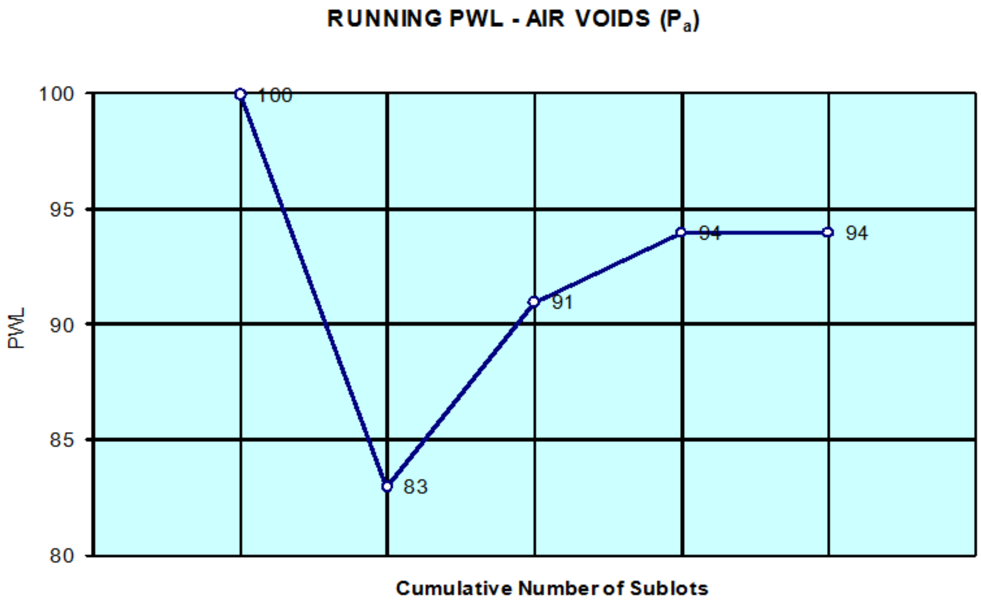
Any QLA analysis performed by the contractor for Quality Control purposes is NOT to be used by either the contractor or the agency as a basis for Acceptance decisions. These QLA plots are only to be used by the contractor party (i.e., prime contractor, subcontractor, producer, fabricator, manufacturer) to control the quality of the product being produced or placed. These QLA plots charts should be used in conjunction with the other previously discussed control charts to make more informed decisions about each production or placement operation.

Examples of QLA Used for Quality Control

Example 9-E: Using the HMA Air Voids from Example 9-B and corresponding Binder Content data, the contractor calculated the PWL for the two Quality Characteristics (Air Voids and Binder Content) after each five sublots. The Specification Limits for Air Voids were 3-5%, and the Specification Limits for Binder Content were 4.7 to 5.3. The data was cumulatively plotted on a chart after every 5 sublots were tested.

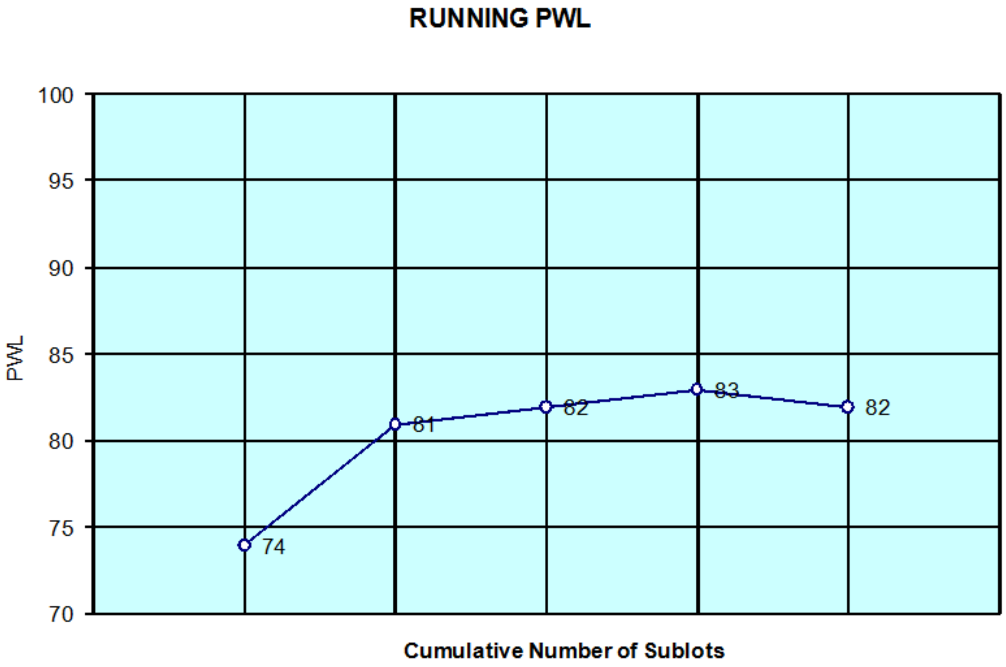
Sample	**Air Voids (P_a)**	**Binder Content (P_b)**
Sublot 1	3.6	5.2
Sublot 2	4.5	4.8
Sublot 3	4.4	5.3
Sublot 4	3.9	5.3
Sublot 5	4.6	5.2
Sublot 6	4.8	5.1
Sublot 7	4.6	4.9
Sublot 8	5.2	4.7
Sublot 9	4.8	5.3
Sublot 10	5.0	4.9
Sublot 11	3.8	5.1
Sublot 12	4.2	5.2
Sublot 13	4.2	5.1
Sublot 14	4.3	4.8
Sublot 15	4.0	4.7
Sublot 16	4.3	5.1
Sublot 17	4.0	4.7
Sublot 18	3.6	4.7
Sublot 19	3.6	5.0
Sublot 20	3.5	5.2
Sublot 21	4.3	5.3
Sublot 22	4.2	4.7
Sublot 23	4.6	5.0
Sublot 24	3.0	4.9
Sublot 25	3.7	4.7

Example 9-E (Continued):



Summary of Quality Level Analysis for HMA Air Voids							
Number of Cumulative Sublots	$\bar{X}$	s	Q_U	Q_L	P_U	P_L	PWL
1 to 5	4.20	0.430	1.86	2.79	100	100	100
1 to 10	4.54	0.484	0.95	3.18	83	100	83
1 to 15	4.39	0.456	1.34	3.05	91	100	91
1 to 20	4.24	0.497	1.53	2.49	94	100	94
1 to 25	4.19	0.524	1.55	2.27	94	100	94

Example 9-E (Continued):

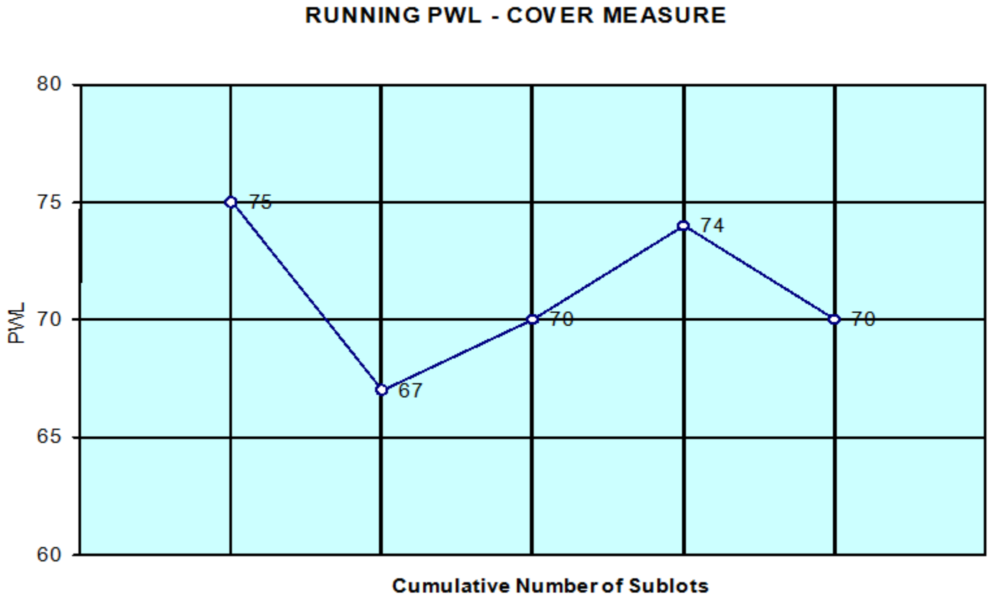


Summary of Quality Level Analysis for HMA Binder Content							
Number of Cumulative Sublots	$\bar{X}$	**s**	**Q_U**	**Q_L**	**P_U**	**P_L**	**PWL**
1 to 5	5.2	0.21	0.68	2.22	74	100	74
1 to 10	5.1	0.23	1.02	1.63	85	96	81
1 to 15	5.0	0.22	1.18	1.55	88	94	82
1 to 20	5.0	0.22	1.29	1.43	90	93	83
1 to 25	5.0	0.22	1.35	1.32	91	91	82

Example 9-F: Using the PCC cover data from Example 9-C, the contractor calculated the PWL after each five sublots. The Specification Limits (LSL and USL) for cover were 2 in. (50 mm) and 3 in. (75 mm). The data was cumulatively plotted on a chart after every 5 sublots were tested.

Sample	PCC Cover, in. (mm)
Sublot 1	2.16 (55)
Sublot 2	2.05 (52)
Sublot 3	1.89 (48)
Sublot 4	2.20 (56)
Sublot 5	2.44 (62)
Sublot 6	2.05 (52)
Sublot 7	2.28 (58)
Sublot 8	1.85 (47)
Sublot 9	1.81 (46)
Sublot 10	2.16 (55)
Sublot 11	2.01 (51)
Sublot 12	1.97 (50)
Sublot 13	2.20 (56)
Sublot 14	2.32 (59)
Sublot 15	2.01 (51)
Sublot 16	2.48 (63)
Sublot 17	2.28 (58)
Sublot 18	2.13 (54)
Sublot 19	2.28 (58)
Sublot 20	1.89 (48)
Sublot 21	1.93 (49)
Sublot 22	2.05 (52)
Sublot 23	2.01 (51)
Sublot 24	1.97 (50)
Sublot 25	1.93 (49)

Example 9-E (Continued):



Summary of Quality Level Analysis for PCC Cover							
Number of Cumulative Sublots	$\bar{X}$	s	Q_U	Q_L	P_U	P_L	PWL
1 to 5	2.15	0.2027	4.20	0.73	100	75	75
1 to 10	2.09	0.1999	4.56	0.45	100	67	67
1 to 15	2.09	0.1796	5.05	0.52	100	70	70
1 to 20	2.12	0.1914	4.58	0.64	100	74	74
1 to 25	2.09	0.1815	4.99	0.52	100	70	70

-END OF CHAPTER 9-

CHAPTER 10

Applications for Acceptance and Payment

Chapter 10

Applications for Acceptance and Payment

Chapter Overview

In this chapter, the following mathematical applications for agency Acceptance will be specifically discussed:

10.1 - Targets and Quality Limits Used for Acceptance

10.2 - Correlation of Test Data

10.3 - Validation of QC Data Used in Acceptance Determination

10.4 - Using PWL to Compute Pay Factors

10.5 - Using Composite Pay Factors

10.6 - Determining Pay Adjustments

10.1 - Targets and Quality Limits Used for Acceptance

Target Value

Quality Assurance Specifications will typically include a ***target value*** for each Quality Characteristic identified for Acceptance measurement or testing. The target value represents the desired average or mean value for all of the material samples representing a lot. The target value is defined as follows:

> **Target Value** - "The value that is placed on a Quality Characteristic that represents the mean of the expected distribution of the specified population."

As will be further discussed below, target values are used with Quality Limits to evaluate the acceptability of construction material. The target value defines the ideal value for the Quality Characteristic being measured and should be oriented at the midpoint between the Quality Limits.

It is desirable for agency Acceptance test results to fall close to the target value. When a majority of the test results are grouped around the expected mean, the Quality Level Analysis will indicate a higher degree of Percent Within Limits (PWL), which in turn represents a higher level of product quality. Recall that populations with normal distributions will have a majority of the data grouped around the mean.

Agency QA Specifications will assign target values based upon industry standards/codes or engineering requirements together with known population parameters based upon the evaluation of pilot project data. Target values for individual Quality Characteristics are generally assigned as the mean value. In some instances, the target value is selected from a specified range and established with the approved job mix formula (JMF), such as for an HMA mixture.

Quality Limits

As explained in Chapter 4, there are three general types of Quality Limits that are typically included in Quality Assurance Specifications. They include:

- Specification Limits
- Engineering Limits
- Acceptance Limits

Although each type of Quality Limit serves a different specific function, they are used together to evaluate the quality of a lot. An example of how Quality Limits may appear in a QA Specification is shown in the table below. Each of these Quality Limits is further described below.

Example - Quality Limits for PG Asphalt Binder Content and HMA Air Voids

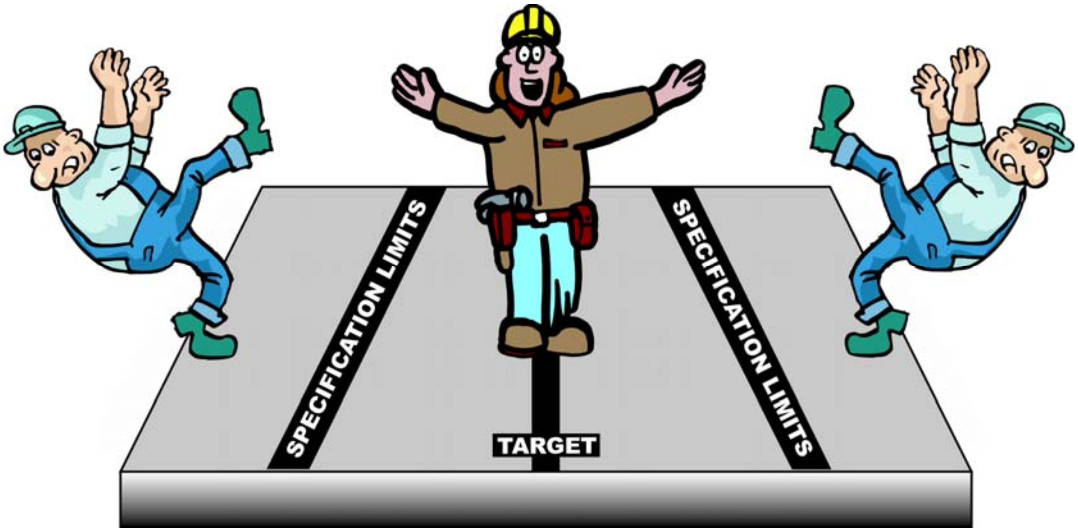
Quality Characteristic	Target	Specification Limits		Engineering Limits		Acceptance Limit
		LSL	USL	LEL	UEL	
PG Asphalt Binder Content	Per JMF	Target - 0.4 %	Target + 0.4 %	Target - 0.6 %	Target + 0.6 %	60 PWL
Air Voids (Lab Compacted)	4 %	3 %	5 %	2 %	6 %	60 PWL

Specification Limits

The first type of Quality Limits found in QA Specifications are “soft” statistical limits used to evaluate all of the test results for a lot and are called the ***Specification Limits***. Specification Limits are defined as follows:

> **Specification Limits** - “The statistically based limiting value(s) placed on a Quality Characteristic which are applied with a particular Quality Measure (such as PWL) to evaluate the quality of a lot.”

Specification Limits are usually comprised of an Upper Specification Limit (USL), a Lower Specification Limit (LSL), or both. It is important to recognize that since Specification Limits are statistical limits, individual sample test results may fall beyond the USL or LSL and still be included in the Acceptance determination. The Specification Limits will ultimately be used for computation of Quality Levels (e.g., PWL), which will be used in calculating pay factors for a lot.



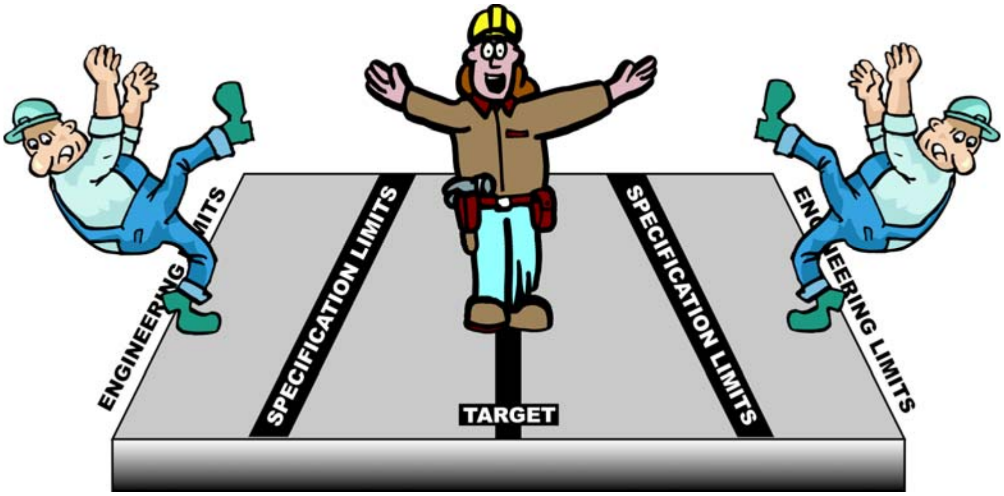
Specification Limits are typically established for individual Quality Characteristics based on a combination of the desired mean and the desired standard deviation for a population of material. Pilot project data should be used to optimize the Specification Limits and ensure that they reflect the inherent variability for a specific Quality Characteristic.

Engineering Limits

The second type of Quality Limits found in QA Specifications are "hard" absolute limits used to evaluate the individual test results for a lot and are called ***Engineering Limits***. Engineering Limits provide an absolute threshold value for individual material samples and are defined as follows:

> **Engineering Limits** - "The absolute limiting value(s) placed on a Quality Characteristic beyond which the test result for an individual sample is considered to be unacceptable."

Engineering limits are established to identify material that does not provide the minimum required engineering properties. They usually have an Upper Engineering Limit (UEL), a Lower Engineering Limit (LEL), or both. The Engineering Limits <u>may</u> be the same as the Specification Limits. Individual sample test results that fall beyond the Engineering Limits are considered to represent material that appears to be below an acceptable level and which should be further evaluated to support an appropriate disposition.



Acceptance Limits

The third type of Quality Limits found in QA Specifications is referred to as the ***Acceptance Limits***. Unlike Specification Limits or Engineering Limits which are placed on a Quality Characteristic, an Acceptance Limit is the limit placed on a Quality Measure. The TRB Glossary (E-C074) defines an Acceptance Limit as follows:

> **Acceptance Limit** - “In variables Acceptance plans, the limiting upper or lower value, placed on a Quality Measure, that will permit acceptance of a lot.”

While the test values for material samples are evaluated with Specification Limits and Engineering Limits, the computed quality level for a specific Quality Measure is evaluated against the Acceptance Limit. A typical Quality Measure used in the “Acceptance Plan” of a QA Specification is Percent Within Limits. For example, the minimum allowable PWL called out in a QA Specification might be 65 PWL. This is the Acceptance Limit. If the final calculated PWL for a lot is found to be less than 65 PWL, it is below the Acceptance Limit, and therefore, a disincentive would be applied. (Material would be rejected only if it was found to be below the Rejectable Quality Level, or RQL.)

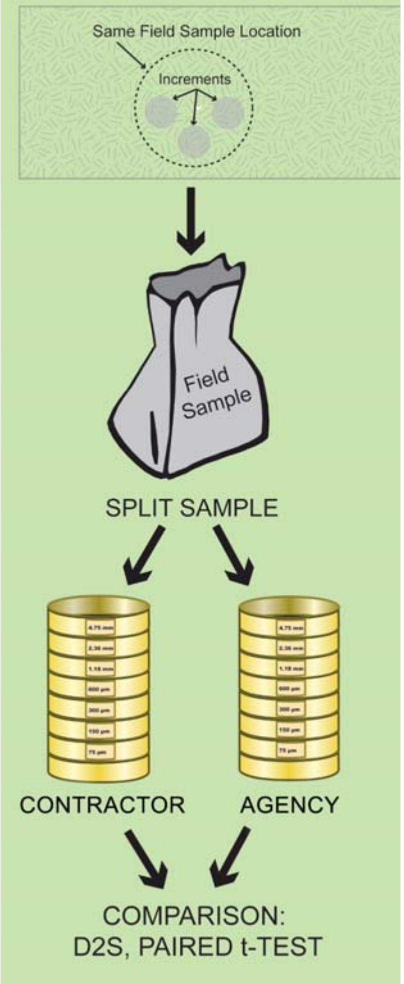
10.2 - Correlation of Test Data

Split Sample Correlation Defined

When the agency elects to include contractor Quality Control test results in the acceptance determination, a recommended practice is to compare contractor and agency results to one another in a two step process. The first step is known as ***correlation***, which is defined as follows:

> **Split Sample Correlation** - "The comparison of split samples tested by different parties (e.g., agency vs. contractor) against an allowable degree of test result difference attributable to sampling and testing variability."

SPLIT SAMPLE CORRELATION



Function of Split Sample Correlation

There are two principal applications of correlation. First, prior to or in the early stages of production (or whenever necessary during production), correlation of QC and Acceptance sampling and testing should be performed on split samples to assure that the contractor and agency results being generated are comparable.

In the second instance, if the agency acceptance determination uses the option of including all validated QC test results plus splits of the agency Acceptance results (Approach #2, Option B, described in Chapter 2 and Chapter 6), then the split samples tested by the contractor are correlated with the agency samples.

Split Sample Correlation Approaches

Normally initial correlation testing will be required prior to the start of production or placement of material. The specification may additionally require subsequent correlation testing at a stated frequency during production or placement. Also, as mentioned above, correlation must be performed on split samples that are utilized in the agency acceptance determination. The correlation comparison is valid only for the procedure(s) and equipment being used. Correlation does not identify discrepancies in the overall population (lot). It is only intended to identify test value differences between the contractor and the agency attributable to sampling and testing. The correlation procedure will typically follow one of the following two approaches:

- Use AASHTO D2S precision statements.
- Use the paired t-test.
- Use state-developed comparison limits.

Agency QA Specifications should identify the correlation procedure to be used. Both of the above correlation approaches are described below.

Split Sample Correlation Using AASHTO D2S Precision Statements

D2S represents two standard deviation limits for the difference between two random variables drawn from the same normal distribution. D2S limits are determined using the following formula:

$$\text{D2S} = 2 \times \sqrt{2} \times (1\text{S})$$

If the contractor and agency split sample test results differ by more than D2S, there is only about a 5% chance that they came from the same population.

Some AASHTO test procedures contain D2S precision statements that can be used for correlation of contractor and agency test results from a single split sample. The correlation procedure involves comparing the contractor and agency split sample test results directly against the AASHTO D2S limit. As long as the two test results differ by no more than the D2S value, they are considered to correlate. Examples of D2S precision values for some AASHTO test procedures are listed in the table below.

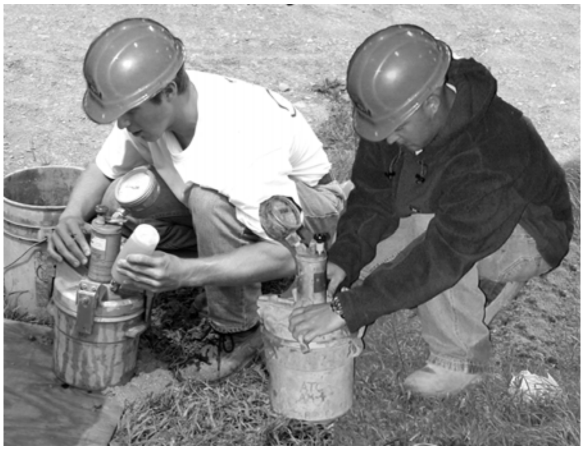
Examples of AASHTO D2S Precision Values		
AASHTO Test Method	**Title**	**D2S Limit***
T 27	Sieve Analysis of Fine and Coarse Aggregate (Coarse Aggregate - Total % of Material Passing < 100, ≥ 95)	1.0
T 164	Quantitative Extraction of Bitumen from Paving Mixtures	0.81
T 304	Uncompacted Void Content of Fine Aggregate	0.93

*NOTE: See specific AASHTO Test Method for any specific qualifications to D2S values.

Split Sample Correlation Using the Paired t-Test

The D2S comparison is simple and can be done for each split sample that is obtained. However, this procedure compares only two test results (from one split sample), and is not very powerful due to the limited amount of data being evaluated. The ***paired t-test***, on the other hand, compares multiple sets of split samples, and is a better method for comparison since this test uses the difference between multiple pairs of tests and determines whether the average difference is statistically different from zero (0). That is, we are trying to determine whether the average difference between pairs is larger than what is probable (reasonably expected) from splits of the same material sample. It is the difference within pairs, not between pairs, that is being tested. It is for this reason that the paired t-test should be used for multiple or accumulating split samples.

It is recommended to use a larger amount of agency correlation testing early in a project. Having more data available to perform the correlation lends greater credence to the comparison between agency and contractor results. A minimum of eight (8) paired test results is suggested.



The t-test for paired measurements, or paired t-test, uses the difference between each pair of tests of split samples and determines whether the difference is much different from zero (0). The t-test for paired measurements calculates a ***paired t value*** (t_{pair}) from the differences in the split sample test results. The t_{pair} value is calculated using the following formula:

$$t_{pair} = \frac{\left|\overline{X}_d\right|}{\left(\frac{S_d}{\sqrt{n}}\right)}$$

Where: X_d = Individual difference between split sample test results

n = Number of split samples

$\overline{X}_d$ = Mean of the differences between the split sample test results, calculated as follows:

$$\overline{X}_d = \frac{(x_{d1} + x_{d2} + \ldots x_n)}{n}$$

S_d = Standard deviation of the differences between the split sample test results, calculated as follows:

$$S_d = \sqrt{\frac{\sum (x_d - \bar{x}_d)^2}{n-1}}$$

The calculated t_{pair} value is then compared to a ***critical t value*** (t_{crit}) obtained from the *FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications* (found online at http://www.tfhrc.gov/pavement/pccp/pubs/02095/02095.pdf). The table shown below provides several levels of significance.

t-test Critical Values for Various Levels of Significance

Degrees of freedom	α = 0.01	α = 0.05	α = 0.10	α = 0.025
1	63.657	12.706	6.314	24.452
2	9.925	4.303	2.920	6.205
3	5.841	3.182	2.353	4.177
4	4.604	2.776	2.132	3.495
5	4.032	2.571	2.015	3.163
6	3.707	2.447	1.943	2.969
7	3.499	2.365	1.895	2.841
8	3.355	2.306	1.860	2.752
9	3.250	2.262	1.833	2.685
10	3.169	2.228	1.812	2.634
11	3.106	2.201	1.796	2.593
12	3.055	2.179	1.782	2.560
13	3.012	2.160	1.771	2.533
14	2.977	2.145	1.761	2.510
15	2.947	2.131	1.753	2.490
16	2.921	2.120	1.746	2.473
17	2.898	2.110	1.740	2.458
18	2.878	2.101	1.734	2.445
19	2.861	2.093	1.729	2.433
20	2.845	2.086	1.725	2.423
21	2.831	2.080	1.721	2.414
22	2.819	2.074	1.717	2.405
23	2.807	2.069	1.714	2.398
24	2.797	2.064	1.711	2.391
25	2.787	2.060	1.708	2.385
26	2.779	2.056	1.706	2.379
27	2.771	2.052	1.703	2.373
28	2.763	2.048	1.701	2.368
29	2.756	2.045	1.699	2.364
30	2.750	2.042	1.697	2.360
40	2.704	2.021	1.684	2.329
60	2.660	2.000	1.671	2.299
120	2.617	1.980	1.658	2.270
∞	2.576	1.960	1.645	2.241

Based on the comparison of the calculated t_{pair} value for the split sample test results to the appropriate t_{crit} value from the above table, one of two decisions will be made:

- **When $t_{pair} \geq t_{crit}$** – The difference between the paired test results of the split samples is greater than is likely to occur from chance, and therefore the contractor's and agency's test result differences are not similar.

- **When $t_{pair} < t_{crit}$** – There is no reason to believe that the paired test results are different and therefore they may be assumed to have come from the same population.

Paired t-Test Examples

Example 10-A: An agency and contractor are required to perform correlation using the paired t-test on split samples. The table below presents the split sample test results for laboratory-compacted HMA Air Voids. Determine whether a difference exists between the contractor and agency results.

Example 10-A – HMA Air Void Test Results

Split Sample No.	Contractor	Agency	Difference (X_d)*
1	3.8	4.6	-0.8
2	3.4	4.4	-1.0
3	3.1	3.7	-0.6
4	4.1	4.5	-0.4
5	3.9	4.8	-0.9
		$\bar{X}_d$ =	-0.74
		s_d =	0.2408

*NOTE: This difference is not the absolute difference, it is the algebraic difference. Make sure that the subtraction (i.e., contractor minus agency) is performed in the same direction for every set of split samples.

Example 10-A (Continued):

Step 1: Compute the t-statistic for the paired measurements

- The t_{pair} value for the split sample test results is determined as follows:

$$t_{pair} = \frac{\left|\overline{X}_d\right|}{\left(\frac{S_d}{\sqrt{n}}\right)}$$

$$t_{pair} = \frac{\left|-0.74\right|}{\left(\frac{0.2408}{\sqrt{5}}\right)} = \frac{0.74}{\left(\frac{0.2408}{2.2361}\right)} = \frac{0.74}{0.1077} = 6.8709 = 6.871$$

Step 2: Determine the appropriate t_{crit} value

- For n - 1 (5 - 1 = 4) degrees of freedom and an α =0.01, the t_{crit} value is determined from the table of t-test critical values (See page 10-12).

$$t_{crit} = 4.604$$

Step 3: Determine if contractor and agency split sample values correlate

$6.871 > 4.604$ ($t_{pair} \geq t_{crit}$)

Conclusion: Since the calculated t_{pair} value is greater than the t_{crit} value, the difference between the paired test results of the split samples is greater than is likely to occur from chance (i.e., the split samples are not considered to be from the same population). We therefore assume the contractor's and agency's test results from paired measurements are not similar (i.e., do not correlate). This indicates that the technicians, testing methods, and test equipment are not providing similar results. Keep in mind that we can conclude nothing about the material variation.

Example 10-B: Prior to the start of crushed aggregate base production on a project, it is desirable that correlation be performed by the contractor and agency for the 75µm (No. 200) sieve. The split sample test results are provided in the table below. Determine whether a difference exists between the contractor and agency results.

Example 10-B – Percent Passing 75µm Test Results

Split Sample No.	Contractor	Agency	Difference (X_d)*
1	5.2%	5.4%	-0.2%
2	5.7%	6.0%	-0.3%
3	5.1%	6.2%	-1.1%
4	6.0%	6.5%	-0.5%
5	5.8%	5.7%	0.1%
6	5.3%	5.8%	-0.5%
		$\overline{X}_d$ =	-0.4167
		s_d =	0.4021

*NOTE: This difference is not the absolute difference, it is the algebraic difference. Make sure that the subtraction (i.e., contractor minus agency) is performed in the same direction for every set of split samples.

Step 1: Compute the t-statistic for the paired measurements

- The t_{pair} value for the split sample test results is determined as follows:

$$t_{pair} = \frac{\left|\overline{X}_d\right|}{\left(\frac{S_d}{\sqrt{n}}\right)}$$

$$t_{pair} = \frac{\left|-0.4167\right|}{\left(\frac{0.4021}{\sqrt{6}}\right)} = \frac{0.4167}{\left(\frac{0.4021}{2.4495}\right)} = \frac{0.4167}{0.1642} = 2.538$$

Example 10-B (Continued):

Step 2: Determine the appropriate t_{crit} value

- For n - 1 (6 - 1 = 5) degrees of freedom and an α =0.01, the t_{crit} value is determined from the table of t-test critical values (See page 10-12).

$$t_{crit} = 4.032$$

Step 3: Determine if contractor and agency split sample values correlate

$$\mathbf{2.538 < 4.032\ (t_{pair} < t_{crit})}$$

Conclusion: Since the calculated t_{pair} value is less than the t_{crit} value, there is no reason to believe that the test results of the split samples are different (i.e., the split samples are assumed to be from the same population). We therefore assume the contractor's and agency's test results from paired measurements are similar (i.e., they do correlate).

If, during the correlation process, we determine that the contractor and agency's test results from paired measurements indicate that the test method, technicians and/or test equipment provide different results, what do we do?

We must look for a source of variation in one or more of the following:

- The test procedure
- The technicians
- The equipment

The source of the difference must be found before continuing the correlation procedure. If the test results are not repeatable using split samples, there is little reason to think that validation of independent samples will produce comparable results.

Example 10-C: Correlation of contractor and agency split sample test results was performed for the entrained air content of PCC. The Excel spreadsheet below was used to perform the paired t-test analysis.

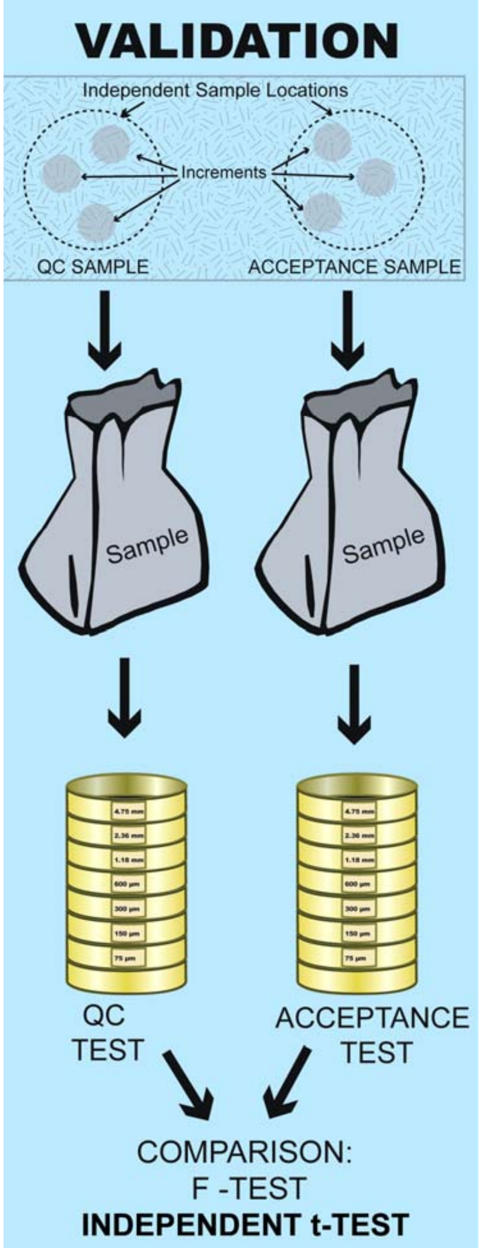
Pair Number	**Test Results**		**Difference**
	QC	Acceptance	
1	5.1	8.0	-2.9
2	4.5	7.0	-2.5
3	4.8	7.6	-2.8
4	6.6	8.2	-1.6
5	4.8	7.9	-3.1
6	6.0	7.5	-1.5
7	6.0	8.0	-2.0
8	6.9	8.7	-1.8
9	4.5	6.5	-2.0
10	4.5	5.5	-1.0
11	4.6	4.9	-0.3
12	4.9	3.2	1.7
$\sum X_d$			-19.8
$\overline{X}_d$			1.65
S_d			1.3304

CORRELATION RESULTS	
Number of tests (n)	12
Deg of freedom (n - 1)	11
Alpha	0.01
t_{pair}	4.296
t crit	3.106
t_{pair} > tcrit?	**yes: paired tests are different**

Conclusion: Since the calculated t_{pair} value is greater than the t_{crit} value, the difference between the paired test results of the split samples is greater than is likely to occur from chance (i.e., the split samples are not considered to be from the same population). We therefore assume the contractor's and agency's test results from paired measurements are not similar (i.e., do not correlate).

10.3 - Validation of QC Data Used in Acceptance Determination

Validation Defined



The correlation process provides a level of confidence that the testing procedures of the contractor and agency can produce acceptable similar results. This is important as a transition to ***validation***, which is the comparison of independently obtained QC and Acceptance sample results. Accordingly, validation is defined as follows:

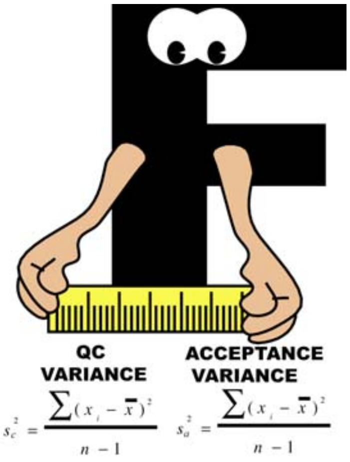
> **Validation** - "The mathematical comparison of two independently obtained sets of data (e.g., agency Acceptance data vs. contractor QC data) to determine whether it can be assumed they came from the same population."

The purpose of validation is to provide a method of comparing two different data sets of multiple test results to determine if the material tested came from the same population. The mathematical tests used to make the comparison are called ***hypothesis tests*.**

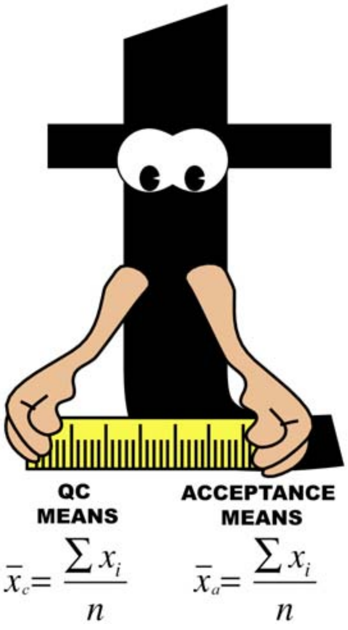
When comparing two data sets for validation, such as contractor QC test results and agency Acceptance test results (or when comparing independently obtained samples for IA), it is important to compare both the means and the variances. A different test is used for each of these properties. The two tests used for validation are:

- F-test
- Independent t-test

Hypothesis Tests Used for Validation



The first hypothesis test used in the validation process is the ***F-test***. The F-test provides a method for comparing the **variances** (standard deviation squared) of two sets of data. The F-test is based on the ratio of the statistical sample variance of the contractor's QC test results, s_c^2, (or the standard deviation of the contractor's independent tests, squared), and the statistical sample variance of the agency's Acceptance test results, s_a^2, (or the standard deviation of the agency's independent tests, squared). The ratio of the two calculated variances (s_c^2 and s_a^2) provides an ***F statistic*** (F), which is then compared to an ***F critical*** (F_{crit}) value obtained from a table similar to that used for the paired t-test. The F-test by itself cannot determine whether or not the two independent sets of data have come from the same population. The F-test is used to determine which version of the independent t-test to run.



The second hypothesis test used in the validation process is the ***independent t-test*** (not the paired t-test). The independent t-test assesses the differences in <u>means</u> of two sets of independently obtained data. The t-test is used to test whether the statistical sample mean of the contractor's QC test results ($\overline{X}_c$) and the statistical sample mean of the agency's Acceptance test results ($\overline{X}_a$) came from populations with the same mean. Depending upon the outcome of the F-test, one of two formulas is used to compute a ***t statistic*** (t), which is then compared to a ***t critical*** (t_{crit}) value obtained from the same table used for the paired t-test. If the computed t statistic (t) is less than the t critical (t_{crit}) value, then the QC data and the Acceptance data can be assumed to have come from the same population.

Conducting the F-test and Independent t-test

Hypothesis tests such as the F-test and the independent t-test are conducted at a selected level of significance, Alpha (α). The level of significance is the probability of incorrectly deciding the data sets are different when they actually come from the same population. It is recommended to use a level of significance for α between 0.01 and .05.

When validating independently obtained contractor QC samples and agency Acceptance samples using the F-test and the independent t-test, it is important that the following considerations have been met:

- Random sampling was used when obtaining the material samples.
- The samples were obtained independently from one another (no split pairs).
- The two sets of test results must have been sampled from the same lot.
- The same correlated sampling and testing procedures have been used.

The ability of the validation procedure to identify differences between two sets of independent test results depends upon the number of test results that are being compared. The greater the number of tests, the greater the ability of the procedure to identify valid differences.

If it is determined that a significant difference is likely between either the variance or the mean, then the source of the difference should be identified. Remember that these tests identify a difference, not a cause. Determining the actual cause of the difference will require some investigation. Split sample correlation testing is one manner of investigation that can lead to a discovery of the cause.

The following pages summarize the key steps for performing the validation procedure.

Step 1: Perform the F-test

- **Compute the variance** (s^2) for each set of test results (contractor and agency).

$$s_c^2 = \frac{\sum(x_i - \bar{x}_c)^2}{n_c - 1} \qquad s_a^2 = \frac{\sum(x_i - \bar{x}_a)^2}{n_a - 1}$$

Where: s_c^2 = Variance of contractor QC samples
s_a^2 = Variance of agency Acceptance samples
X_i = Individual test values
$\bar{x}$ = Mean of tests
n = Number of tests

- **Compute the F statistic** using the larger of s_c^2 or s_a^2 in the numerator and the smaller of s_c^2 or s_a^2 in the denominator of the F equation.

$$F = \frac{s_a^2}{s_c^2} \quad \text{or} \quad F = \frac{s_c^2}{s_a^2}$$

- **Determine the degrees of freedom** for both the numerator and the denominator in the F equation. The degrees of freedom is simply the number of samples (n) minus one, used to compute the F statistic above.

- **Determine F_{crit}** from Table 1 (Critical Values, F_{crit}, for the F-test for a Level of Significance) (*FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications*). Be sure to use the correct degrees of freedom for both the numerator and the denominator.

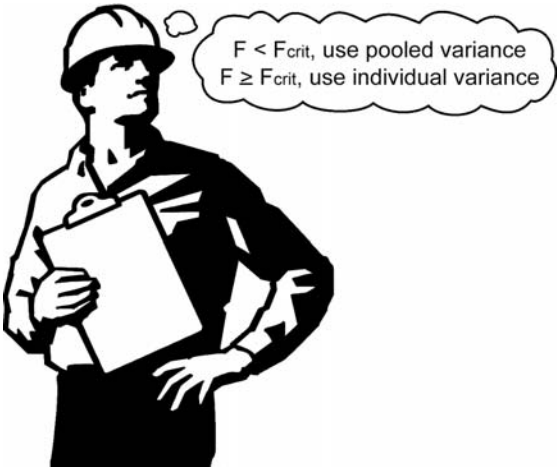
Step 1: Perform the F-test (Continued)

- **Make conclusion from F-test:**

- If computed F is less than F_{crit} – There is no reason to believe that the two sets of data have different variabilities. The Independent t-test will be performed using the pooled variance to determine whether there is a statistically significant difference between the sample means.

- If F is greater than or equal to F_{crit} – The two sets have significantly different variabilities. The Independent t-test will be performed using the individual variances to determine whether there is a statistically significant difference between the sample means.

- Note – When applying the independent t-test in accordance with the procedures outlined in *the FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications*, the F-test by itself cannot determine whether or not the two sets of data have come from the same population. The F-test is used to determine which version of the t-test will need to be run.



Step 2: If F < F_{crit}, perform the independent t-test using the pooled variance

- **Compute the mean** for each set of tests (contractor and agency).

$$\bar{x}_c = \frac{\sum x_i}{n} \qquad \bar{x}_a = \frac{\sum x_i}{n}$$

Where: $\bar{x}_c$ = Mean of contractor QC samples
$\bar{x}_a$ = Mean of agency Acceptance samples
X_i= Individual test values
n = Number of tests

- **Compute the Independent t-test using the pooled variance** using both QC and Acceptance data.

$$s_p^2 = \frac{s_c^2(n_c - 1) + s_a^2(n_a - 1)}{n_c + n_a - 2}$$

Where: s_p^2 = Pooled Variance
s_c^2 = Variance of the QC tests
s_a^2 = Variance of the Acceptance tests
n_c = Number of QC tests
n_a = Number of Acceptance tests

Step 2: If F < F_{crit}, perform the Independent t-test using the pooled variance (Continued)

- **Compute the t statistic** (using the equation for pooled variance)

$$t = \frac{\left|\bar{x}_c - \bar{x}_a\right|}{\sqrt{\frac{s_p^2}{n_c} + \frac{s_p^2}{n_a}}}$$

Where: t = t statistic

$\bar{x}_c$ = Mean of QC tests

$\bar{x}_a$ = Mean of Acceptance tests

s_p^2 = Pooled Variance

n_c = Number of QC tests

n_a = Number of Acceptance tests

- **Determine the pooled degrees of freedom** for both the numerator and the denominator. The pooled degrees of freedom of freedom = (n_c + n_a – 2).

- **Determine t_{crit}** from Table 2 (Critical Values, t_{crit}, for the t-test for Various Levels of Significance) found in *FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications.*

- **Make conclusion from Independent t-test using pooled variance:**

- If computed t is less than t_{crit} - There is no reason to believe that the two sets of data have different means, and it reasonable to assume that the sets of data describe the same population.

- If computed t is greater than t_{crit} - There is reason to believe that the two sets of data have different means, and therefore do not describe the same population.

Step 3: If F ≥ F_{crit}, perform the Independent t-test using the individual variances

- **Compute the mean** for each set of tests (contractor and agency).

$$\bar{x}_c = \frac{\sum x_i}{n} \qquad \bar{x}_a = \frac{\sum x_i}{n}$$

Where: $\bar{x}_c$ = Mean of contractor QC samples
$\bar{x}_a$ = Mean of agency Acceptance samples
X_i= Individual test values
n = Number of tests

- **Compute the t statistic** (using the equation for individual variances)

$$t = \frac{\left|\bar{x}_c - \bar{x}_a\right|}{\sqrt{\frac{s_c^2}{n_c} + \frac{s_a^2}{n_a}}}$$

Where: t = t statistic
$\bar{x}_c$ = Mean of QC tests
$\bar{x}_a$ = Mean of Acceptance tests
s_c^2 = Variance of QC tests
s_a^2 = Variance of Acceptance tests
n_c = Number of QC tests
n_a = Number of Acceptance tests

Step 3: If F ≥ F_{crit}, perform the Independent t-test using the individual variances (Continued)

- **Determine the effective degrees of freedom (f')**

$$f' = \left[\frac{\left(\frac{s_c^2}{n_c} + \frac{s_a^2}{n_a} \right)^2}{\frac{\left(\frac{s_c^2}{n_c} \right)^2}{n_c + 1} + \frac{\left(\frac{s_a^2}{n_a} \right)^2}{n_a + 1}} \right] - 2$$

Where: f' = Effective degrees of freedom
s_c^2 = Variance of QC tests
s_a^2 =Variance of Acceptance tests
n_c = Number of QC tests
n_a = Number of Acceptance tests

- **Determine t_{crit}** from Table 2 (Critical Values, t_{crit}, for the t-test for various levels of significance).

- **Make conclusion from the independent t-test using the Individual variances:**

➢ If computed t is less than t_{crit} - There is no reason to believe that the two sets of data have different means, and it reasonable to assume that the sets of data describe the same population.

➢ If computed t is greater than t_{crit} - There is reason to believe that the two sets of data have different means, and therefore do not describe the same population.

Example 10-D: Using the HMA Air Void data from Chapter 8, Example 8-C (agency Acceptance samples) and Chapter 9, Example 9-E (contractor QC Samples), validation of the QC data was performed by the agency with the F-test and independent t-test using a computer spreadsheet with the following results. The level of significance (alpha) value was selected as 0.01.

Quality Control Sample Data	Acceptance Sample Data
3.6	8.2
4.5	3.9
4.4	4.7
3.9	5.4
4.6	4.1
4.8	
4.6	
5.2	
4.8	
5.0	
3.8	
4.2	
4.2	
4.3	
4.0	
4.3	
4.0	
3.6	
3.6	
3.5	
4.3	
4.2	
4.6	
3.0	
3.7	

F test		
	QC	**Acceptance**
count of data	25	5
S	0.524	1.744
S^2	0.275	3.042
F	11.06	
Deg. of Freedom, Numerator:	4	
Deg. of Freedom, Denominator:	24	
F_{crit} (Table 1)	4.89	
$F<F_{crit}$?	NO, USE INDIVIDUAL VARIANCE	

Independent t-test (pooled variance), $F<F_{crit}$		
Pooled Variance	NA	
Mean	4.19	5.26
t test	NA	
Pooled Deg Freedom	NA	
t_{crit}	NA	
$t<t_{crit}$?	NA	
Independent t-test (individual variances), $F^{3}F_{crit}$		
t statistic	1.360	
f' numerator	0.38365636	
f' denominator	4.65385E-06	0.06169176
f' (effective degrees freedom)	4	
t_{crit} (Table 2)	4.604	
$t<t_{crit}$?	YES, SAME POPULATION	

Despite the fact that the F-test indicates a statistically significant difference between the variances for the two sets of data, the independent t-test indicates that the two sets of data could still be considered to have come from the same population.

Example 10-E: Using the HMA Binder Content data from Chapter 8, example 8-C (agency Acceptance samples) and Chapter 9, example 9-E (contractor QC Samples), validation of the QC data was performed by the agency with the F-test and independent t-test using a computer spreadsheet with the following results. The level of significance (alpha) value was selected as 0.01.

Quality Control Sample Data	Acceptance Sample Data
5.2	5.7
4.8	5.7
5.3	4.8
5.3	5.2
5.2	5.4
5.1	
4.9	
4.7	
5.3	
4.9	
5.1	
5.2	
5.1	
4.8	
4.7	
5.1	
4.7	
4.7	
5.0	
5.2	
5.3	
4.7	
5.0	
4.9	
4.7	

F test		
	QC	**Acceptance**
count of data	25	5
S	0.224	0.378
S^2	0.05	0.143
F	2.86	
Deg. of Freedom, Numerator:	4	
Deg. of Freedom, Denominator:	24	
F_{crit} (Table 1)	4.89	
$F<F_{crit}$?	YES, USE POOLED VARIANCE	

Independent t-test (pooled variance), F <F_{crit}		
Pooled Variance	0.063	
Mean	5	5.36
t test	2.921	
Pooled Deg Freedom	28	
t_{crit}	2.763	
$t<t_{crit}$?	DIFFERENT POPULATION	
Independent t-test (individual variances), F³F $_{crit}$		
t statistic	use pooled variance	
f' numerator	NA	
f' denominator	NA	NA
f' (effective degrees freedom)	NA	
t_{crit} (Table 2)	NA	
$t<t_{crit}$?	use pooled variance	

In this example, the F test indicates that there is no statistically significant difference between the variances for the two sets of data. However, the independent t-test (using an alpha factor of 0.01) indicates that a statistically significant difference does exist between the means of the two sets of data. Therefore, we would conclude the two sets of data <u>did not</u> come from the same population.

Example 10-F: Using the PCC cover data from Chapter 8, example 8-H (agency Acceptance samples) and Chapter 9, example 9-F (contractor QC Samples), validation of the QC data was performed by the agency with the F-test and independent t-test using a computer spreadsheet with the following results. The level of significance (alpha) value was selected as 0.01.

Quality Control Sample Data	Acceptance Sample Data
2.16	2.13
2.05	2.64
1.89	2.24
2.20	1.89
2.44	2.32
2.05	
2.28	
1.85	
1.81	
2.16	
2.01	
1.97	
2.20	
2.32	
2.01	
2.48	
2.28	
2.13	
2.28	
1.89	
1.93	
2.05	
2.01	
1.97	
1.93	

F test		
	QC	**Acceptance**
count of data	25	5
S	4.646	6.964
S^2	21.585	48.497
F	2.25	
Deg. of Freedom, Numerator:	4	
Deg. of Freedom, Denominator:	24	
F_{crit} (Table 1)	4.89	
$F<F_{crit}$?	YES, USE POOLED VARIANCE	

Independent t-test (pooled variance), F <F_{crit}		
Pooled Variance	25.430	
Mean	53.2	57
t test	1.538	
Pooled Deg Fre	28	
t_{crit}	2.763	
$t<t_{crit}$?	SAME POPULATION	
Independent t-test (individual variance), F^3F_{crit}		
t statistic	use pooled variance	
f' numerator	NA	
f' denominator	NA	NA
f' (effective degrees freedom)	NA	
t_{crit} (Table 2)	NA	
$t<t_{crit}$?	use pooled variance	

In this example, the F-test indicates that there is no statistically significant difference between the variances for the two sets of data. The independent t-test (using an alpha of 0.01) also indicates there is no statistically significant difference between the means of the two sets of data. Therefore, we would conclude that the two sets of data came from the same population.

Key Points for Validation

The following important points should be remembered when using the F-test and the independent t-test to perform validation:

- Validation is performed using the F-test and independent t-test
- Run the F-test first
- The independent t-test holds more weight than the F-test
- If the tests show that the populations are not the same, then use the agency's test results only for contract compliance.
- It is suggested that all available random contractor QC sample results and agency Acceptance results for a given lot be used when performing validation. It is recommended to use all random data and keep building the numbers (n) within the lot. However, be aware if the n value becomes too large, the sensitivity to individual test values is diminished.
- As you continue using this tool, it is possible to use a moving average of samples, either within a lot or across multiple lots. Therefore, after you have obtained the agency required minimum number of samples, say eight for example, then begin to drop the earlier tests and add the new tests such that you maintain an updated Statistical Sample size of, in this case, eight.
- When performing the t-test, it is recommended to use a level of significance, α, of 0.01 when entering Table 2 (from *FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications)*.
- When performing the F-test, use n-1 for the degrees of freedom as input when entering Table 1 in Appendix F of the FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications.
- Since the F-test is the ratio of one number over another number, always use the larger number as the numerator.

10.4 - Using PWL to Compute Pay Factors

Pay Factor Defined

As demonstrated in Chapter 8, the Quality Level for a particular Quality Characteristic is represented by the Percent Within Limits (PWL). There will be a certain PWL as listed in the specification that warrants 100% pay. QA Specifications will also provide a mechanism to adjust payment with respect to the quality of the material. Accordingly, ***pay factors*** correspond to PWL.

A pay factor is defined as follows:

> **Pay Factor** - "A multiplication factor, often expressed as a percentage, that considers a single Quality Characteristic and is used to determine the contractor's payment for a unit of work."

Typically, the term "pay factor" applies to only one Quality Characteristic. The purpose of pay factors is to recoup losses expected from poor quality work and to reward for increased performance obtained through increases in product consistency. A pavement of poor quality might warrant a low pay factor of 75% while a pavement of such exceptional quality might warrant an incentive factor of 10%.

Approaches to Using Pay Factors

Some pay schedules are biased downward and fail to award 100 percent payment, on the average, when the work is exactly at the level of quality that has been defined as acceptable, that is, at the Acceptable Quality Level (AQL). The AQL is defined as follows:

> **Acceptable Quality Level (AQL)** - "The minimum level of established actual quality for a Quality Characteristic that is considered fully acceptable when using a particular Quality Measure."

For example, when the Quality Measure used is Percent Within Limits (PWL), the AQL is the established (not estimated) PWL at which the lot can be considered fully acceptable. Acceptance plans should be designed so that AQL material will receive an expected pay (EP) of 100%.

A downward biased pay schedule is the result of limiting the maximum pay factor to 100 percent. This can be overcome by applying a positive pay factor that can be justified to be applied to greater quality. It is recommended to set the Acceptable Quality Level at, say 95%, and award 100% payment at this level.

Quality Assurance specifications typically use one of the following approaches to determine pay factors:

- Pay Factor Tables
- Pay Factor Formulas
- Pay Factor Curves

Under each approach, the pay factors are directly related to the Percent Within Limits (PWL) obtained from the Quality Level Analysis. It is recommended to use continuous payment schedules rather than stepped pay factors. Pay factors should eventually be based upon a present worth, life-cycle cost assessment. Each of these pay factor approaches is further discussed below.

Pay Factor Tables

Historically, pay factor tables have been the most common means used to relate pay to PWL. The advantage of pay factor tables is that they provide a simple look up format (based on the computed PWL and the number of samples used to calculate the PWL) in order to derive the pay factor. The following excerpted pay factor table (reproduced from USDOT FHWA FP-03, *Standard Specifications for Roads and Bridges on Federal Highway Projects*) is typical in the manner of presentation and lookup to other pay factor tables.

Required Quality Level (PWL) for a Given Sample Size (n) and Corresponding Pay Factor

Pay Factor	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=17	n=18 to n=22	n=23 to n=29	n=30 to n=42	n=43 to n=66	n=67 to n= infinity
1.05						100	100	100	100	100	100	100	100	100	100
1.04					100	99	97	95	96	96	96	97	97	97	97
1.03				100	98	96	84	92	93	93	94	95	95	96	96
1.02				99	97	94	91	89	90	91	92	93	93	94	94
1.01	100	100	100	98	95	92	89	87	88	89	90	91	92	92	93
1.00	69	75	78	80	82	83	84	85	86	87	88	89	90	91	92
0.99	66	72	76	78	80	81	82	83	84	85	86	87	89	90	91
0.98	64	70	74	76	78	79	80	81	82	84	85	86	87	88	90
0.97	63	68	72	74	76	77	78	79	81	82	83	84	86	87	88
0.96	61	67	70	72	74	75	76	78	79	81	82	83	84	86	87
0.95	59	65	68	71	72	74	75	76	78	79	80	82	83	84	86
0.94	58	63	67	69	71	72	73	75	76	78	79	80	82	83	85
0.93	57	62	65	67	69	71	72	73	75	76	78	79	80	82	84
0.92	55	60	63	66	68	69	70	72	73	75	76	78	79	81	82
0.91	54	59	62	64	66	68	69	70	72	74	75	76	78	79	81

One of the disadvantages of a pay factor table is that it contains gaps in PWL for various population sizes (note in the table above where n = 6, between pay factors of 0.99 and 1.00 there is a gap in PWL of 2%). Gaps in pay factor tables produce what is termed a “stepped” pay adjustment since there is no way to derive values in between the steps of the table. This has the effect of misrepresenting pay for some calculated PWL’s.

Pay Factor Formulas

Unlike a pay factor table, which provides a stepped pay schedule, a pay factor formula presents a mathematical equation that typically derives a linear schedule of pay from the PWL. Pay factor formulas may vary from one Transportation agency to another. Below is the pay factor formula provided in *FHWA-RD-02-095, Optimal Procedures for Quality Assurance Specifications.*

$$\textbf{Pay Factor (PF)} = 0.55 + 0.5\ (\textbf{PWL}^*)$$

*NOTE: PWL is expressed as a decimal value (e.g., 0.85) in this equation. For a PWL of 60 (0.60) or less, the agency will make a special evaluation of the material and determine the appropriate action. The agency may want to choose other expressions of the relationship for the pay factor.

Unlike pay factor tables, the pay factor formula does not produce any gaps in PWL, and therefore provides a continuous rather than a stepped approach to pay factors. For simplicity, one pay factor formula is used in the examples below.

Pay Factor Curve

A pay factor curve is simply a graphical representation of a pay equation. Like the pay factor table, lookup is facilitated and no additional math is required. Unlike the pay factor tables, however, the curve (since it relies on the equation) is not stepped, and provides another means of continuous pay adjustment.

Pay Factor Examples

Example 10-G: The agency Acceptance data for Air Voids from Chapter 8, as well as the contractor's QC data for Air Voids from Chapter 9 (n = 30) was used to determine the PWL. Recall that the QC data was validated against the agency's data in Example 10-D, and subsequently a PWL of 70% was calculated. Using the pay factor formula, determine the pay factor for this lot of material.

PF = 0.55 + 0.5 (PWL)
PF= 0.55 + 0.5 (0.70)
PF = 0.55 + 0.35
PF = 0.90, or 90%

Example 10-H: The agency Acceptance data for Binder Content from Chapter 8 (n = 5) was used to determine the PWL. Recall that the contractor's QC data was not validated against the agency's data in Example 10-E, and therefore only agency Acceptance data was used to compute pay. A PWL of 45% was calculated. Using the pay factor formula, determine the pay factor for this lot of material.

PF = 0.55 + 0.5(PWL)
PF= 0.55 + 0.5 (0.45)
PF = 0.55 + 0.225
PF = 0.775, or 77.5%

Example 10-I: The agency's Acceptance PCC Cover data from Chapter 8, as well as the contractor's QC PCC Cover data from Chapter 9 (n = 30) was used to determine the PWL. Recall that the QC data was validated against the agency's data in Example 10-F, and subsequently a PWL of 72 was calculated. Using the pay factor formula, determine the pay factor for this lot of material.

PF = 0.55 + 0.5 (PWL)
PF = 0.55 + 0.5 (0.72)
PF = 0.55 + 0.36
PF =0.91, or 91.0%

10.5 - Using Composite Pay Factors

Composite Pay Factor Defined

Since the ultimate performance of most construction items is dependent upon several Quality Characteristics, highway construction specifications usually include multiple acceptance requirements, many of which result in adjustments to the contract bid amount. When two or more pay factor clauses appear in a single specification they are typically combined into a ***composite pay factor***. A composite pay factor is defined as follows:

> **Composite Pay Factor** - “A multiplication factor, often expressed as a percentage, that considers two or more Quality Characteristics and is used to determine the contractor’s final payment for a unit of work.”

Composite Pay Factor Approaches

The manner in which a composite pay factor is structured must be explicitly stated since there are several ways in which this can be done. As discussed in Chapter 6, the four suggested methods or approaches include:

- Minimum Individual Pay Factor
- Average (or Weighted Average) Method
- Product Method
- Summation Method

Most Quality Assurance specifications utilize the Weighted Average Method to arrive at a composite pay factor for the lot, which is further discussed below.

Weighted Average Approach

Using the Weighted Average Method, the individual pay factors (PF_n) are determined then multiplied by their respective weighting factors (f_i). The value of each weight is determined by the agency through empirical observation or other engineering considerations and usually shows up as a table in the Quality Assurance specifications. These products are then added and divided by the sum of the weights ($\sum f$) as represented by the following equation:

$$CPF = \frac{[f_1(PF_1) + f_2(PF_2) + \ldots f_i(PF_i)]}{\sum f_i}$$

Where:

CPF = Composite pay factor

f_i = Pay adjustment weight factor listed in the specifications for the applicable Quality Characteristic

PF_i = Pay factor for the applicable Quality Characteristic

$\sum f$ = Sum of the "f" (pay adjustment) weight factors

Example 10-J: Using the pay factors for the related Hot Mix Asphalt Quality Characteristics, determine the composite pay factor (CPF) for one lot of material in accordance with the given weighted pay factors. Each of the individual Quality Characteristics includes a maximum pay of 104%.

Quality Characteristic	Pay Factor (%)	Pay Adjustment Weight (%)
Binder Content	103.2	20
Laboratory Air Voids	102.5	35
Voids in the Mineral Aggregate (VMA)	104.0	10
In-Place Density	99.8	35

$$CPF = [f_1(PF_1) + f_2(PF_2) + f_3(PF_3) + f_4(PF_4)] / \sum f$$

$$CPF = [20(103.2) + 35(102.5) + 10(104.0) + 35(99.8)] / 100$$

$$CPF = (2064 + 3588 + 1040 + 3493) / 100$$

$$CPF = 10185 / 100$$

CPF = 101.85 rounds to 101.8

Example 10-K: Using the Pay Factor determined for cover over steel in Example Problem 10-I, and the additional Pay Factor information as presented in the table, along with the weight factors presented, determine the Composite Pay Factor for the Lot of material.

Quality Characteristic	Pay Factor (%)	Pay Adjustment Weight (%)
Cover over Steel	91.0	20
Concrete Strength	105.0	50
Air Content	98.5	20
Rapid Chloride Permeability	96.7	10

$CPF = [f_1(PF_1) + f_2(PF_2) + f_3(PF_3) + f_4(PF_4)] / \sum f$

$CPF = [20\ (91.0) + 50(105) + 20(98.5) + 10(96.7)] / 100$

$CPF = (1820 + 5250 + 1970 + 967) / 100$

$CPF = 10007 / 100$

CPF = 100.07, rounded to 100.1 (or 1.00)

10.6 - Determining Pay Adjustment

Pay Adjustment Defined

A ***pay adjustment*** is defined as follows:

> **Pay Adjustment** - "The actual amount, either in dollars or in dollars per area/weight/volume, that is to be added or subtracted to the contractor's final payment for a unit of work."

Pay adjustments are applied to all pay factors and composite pay factors that have been defined for a pay item under Quality Assurance Specifications. Once all pay adjustments have been determined, they can be added together to determine the final pay adjustment.

Pay adjustments generally take one of two forms:

- Individual Pay Adjustments
- Composite Pay Adjustments

Individual Pay Adjustments

The formula for the individual pay adjustment applied to pay factors is as follows:

$$\mathbf{PA = (PF_i - 1)\ (Q_i)\ (P_i)}$$

Where:

PA = Pay adjustment in dollars

PF_i = Pay factor (decimal form) for the individual Quality Characteristic

Q_i = Quantity represented by individual lot (n)

P_i = Contract unit price per unit of measure.

Composite Pay Adjustments

The formula for the pay adjustment applied to composite pay factors is as follows:

$$\mathbf{PA = (CPF_i - 1)\ (Q_i)\ (P_i)}$$

where:

PA = Pay adjustment in dollars.

CPF_i = Composite pay factor (decimal form) for the Quality Characteristics

Q_i = Quantity represented by individual lot (n).

P_i = Contract unit price per unit of measure.

Examples for Pay Adjustments

Example 10-L: Using the HMA Composite pay factor as determined above in Example 10-K determine the composite pay adjustment where the total quantity shipped was 5,000 tons, the unit price was $50 per ton.

Pay Adjustment Item	Composite Pay Factor (%)
HMA	101.8

Pay Adjustment: PA = (CPF$_i$ – 1) (Q$_i$) (P$_i$)
PA = (101.8 – 1) (5,000) (50)~~)~~
PA = 0.018) (5,000) (50)
PA = $4,500.00

Total HMA Pay Adjustment = $4,500

Example 10-M: Using the pay factor for Water/Cementitious Materials Ratio in the following table, calculate the pay adjustment for the item listed. A total of 500 cubic yards of concrete was placed at a unit price of $150 per cubic yard.

PCC Quality Characteristics	Pay Factor (%)
Water/Cementitious Materials Ratio	101.0

Water/Cementitious Materials Ratio Pay Adjustment:

PA = (PF$_i$ – 1) (Q$_i$) (P$_i$)
PA = (1.01– 1) (500) (150)
PA = 0.01(500) (150)
PA = $750.00

- END OF CHAPTER 10 -

CHAPTER 11

Quality Assurance Project Scenarios

Chapter 11

Quality Assurance Project Scenarios

Chapter Overview

The intent of this chapter is to illustrate and reinforce some of the key concepts of Quality Assurance as discussed earlier in this manual through the use of individual ***Quality Assurance Project Scenarios*** that concentrate on major topic areas. Each Scenario that has been developed is a fictional account based on actual experiences of managers, technicians, and inspectors working under Quality Assurance Specifications on projects throughout New England. Following each Scenario is a group of multiple-choice questions intended to either indicate necessary corrections in the preceding Scenario (to provide consistency with standard Quality Assurance practices) or to validate the activities in the Scenario as being consistent with standard practices.

Scenarios are presented for the following major topic areas:

11.1 - Quality Control Plan Contents and Requirements

11.2 - Quality Control Responsibilities

11.3 - Acceptance Responsibilities

11.4 - Sampling Protocols

11.5 - Inherent Variability and the Normal Distribution Curve

11.6 - Control Charts

11.7 - Correlation and Validation of Test Results

11.1 - Quality Control Plan Contents and Requirements

Scenario 11-A: A paving Contractor on a QA HMA resurfacing project submitted a Quality Control Plan to the Agency during the preconstruction conference. Printed copies of the QC Plan were distributed to the attendees and the Contractor made a brief oral presentation of the plan, walking through each of the major areas addressed by the QC Plan. Since the paving Contractor was sub-contracting the production of the HMA to a third party, the Plan stated that all production-related QC would be handled by the Producer under the Producer's QC Plan that had been previously approved for another QA project, however copies of the Producer's QC Plan were not included in the Contractor's submittal.

The paving Contractor was also sub-contracting the milling to a third party and included a letter from that Subcontractor that briefly stated the schedule of the milling operation (station to station milling and dates), the maintenance and protection of traffic during milling, what equipment would be used to perform the milling, where and how the millings would be deposited, and that the grades and cross sections would be maintained in accordance with the drawings during the operation.

Since the paving Contractor did not have a QC department, or employ personnel whose sole responsibility was QC, the Contractor had a roller operator certified as a paving inspector through a certifying organization. The QC Plan indicated that the roller operator would act both as an operator and as the Plan Administrator for the Contractor, and would also serve as lead QC Inspector during construction, when available. In addition, the Contractor hired a Consultant testing firm to supplement his own QC during the project. The Consultant testing firm listed several certified individuals who might be sent to staff the project, along with resumes for each of those individuals. Their responsibilities, as indicated in the QC Plan, were to “assist the Plan Administrator in the execution of Quality Control.” Additional information on coring was also included, and was stated as follows: “cores will be obtained in accordance with the frequencies as required by the Agency and as stated in the Agency’s Standard Specifications.”

Following the presentation of the QC Plan during the preconstruction conference, the Agency stated that further revision and review would be necessary prior to accepting the QC Plan. However, due to the fact that the project was scheduled to begin the next week, the Agency stated that the Contractor would be able to begin work without a fully approved QC Plan.

Based on what you have learned regarding Quality Control Plans, and the information contained in the preceding Scenario, answer the following questions:

1. Which of the following things the Contractor did, with regard to submitting the QC Plan, is NOT in agreement with standard practices as previously discussed?
    a) Distributed copies of the QC Plan to attendees at the preconstruction meeting
    b) Made a brief oral presentation of the QC Plan
    c) Submitted the QC Plan to the Agency at the preconstruction meeting
    d) The Contractor did everything according to standard practices

2. Since the HMA Producer had a QC Plan previously approved by the Agency for another QA Project, the Agency;
    a) Should accept this as relevant for the current project
    b) Should require resubmittal and possible revision for the current project
    c) Should not require that the Contractor include a copy of the Producer’s QC Plan with the Contractor’s QC Plan
    d) Should require that the Contractor synthesize his QC Plan with the Producer’s QC Plan to create one single modified QC Plan

3. Which of the following statements in the milling Subcontractor’s letter is MOST relevant to information that is required in a QC Plan?
    a) Schedule of the milling operation
    b) The type of milling equipment being used
    c) Maintenance and protection of traffic during milling
    d) Where and how millings would be deposited

4. The milling Subcontractor’s letter also stated that “grades and cross-sections will be maintained in accordance with the drawings.” What additional information may be beneficial for the QC Plan to include with this statement?
    a) Specifically HOW this would be accomplished (equipment, manner of checking, frequency of checking, response to deficiencies, etc).
    b) A copy of the drawings referred to or specific reference to drawing number
    c) The individual(s) responsible for performing this function
    d) All of the above

5. Which of the following statements regarding the roller operator/Plan Administrator/Lead QC Inspector is MOST consistent with standard practice as outlined in this Course Manual?
    a) Under no circumstances should the Agency allow this to occur
    b) Ideally, these roles are better served by separate individuals
    c) Laborer and operators should never be certified as QC Inspectors
    d) All of the above

6. The responsibilities listed for the Consultant testing firm personnel were to “assist the Plan Administrator in execution of Quality Control.” Which of the following statements best characterizes the impact of this statement?
    a) The Consultant testing firm’s personnel will not have a clear understanding of their roles and responsibilities during the project
    b) The Plan Administrator will have to constantly monitor the QC personnel’s actions
    c) The Consultant testing firm’s personnel will know that the Plan Administrator is in charge of Quality Control
    d) The Consultant testing firm’s personnel will know exactly what their roles will be

7. The information on coring stated that the cores would be “obtained in accordance with the frequencies as required by the Agency and as stated in the Agency’s Standard Specifications.” This statement exemplifies;
    a) An appropriate reference to Agency Specifications
    b) An inappropriate reference to Agency Specifications since they should never be referenced in QC Plans
    c) An unnecessary detail that QC Plans generally should not deal with
    d) A vague reference that needs to be spruced up with specific information (statement of frequency, reference to section, paragraph, etc. in Agency specifications).

8. The decision of the Agency to proceed with work despite NOT having a fully approved QC Plan can be best described as;
    a) Prudent
    b) Practical
    c) Perfect
    d) Poor

Scenario 11-B: A Producer required to write a QC Plan as part of a Quality Assurance project submitted the following table that indicated the QC Quality Characteristics subject to statistical evaluation, along with random sampling and testing methods, locations, and frequencies for QC sampling and testing.

Quality Characteristic	Test Method	Sublot Size/ Test Frequency	Lot Size	Point of Sampling
Asphalt Binder content	AASHTO T 308	1 sample per 750 tons (680 Mg) but not less than 1 per day	Up to 10,000 tons (9072 Mg) per JMF	Haul vehicle at plant
Composite Aggregate Gradation (Belt)	AASHTO T 27	1 sample per 750 tons (680 Mg) but not less than 1 per day	Up to 10,000 tons (9072 Mg) per JMF	Production Facility
In-Place Air Voids(1)	AASHTO T 269 AASHTO T 230 AASHTO T 209 AASHTO T 166	1 sample per 750 tons (680 Mg) but not less than 1 per day (2)	Up to 10,000 tons (9072 Mg) per JMF	Compacted roadway (3)
Thickness (4)	AASHTO T 269 ASTM D 3549	1 sample per 750 tons (680 Mg) but not less than 1 per day (2)	Total Quantity of HMA	Compacted roadway (3)
Ride Quality	As specified in Standard Specs 845.35 (E)	0.1 lane mile (200 m) each wheel path	Total Quantity of HMA	As specified

(1) Loose plant mix to be used for determining T 209 results
(2) Two cores per sample, within a 2 ft (600 mm) radius
(3) Excluding bridge pavements
(4) Measurements to be taken from full depth cores obtained for air voids determination

Based on the information in the preceding table, and what you have learned regarding QC Plans, answer the following questions:

1. The purpose for including such a table in a QC Plan is to;
   a) Provide an outline for QC personnel to follow so that they will be able to control the production process
   b) Provide an outline of required random samples subject to statistical evaluation so QC is aware when and how to sample
   c) Provide an outline for Acceptance personnel to follow so that they will be able to obtain their acceptance samples
   d) Outline information required for Independent Assurance inspectors

2. The per JMF Lot size for Asphalt Binder Content, Gradation, and In-Place Air Voids, according to the table, is;
   a) 750 tons (680 Mg)
   b) the entire JMF quantity
   c) Up to 10,000 tons (9072 Mg)
   d) none of the above

3. If an HMA plant produced 750 tons (680 Mg) over a three day period, how many required random samples for in-place air voids should QC have obtained?
   a) 1
   b) 2
   c) 3
   d) 4

4. If an HMA plant produced 2500 tons (2268 Mg) over a 3 day period in equal amounts, QC should have obtained no more than how many random samples for a single Quality Characteristic?
   a) 1
   b) 2
   c) 3
   d) 4

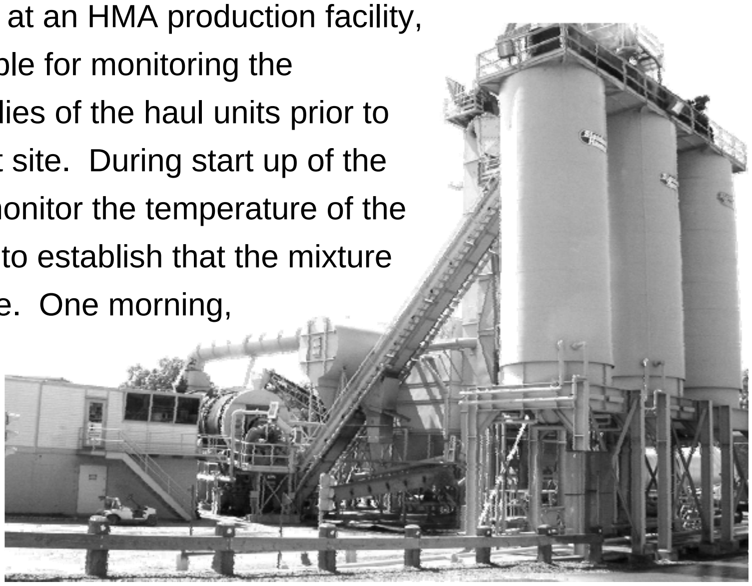
5. Which of the following Quality Characteristics are determined from the same material sample?
   a) Asphalt Content and Gradation
   b) Gradation and In-Place Air Voids
   c) In-Place Air Voids and Thickness
   d) Thickness and Ride Quality

6. What size (diameter) cores should be obtained for In-Place Air Voids?
   a) 12 in. (300 mm)
   b) 24 in. (600 mm)
   c) 36 in. (900 mm)
   d) table doesn't specify

7. How many Lots will there be for Ride Quality on this project?
   a) 1
   b) 2
   c) 3
   d) 4

8. According to the table, what is the sublot size for Ride Quality?
   a) 750 tons (680 Mg)
   b) 10,000 tons (9072 Mg)
   c) every 0.1 lane mile (200 meters) per wheelpath
   d) none of the above

11.2 - Quality Control Responsibilities



Scenario 11-C: A QC Technician at an HMA production facility, among other duties, was responsible for monitoring the temperature of the HMA in the bodies of the haul units prior to shipping the material to the project site. During start up of the facility, it was regular practice to monitor the temperature of the first few haul units loaded in order to establish that the mixture was at the appropriate temperature. One morning, the first load tested was approximately 10˚C (50˚F) below the minimum required. The QC Technician informed the driver to wait at the rack while another thermometer was obtained from the lab (since the Technician wanted to verify that the thermometer being used was correct). When the QC Technician returned, the previous haul unit was no longer at the rack, and another haul unit was waiting in its place. Alarmed and confused, the Technician took the temperature of the second load (wondering where the first one was), and noted that the second load was also quite low in temperature. The Technician informed the second haul unit to wait at the rack, and went back to the lab to inform the Plan Administrator of the situation (and to find out where the first load was).

Before the Technician was able to pick up the phone, the plant operator radioed the lab and stated that he had rejected the first two trucks due to low temperature, and requested that the QC Technician test the next five loads for temperature. Temperature results on the next 5 loads indicated the mixture was within the required range.

Later, the plant operator explained to the QC Technician that he could see the material was cold based on how it was falling out of the silo into the trucks, and subsequently radioed both drivers to discard their loads in the recycle pile. At the same time, the plant operator increased the temperature inside the drum to compensate for the unusually cold start up. Investigation into the cause of the cold startup revealed that the operator had not taken into account the effect of colder overnight temperatures on the stockpiled aggregates.

Based on what you have learned regarding the responsibilities of Quality Control personnel, and the information contained in the preceding Scenario, answer the following questions:

1. Obtaining the temperature of the first few loads of mix each day exemplifies which of the following?
    a) Random sampling
    b) Quota sampling
    c) Uniform interval sampling
    d) Selective sampling

2. The temperature information obtained each day on the first few loads was used for which of the following?
    a) Production Quality Control
    b) Quality Level Analysis
    c) Acceptance decisions
    d) Independent Assurance

3. Which of the following best characterizes the action taken by the plant operator in rejecting the loads?
    a) QC is the responsibility of everyone, not just the QC Technician
    b) Covering up his own mistakes
    c) Overstepping the job responsibilities of a plant operator
    d) Presumptuous decision based on an inaccurate visual observation

4. Assuming the out of specification loads had been sent to the job, which of the following could NOT have occured?
    a) Acceptance Inspectors may have rejected the loads
    b) The loads may have been placed anyway
    c) The Producer provided high quality material
    d) QC Inspectors in the field may have rejected the loads

5. The fact that the operator increased the temperature of the mixture during production is a good example of;
    a) The Variability of material production
    b) The ability to make positive changes in real time
    c) The silliness of limits in the QA Specification
    d) An extraordinary situation resolved by extreme measures

6. Which of the following is the best possible way to prevent the same process error from occurring again?
    a) Fire the plant operator
    b) Fire the QC Technician
    c) Note the conditions that caused the error for future reference
    d) Store the stockpiled aggregate in heated enclosures

Scenario 11-D: A QC Technician on an Agency PCC Project using QA Specifications obtained a Selective sample (no strength tests) from a revolving drum truck mixer using standard concrete sampling procedures (obtaining at least two increments from the middle portion of the batch). Slump and Air Content tests indicated that the plastic concrete was outside of the Engineering Limits for both Quality Characteristics. By the time the test results were completed, the truck had discharged all the concrete into the forms. Since the sample was obtained for informational purposes only (i.e. it was not a required random QC sample), the QC Technician opted to discard the results.

Based on what you have learned regarding the responsibilities of Quality Control personnel, and the information contained in the preceding Scenario, answer the following questions:

1. Which of the following methods of sampling could be used to obtain an informational sample?
    a) Selective Sampling
    b) Random Sampling
    c) Stratified Random Sampling
    d) All of the above

2. When a Selective sample is being obtained, the sampler;
    a) May modify the sampling procedure to expedite results
    b) Must follow standard procedure
    c) Does not need to document where the sample was obtained
    d) Either A or B, depending on circumstances

3. If the sample obtained had been a required random QC sample, the sampler;
    a) May modify the sampling procedure to expedite results
    b) Must follow standard procedure
    c) Does not need to document where the sample was obtained
    d) Either A or B, depending on circumstances

4. If, as in the Scenario, a Selective sample indicates that the Engineering Limits have been exceeded, the QC Technician should;
    a) Quit his job and become an insurance adjustor
    b) Alert the Field Superintendent and the QC Plan Administrator of the situation
    c) Hide the test results from any Acceptance Inspectors on site
    d) Stop the placement immediately and reject further material

5. If the Selective sample had generated results at the target levels, and a subsequent required random sample generated results outside the Engineering Limits;
   a) The QC Technician should switch the results to improve the PWL
   b) The QC Technician should avoid taking further Selective samples since they aren't good indicators
   c) The QC Technician should discard the random sample and change the random number to indicate another sample location
   d) None of the above

6. Which of the following situations would warrant discarding test results?
   a) When they come from non-random samples
   b) When they exceed the Specification Limits
   c) When they are determined to be Outliers resulting from poor testing technique
   d) Test results should never be discarded

Scenario 11-E: An Agency Acceptance Inspector arrived at a production facility during production of mixture for an Agency project in order to monitor QC activities. As part of the Agency monitoring, the Acceptance Inspector was to observe the Producer's recordkeeping and review the QC Record Book, or summary of QC test results, which according to the Agency specification (and the Producer's approved QC Plan) was to be updated within a 24 hour period of any production. When the Acceptance Inspector asked to see the QC Record Book, he was informed that the QC Record Book was at another production facility with the QC Technician, who had left for the other plant about an hour earlier. The Acceptance Inspector was informed that all of the required QC testing had already been performed at that facility, and had fulfilled his responsibilities. However, since all test results were placed into the QC Record Book, none were available for the Acceptance Inspector's review.

Based on what you have learned regarding Quality Control responsibilities, and the information contained in the preceding Scenario, please answer the following questions:

1. Typically, QC Technicians are required to be present at the production facility;
    a) Only until the required testing has been completed
    b) Throughout production of mixture for Agency projects
    c) As long as Acceptance Inspectors are present
    d) For a majority of the production, not to exceed an eight hour day

2. Records of QC test results obtained during production are typically required to be maintained;
    a) In a QC Record Book in the QC Technician's possession at all times
    b) At a location accessible to the Agency (e.g., Contractor's field office)
    c) In a QC Record Book at the production facility
    d) Both b and c

3. A Producer that operates multiple facilities should;
    a) Use one QC Record Book for all the facilities
    b) Use one QC Record Book for all facilities, as long as the facilities are the same type (e.g., batch plants, drum mix plants, transit mix plants, central mix plants)
    c) Use a separate QC Record Book per production facility
    d) Not be required to keep QC Record Books due to the amount of data that multiple facilities generate

4. Statements in QC Plans regarding QC responsibilities, including recordkeeping policies;
    a) Are just written to satisfy Agency requirements and do not need to be executed
    b) Should not result in the Producer making any extra effort beyond what has been done under previous specifications
    c) Are external to the Producer’s Quality Control and do not contribute to improvements in the process
    d) None of the above

5. Maintaining current records of production in a QC Record Book should be viewed as;
    a) An activity that is secondary to sampling and testing
    b) An integral part of the QC function
    c) A paper exercise to satisfy Acceptance Inspectors
    d) None of the above

6. Considering that no QC Technician was present at the plant during production, and no QC Record Book was available for review, the Acceptance Inspector could have;
    a) Reprimanded the Producer and increased frequency of Agency monitoring of Quality Control
    b) Required the Producer to deliver the QC Record Book immediately for review
    c) Required the Producer to cease production for Agency projects
    d) All of the above

11.3 - Acceptance Responsibilities

Scenario 11-F: An Agency Acceptance Inspector on a Quality Assurance project was monitoring the density of a select structural fill around bridge abutment footings using a nuclear gauge (in accordance with the Agency's density testing requirements). The density in the randomly sampled areas was within Specification Limits. Some areas that had not been randomly selected for density testing looked questionable to the Acceptance Inspector, so she took some density readings in those areas using Selective Sampling techniques and found out that these areas were outside of the Specification Limits, but within the Engineering Limits. Based on these findings she informed the QC Inspector for the Contractor that, while the randomly sampled test locations were within the Specification Limits, the Selectively Sampled areas were not. The QC Inspector informed her that since all of her Randomly Sampled tests indicated that the density was within the Specification Limits that no corrective action would be taken by the Contractor.

Furthermore, The QC Inspector stated that Selective Samples represented a form of Biased Sampling, and should not be used to direct the actions of the Contractor. The Agency Inspector then requested that the Selectively Sampled areas identified through her visual inspection be delineated separately from the rest of the material and that additional randomly selected tests be obtained in order to determine the extent of the deficiency in density within those areas. The QC Inspector then directed the Contractor to provide additional compaction to those areas identified by the Acceptance Inspector to be deficient in density.

Based on what you have learned regarding Acceptance responsibilities and the information in the preceding Scenario, please answer the following questions:

1. The Acceptance Inspector was initially taking density readings in randomly selected areas because;
    a) Acceptance test locations should be selected randomly
    b) The Inspector wasn't sure where the samples should be
    c) The Inspector was attempting to avoid the deficient areas
    d) Randomly selected samples do not require documentation

2. With regard to the Acceptance Inspector's Selective Sampling of questionable areas;
    a) Selective Sampling is never allowed under QA specifications
    b) Selective Sampling is allowed, but only when QC concurs
    c) Selective Sampling is used, but not on questionable areas
    d) Acceptance Inspectors are allowed to sample any material at any time

3. If the selectively sampled areas that were outside the Specification Limits (but inside the Engineering Limits) had been randomly sampled;
    a) They would have been part of the QLA data and lowered the PWL
    b) They would not have been part of the QLA, and the PWL would not be affected
    c) They would have been part of the QLA and raised the PWL
    d) None of the above

4. If the selectively sampled areas had been found to be outside of the Engineering Limits;
    a) Then the Acceptance Inspector should stop the work and require correction
    b) Then the Acceptance Inspector should inform QC of the situation, and QC should stop the work and further evaluate to determine appropriate action
    c) The Acceptance Inspector should tell QC what to do in order to solve the problem
    d) QC should retest the material

5. The Acceptance Inspector informing the QC Inspector of the test results is best described as an example of;
    a) Acceptance and QC working together
    b) Acceptance imposing themselves on QC
    c) Acceptance attempting to direct the actions of the Contractor
    d) Acceptance performing the QC function

6. QC's decision not to take corrective action based on the results of the Selective Samples;
    a) Was acceptable considering the results did not exceed the Engineering Limits
    b) Was acceptable since Selective Samples are not allowed in the determination of the QLA
    c) Was unacceptable since apparently deficient areas would be allowed to remain
    d) Was unacceptable since QC must do whatever the Acceptance Inspector says

7. The Acceptance Inspector's decision to request delineation of suspect areas with additional Random Sampling was;
    a) Incorrect since Random Sampling was not originally used
    b) Incorrect since the areas were already identified as not meeting the Specification Limits
    c) Correct since areas of visible, obvious deficiency should be treated separately and fairly with additional Random Sampling
    d) Correct since additional samples would have undoubtedly proved the point that a deficiency existed

Scenario 11-G: A Quality Assurance specification stipulated Specification Limits and Engineering Limits around a Target Value. The Target Value was established analytically in a laboratory using an approved design process. During production, test results indicated that the Mean value ran consistently above the Target Value, near the upper Specification Limit. An Acceptance Inspector at the production facility noted that Agency specifications required "the Producer to produce material at or near the Target Value established from the mix design." Based on this understanding, and after review of QC test results, the Acceptance Inspector directed QC at the facility to implement specific changes to the production process in order to bring the results back toward the Target Value. QC implemented the changes directed by the Acceptance Inspector, obtained a new sample and tested the material to discover that the results were now outside the Specification Limits. The Acceptance Inspector then informed QC that, if the next sample was also outside the Specification Limits, then the Agency would not allow the production facility to continue providing material to the Agency project, until it could be shown that QC had production "under control."

Based upon what you have learned regarding Quality Assurance Specifications and Acceptance inspection, and the information contained in the Scenario, please answer the following questions:

1. Typically, adjustments to the production process are required when an individual test result indicates a value outside of the;
   a) Target Values
   b) Specification Limits
   c) Engineering Limits
   d) None of the above. Adjustments to the production process are never "required."

2. It is generally expected that the laboratory determined mix design Target Values;
   a) May need to be adjusted during full scale production
   b) Will need to be completely refigured during full scale production
   c) Will not need to be changed at all during full scale production
   d) None of the above

3. Which of the following did the Acceptance Inspector in the Scenario above NOT do in accordance with generally accepted Quality Assurance practices?
   a) Reviewed QC's test results
   b) Enforced Agency specifications and policies
   c) Wanted to see production "under control"
   d) Directed QC to implement specific changes to the production process

4. If, as in the Scenario, several test results indicated values at or near the Specification Limits;
   a) No corrective action would be required unless the cumulative PWL was below a specified Suspension Quality Level (SQL) identified in the QA Specification.
   b) Corrective actions would be necessary regardless of the cumulative PWL
   c) QC Technicians should lobby the Agency to have the Specification Limits changed
   d) No corrective actions should be made unless the value exceeds the Engineering Limits

5. The fact that Agency specifications require “the Producer to produce material at or near the Target Value established from the mix design”;
    a) Justifies the Acceptance Inspector’s actions requiring adjustments
    b) Reinforces the application of Specification Limits around the Target
    c) Is entirely irrelevant in a Quality Assurance Specification
    d) Shows the inadequacy of laboratory mix designs in the real world

6. If two consecutive test results fell outside the Specification Limits;
    a) It is an indication that the process is “out of control”
    b) It means the PWL will fall below the AQL
    c) It is a cause for concern
    d) It is of no concern

7. Based on the information in the Scenario prior to the adjustments to the process, production is best described by which of the following?
    a) Completely in control
    b) Potentially out of control, and needs some adjustment
    c) Nearly out of control
    d) Totally out of control

11.4 - Sampling Protocols

Scenario 11-H: An Agency's QA Specification defined the Lot size as a quantity of placed aggregate not to exceed 10,000 tons (9072 Mg), and the Sublot size as 500 tons (454 Mg). The specification also indicated that if, at the end of a Lot, there was less than or equal to one half a Sublot of material remaining, that the Sublot would not require testing and the Lot would be represented by existing information. However, the specification stated that if there was more than one half of a Sublot of material remaining, that the Sublot would require testing and the results of the testing would be included in the characterization of the Lot.

After three days, production and placement of the entire Lot of aggregate was NOT complete. At the end of the first day of the job, a total of 1244 tons (1129 Mg) of aggregate had been placed. Based on the definition of a Sublot, the QC Technician decided that since there was less than one half of a Sublot at the end of the day, the day could be represented by only 2 material samples. The next day, a total of 1158 tons (1051 Mg) of aggregate had been placed, and was again represented by 2 samples. The third day, a total of 1650 tons (1497 Mg) was shipped, and the day was represented by 3 samples. At the start of the fourth day of Aggregate placement, Acceptance Inspectors arrived for a site visit and asked the QC Technician to turn over all of his split samples representing each Sublot from the first three days. When the QC Technician turned over 7 samples to the Acceptance Inspectors, they asked the QC Technician where his 8th sample was.

Based on what you have learned regarding sampling protocols, and the information contained in the above Scenario, answer the following questions:

1. In the Scenario above, the Lot was defined as;
   a) 500 tons (454 Mg)
   b) A quantity not to exceed 10,000 tons (9072 Mg)
   c) The entire quantity of aggregate shipped to the job
   d) None of the above

2. The provision in the specification regarding sampling at the end of a Lot states that;
   a) Anything more than half a Sublot requires a test
   b) Anything less than or equal to half a Sublot does not require a test
   c) When a sample is not required to be obtained (per b), the existing information will be used
   d) All of the above

3. When the QC Technician decided that sampling at the end of the day was not necessary, it was based on;
   a) What the specification had indicated should be done
   b) A misunderstanding of the definition of the Lot
   c) A misunderstanding of the definition of a sample
   d) None of the above

4. Based on the total amount of aggregate (4,052 tons (3676 Mg)) shipped to the project during the first 3 days, how many random samples (at a minimum) should the QC Technician have obtained?
   a) 4
   b) 6
   c) 8
   d) 10

5. Assume that on the first day the QC Technician selected the following random sample locations: 224 tons, 563 tons, and 1363 tons. Since the last sample would not have been obtained (only 1244 tons was placed), what should the QC Technician have done?
    a) Picked another random number the start of the next day
    b) Calculated the cumulative point at which 1363 tons would occur during the next day's production and obtain the sample at that point
    c) Obtained a sample immediately after it was apparent that the last random sample would not be met
    d) The QC Technician did what was appropriate and did not need to obtain another sample

6. Based on the total amount of aggregate that was placed over the three day period, what is the maximum number of required Random Samples that the QC might have obtained?
    a) 5
    b) 7
    c) 9
    d) 10

Scenario 11-I: QC Technicians were performing random sampling of HMA. At the random sampling location, they obtained several increments of the HMA in order to form a QC sample. The material sample was delivered back to the laboratory where several Marshall specimens were portioned out of the hot mixture immediately. Once the Marshall specimens had been obtained, additional test portions for maximum theoretical specific gravity and extractions were obtained. Since the Quality Assurance specification required that QC retain material split samples for further testing if needed (e.g. split sample Correlation, Dispute Resolution), QC placed the remaining portion of HMA into a labeled bag and stored it in the laboratory. A few days later Agency Acceptance Technicians requested the retained split in order to perform Split Sample Correlation testing. The Agency Technicians obtained the retained split sample and performed the same battery of testing as QC had done previously, but with markedly different results. Based on this information, and concerned that their testing equipment may be malfunctioning, the Agency Acceptance Technicians decided that re-testing was in order, and ran the remaining portion of the HMA split sample through the same battery of test procedures again. Re-testing confirmed the initial results that Acceptance had generated.

Based on what you have learned regarding sampling protocols, and the information contained in the above Scenario, please answer the following questions:

1. When the QC Technicians obtained several increments to form the sample;
    a) They should have obtained the sample in one portion
    b) They were obtaining the sample in an appropriate manner
    c) They should have combined multiple samples to form the test portion
    d) They should have obtained an additional sample for Acceptance Inspectors

2. Which of the following actions should QC have taken with regard to retaining a split sample for potential further testing (e.g. Correlation, Dispute Resolution)?
   a) They should have split the sample using an appropriate splitting method prior to obtaining test portions
   b) They should have split the sample using an appropriate splitting method after the Marshall specimens were obtained
   c) They should have split the remaining portion of the sample after all their tests were completed
   d) The actions taken as described in the Scenario were correct

3. When the Acceptance test results came up different than the QC test results, the most likely cause for the difference was;
   a) The test portion from the sample was not tested properly by QC
   b) The Acceptance Technician used different equipment than QC
   c) The sample was not split properly prior to testing
   d) The split sample Acceptance tested was much older than the QC sample

4. Based on what the Agency Acceptance Technicians knew, when they decided to re-test the split sample;
   a) What they should have been doing was re-sampling
   b) They were retesting in hopes that it would negate their original findings
   c) They should have obtained another independent sample
   d) They were following proper procedure

5. Which of the following is the appropriate course of action to take when concerns of malfunctioning testing equipment are raised?
   a) Re-sampling
   b) Re-testing
   c) Uniform interval sampling
   d) Quota sampling

6. If the Acceptance Technicians had observed the QC Technicians obtaining and splitting the HMA improperly, then which of the following would have been the appropriate course of action to take?
   a) Re-sampling
   b) Re-testing
   c) Uniform interval sampling
   d) Quota sampling

Scenario 11-J: On a Quality Assurance PCC project, both QC and Acceptance Inspectors were required to obtain independent samples of PCC. Acceptance sampling and testing was performed at a reduced frequency (33%) of the QC sampling and testing. If the QC data was Validated (using an F-test and t-test), it would be included in the Agency's acceptance determination (along with the Acceptance data) to characterize the Lot and to determine the Percent Within Limits. During the project, when Acceptance Inspectors were present for a placement, QC Technicians opted to sample the same loads that were randomly selected by the Acceptance Inspectors, rather than their own independently determined random QC sampling locations. QC personnel then used the data generated by these QC samples as part of their QLA. The QC Personnel justified their actions as follows: when both the QC Technicians and Acceptance Inspectors were present during a placement, it was an inconvenience and delay to the Contractor to have to submit to double the usual amount of sampling. Furthermore, since the Acceptance Inspectors had determined their sample locations using a random method, the QC samples were also randomly selected.

Based on what you have learned regarding sampling protocols, and the information contained in the above Scenario, please answer the following questions:

1. When a Quality Assurance Specification requires that QC and Acceptance samples be obtained independently of one another, this means that;
    a) QC personnel should obtain the sample, split it, and turn over a split portion to Agency Acceptance personnel for independent evaluation
    b) Acceptance personnel should sample whenever QC obtains a sample
    c) QC personnel and Acceptance personnel should sample at the same location, but obtain the samples independently
    d) None of the above

2. Under a Quality Assurance specification, Validation of QC test data;
    a) Occurs prior to production and construction
    b) Occurs during the first month of production and construction
    c) Occurs during and through the completion of production and construction
    d) None of the above

3. If, as the Scenario suggests, QC were to use the data generated from their non-random QC samples that were obtained alongside random Acceptance samples;
    a) Then the PWL would be skewed since data would be duplicated for those samples
    b) Then the PWL would be more accurate since the samples were from the same Population
    c) Then the PWL would be more likely to indicate high quality
    d) Then the PWL would be more likely to indicate low quality

4. The QC samples that duplicated the randomly selected Acceptance samples are best described as;
    a) Random samples
    b) Quota samples
    c) Selective samples
    d) Interval samples

11.5 - Inherent Variability and the Normal Distribution Curve

Scenario 11-K: Prior to production of an HMA mixture, QC Technicians and Acceptance Technicians performed testing on split samples of HMA that were Correlated. During production of the HMA, the QC Technicians and Acceptance Technicians obtained independent samples as required to determine conformance to Asphalt Binder Content criteria. Both parties used the Contractor's testing equipment to perform the required testing. The Agency QA Specification listed both Specification Limits and Engineering Limits for the Asphalt Binder Content Quality Characteristic. During the course of a week, QC Technicians obtained 10 samples and Acceptance Technicians obtained 5 samples. After review of the results it was apparent that the Mean of the Acceptance test results was 0.5% higher in Binder Content than the QC Samples. Further comparisons indicated that the results of testing conducted on the same day (QC versus Acceptance) showed some larger than expected differences (up to a 1 percent in Asphalt Binder Content). On the whole, all of the samples (QC and Acceptance) indicated results within the Engineering Limits, however almost half of all the samples (QC and Acceptance) were outside of the Specification Limits. Based on the information and the observations of the high degree of Variability between tests (Acceptance and QC), the Agency issued a Non-Conformance report to the Contractor. QC personnel for the Contractor responded by questioning the credentials of the Acceptance Technician performing the Acceptance testing.

Based on what you have learned regarding Inherent Variability and the Normal Distribution Curve, and the information contained in the preceding Scenario, answer the following questions:

1. The Scenario suggests an Acceptance sampling frequency at what percentage of the Quality Control samples?
    a) 25%
    b) 50%
    c) 75%
    d) 100%

2. The fact that (on average) the Asphalt Binder Content results for Acceptance samples were about 0.5% higher than the Binder Content results for QC samples suggests;
    a) That there was Variability in the sampling procedures used
    b) That there was Variability in the testing procedures used
    c) That there was Variability in the testing equipment used
    d) Absolutely nothing beyond the fact that the results were 0.5% higher on average

3. The fact that there was a significant difference in Asphalt Binder Content on samples obtained the same day suggests;
    a) That there was Variability in the sampling procedures used
    b) That there was Variability in the testing procedures used
    c) That there was Variability in the testing equipment used
    d) Absolutely nothing beyond the fact that there was a significant difference in Asphalt Binder Content results

4. Which of the following best describes the rationale for comparing daily test results to one another?
    a) It provides a statistically sound measure of comparison
    b) It is based on the incorrect notion that individual test results are meaningful when compared individually to one another
    c) It represents the daily analysis of how the process of production is going
    d) It is useful information to plot on a Statistical Control Chart

5. Which of the following is most likely when considering that almost half of the test results were outside of the Specification Limits?
    a) Sampling and testing was being performed incorrectly
    b) The production of the HMA was consistent
    c) The resulting PWL will be less than 100
    d) The Contractor could expect to receive an incentive payment

6. The independent sampling and testing being performed by both QC Technicians and Acceptance Technicians in this Scenario is capable of providing what kind of information?
    a) Data for QLA and Validation
    b) Data for Validation and Correlation
    c) Data for Correlation and Independent Assurance
    d) The weight factors used for Pay Adjustments

7. If the Population represented by the sampling and testing in the Scenario was Normally Distributed, the fact that half the samples were outside the Specification Limits;
    a) Would indicate a bimodal normal distribution
    b) Would indicate a high level of Variability in the Statistical Sample results
    c) Would indicate that half the samples were in excess of 3 standard deviations of the target
    d) Would indicate that the Specification Limits need to be readjusted

8. The Agency's action in issuing a Non-Conformance report based on the Variability of the individual tests (between QC and Acceptance);
    a) Was a correct response to the observed Variability
    b) Was incorrect since individual, independently obtained samples are not directly comparable
    c) Was a correct response since it was intended to limit future Variability
    d) Was incorrect since QC test results and Acceptance test results should never be compared to one another

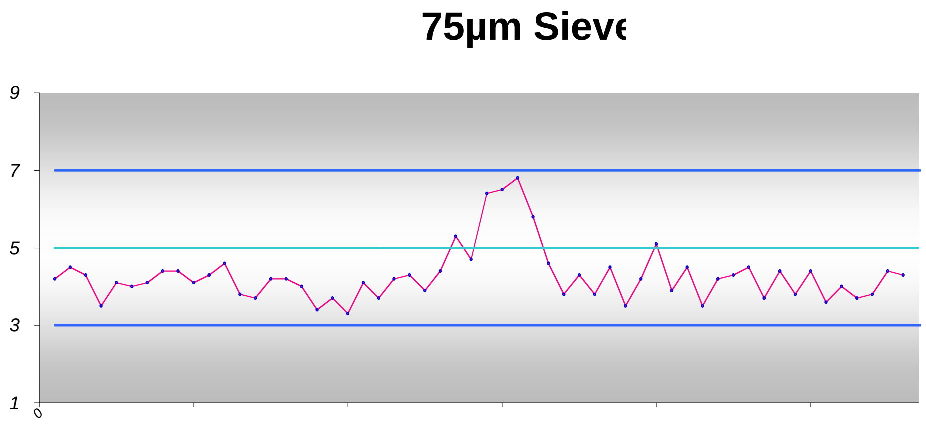
9. Based on the information contained in the Scenario;
   - a) QC personnel had good reason to question the credentials of the Acceptance Technician
   - b) Acceptance should have questioned the credentials of the QC Technician
   - c) There wasn't any real data that suggested either QC or Acceptance Technicians did not have appropriate credentials
   - d) It was obvious that both Acceptance and QC Technicians were performing the procedure properly

10. Assuming that both QC and Acceptance Technicians sampled and tested the material properly, the source of the Variability could have been due to;
    - a) Material Variability
    - b) Construction (i.e. production and placement) Variability
    - c) Chance cause Variability
    - d) All of the above
    - e) None of the above

11.6 - Control Charts

Scenario 11-L: A project was awarded with the Agency's Quality Assurance Specifications that required the Producer to provide Control Charts for several specific Quality Characteristics. Since the specification did not address the type of Control Chart to provide, and the Producer had no experience using Control Charts previously, the Producer used a Run Chart to plot individual test results against the Specification Limits. Whenever a test result was outside of the Specification Limits, the Producer would get nervous and start making changes to the production process. The changes the Producer made seemed to have a positive effect, as often the next test result would plot within the Specification Limits. Over the duration of the project, the Producer forgot about the Control Charts, and weeks went by with no data plotted. One morning, the Producer remembered the Control Charts, and in a panic filled in three weeks of data. The Acceptance Inspector was often impressed with the appearance of the Control Charts. At the end of the project, the Producer turned over all the Control Charts to the Acceptance Inspector. The Producer was not intending to use Control Charts again unless another QA project required them.

Based on what you have learned regarding the use of Control Charts, and the Scenario above, please answer the following questions:



1. The best types of Control Charts to use to discern process changes resulting from causes other than chance are;
    a) Run Charts
    b) Bar Charts
    c) X-Bar Charts and R Charts
    d) none of the above

2. Plotting individual test results against the Specification Limits;
    a) Is a good way to tell when the process Mean has changed
    b) Is a good way to tell when process Variability has changed
    c) Is a good way to identify assignable causes acting on the process
    d) None of the above

3. When the Producer made changes to his production process based on the Control Charts he used;
    a) He was improving the quality of his product
    b) He was keeping quality at the required level
    c) He was preventing future non-compliance
    d) None of the above

4. The changes the Producer made seemed to have a positive effect due to;
    a) The fact that his changes were appropriate
    b) Coincidence and chance
    c) The fact that his Control Charts had the limits set too wide
    d) None of the above

5. Plotting results on Control Charts is intended to;
    a) Help the Producer understand his production process
    b) Provide historical data for subsequent limit adjustment
    c) Enable the Producer to improve the quality of his product
    d) All of the above

6. Control Charts need to be updated how often to be useful?
   a) As often as data is generated
   b) Only when adjustments are made to the process
   c) Prior to Acceptance Inspector visits
   d) Every 3 weeks

7. Control Charts that plot subgroups of data are best used to
   a) Provide a visual record of sample results
   b) Help identify Assignable Causes acting on the process
   c) Cause chance Variability
   d) Fulfill specification requirements

8. Who stands to benefit most from the correct use of appropriate Control Charts?
   a) Agency
   b) Contractor (e.g. Prime Contractor, Subcontractor, Producer)
   c) Testing firm
   d) Architect

9. Using Control Charts only when required by the specification, and not as a normal part of the production operation;
   a) Is prudent since Control Charts take time away from other matters
   b) Is indicative of the lack of understanding on Control Chart usage
   c) Is a requirement of Agency specifications
   d) Is the opposite of what typically happens

Scenario 11-M: A Producer's QC staff began using X-bar Charts and R Charts to monitor production at the start of the production season. The X-bar Chart plotted the Grand Mean of a Subgroup of test results (4 samples/subgroup). The R Chart plotted the Mean Range of each Subgroup. Control Chart Limits were established after about a month of data collection. Samples used to generate this data were obtained randomly. After another few weeks of data collection, there was a sudden jump in the R Chart. QC personnel investigated the production process to discover that a component at the facility had worn well beyond the allowable tolerance. The component was replaced and subsequent data on the R Chart plotted within the established Control Limits. The Producer continued to use the Control Charts as a tool to help identify when process changes were occurring. The Producer was awarded work on a QA project later in the construction season. Due to tight QC and consistent production, the Producer earned a 3% bonus on all material provided to the project.

Based on what you have learned regarding Control Chart usage, and the information contained in the Scenario above, please answer the following questions:

1. Using Control Charts that plot subgroups of data for the entire production season;
    a) Is a good way to get more control over the production process
    b) Is probably overkill
    c) Is detrimental to the activities of QC
    d) None of the above

2. Limits for Control Charts that plot subgroups of data should be established;
    a) Immediately prior to any data collection
    b) After enough random data has been gathered to characterize the Population
    c) Once only and then not readjusted or reconsidered at a later date
    d) Based on the Specification Limits in the QA specification

3. Control Charts that plot subgroups of data are useful in that they;
   a) Identify the cause of the process change
   b) Identify when a process change is occurring
   c) Control the production process
   d) All of the above

4. Which of the following Control Chart indications is the most likely to be the result of an Assignable Cause?
   a) Movement of X-Bar from below central line to above central line
   b) Extreme runs on X-Bar Chart
   c) R Chart out of limits
   d) All of the above

5. The fact that the Producer used existing Control Charts that plot subgroups of data for the QA project;
   a) Was wrong since new Control Charts for that project should have been developed
   b) Was correct since good historical data is needed to establish appropriate control parameters for a production facility
   c) Was wrong since the Agency expects Run Charts, not Control Charts that plot subgroups of data
   d) Was correct since it was the easiest thing to do at the time

6. The fact that the material produced earned an incentive on the QA project;
   a) Was entirely a result of using Control Charts
   b) Might have been attributable in part to the use of Control Charts
   c) Had little or nothing to do with the use of Control Charts
   d) Was a miracle considering Control Charts were used

11.7 - Split-Sample Correlation and Validation of Test Results

Scenario 11-N: The Agency QA Specification for a PCC project stipulated that the Contractor's QC test results were to be included in the Agency acceptance determination as long as the Contractor's QC results were Validated. Acceptance and QC samples were obtained in a random fashion independently of one another. When the QC and Acceptance data was analyzed it was apparent that there were differences in the results. The Agency consulted the AASHTO D2S statements for allowable differences in results (multi-laboratory) and discovered that many of the Acceptance and QC results exceeded the allowable differences. The Agency then conducted an F-test and t-test comparison using splits of retained QC samples in order to Correlate results. The F-test and t-test comparison indicated that the results could have come from the same Population. However, the Agency was still concerned about the differences in results previously noted. As a result, the Agency decided not to include the QC data as part of the Quality Level Analysis for the acceptance determination.

Based on what you have learned regarding Split-Sample Correlation and Validation of QC and Acceptance test results, answer the following questions:

1. When the Agency specification required that the Contractor's results be Validated, Validation should have been performed on;
   a) Split samples
   b) Independent samples
   c) Non-random Selective samples
   d) Just the QC samples, not the Acceptance samples

2. Which of the following items presented in the Scenario was improperly conducted in accordance with standard QA practices?
   a) Random sampling
   b) The use of D2S statements to compare multiple, independently obtained samples
   c) The necessity to Validate Contractor results when including them in the QLA
   d) The use of multi-laboratory D2S statements instead of single-operator D2S statements

3. When using D2S statements to compare test results, the comparison should have been made on;
   a) A split sample of the same material
   b) Independent samples
   c) Non-random Selective Samples
   d) Just the QC samples, not the Acceptance samples

4. Which of the following statements is correct when considering what happened in the Scenario?
   a) Validation was performed properly, Split-Sample Correlation was not performed properly
   b) Validation was performed improperly, Split-Sample Correlation was performed properly
   c) Validation and Split-Sample Correlation were both performed properly
   d) Neither Validation nor Split-Sample Correlation were performed properly

5. While the Agency conducted the F-test and t-test on split samples, they should have conducted the F-test and t-test on;
    a) Non-random samples
    b) Independently obtained random samples
    c) The same exact sample
    d) The Agency was correct using split samples for the F-test and t-test

6. The Agency opted to use AASHTO D2S statements to compare test results. Another more powerful tool the Agency may have used for the multiple split samples is;
    a) The F-test and t-test
    b) The F-test
    c) The paired t-test
    d) Quality level analysis

7. Based on the information in the Scenario, which of the following is true?
    a) The QC test results might have been included in the Agency QLA if the Split-Sample Correlation and Validation procedures had been run properly
    b) The QC test results should not have been included in the QLA despite the fact the procedures were run improperly
    c) The QC test results should not have been included in the QLA since the procedures were run properly
    d) The QC test results should have been included since the F-test and t-test comparison on the split pairs indicated that the samples could have come from the same Population

8. Ideally, Split-Sample Correlation of test results in the Scenario should have occurred;
    a) Prior to production
    b) After production was completed
    c) Prior to and during production as needed
    d) Split-Sample Correlation is not necessary if Validation has been performed

- END OF CHAPTER 11 -

APPENDIX A

Glossary of Terms

Appendix A

Glossary of Terms

Appendix Overview

This ***Glossary of Terms*** includes definitions for many of the various terms that are applicable to Quality Assurance for transportation construction. Differing versions of definitions exist for many of these terms as provided in reference documents from several organizations, including:

- AASHTO
- ASTM
- American Society for Quality (ASQ)
- FHWA
- Transportation Research Board (TRB)

In an effort to achieve national consensus on Quality Assurance terms and definitions for transportation construction, a national Peer Review Team representing the Transportation Curriculum Coordination Council (TCCC) performed a comprehensive review of this Glossary in 2004. The terms and definitions included in Appendix A (as well as those presented in the Chapters of this Reference Manual) have been updated to reflect the comments of the NETTCP and the TCCC Peer Review Team. Accordingly, this Glossary of Terms includes all NETTCP/TCCC agreed upon terms and definitions. Many of these updated terms and definitions have been incorporated into the 2006 update of AASHTO Standard R 10 (*Definition of Terms Related to Quality and Statistics As Used in Highway Construction*). Some new terms and definitions provided by the NETTCP have also been added in this edition of the Glossary.

Acceptable Quality Level (AQL)	The minimum level of established actual quality for a Quality Characteristic that is considered fully acceptable when using a particular Quality Measure. [For example, when the Quality Measure used is Percent Within Limits (PWL), the AQL is the established (not estimated) PWL at which the Quality Characteristic is fully acceptable. Acceptance Plans should be designed so that AQL material will receive an expected pay (EP) of 100%.]
Acceptance	All factors used by the Agency (i.e. sampling, testing, and inspection) to evaluate the degree of compliance with contract requirements and to determine the corresponding value for a given product.
Acceptance Limit	In variables Acceptance Plans, the limiting upper or lower value, placed on a Quality Measure, that will permit acceptance of a Lot. [While the test values for material samples are evaluated with Specification Limits and Engineering Limits, the computed quality level for a specific Quality Measure is evaluated against the Acceptance Limit. For example, the minimum allowable PWL called out in a QA Specification might be 65PWL. This is the Acceptance Limit.]
Acceptance Plan	Also called *Acceptance Sampling Plan* or *Statistical Acceptance Plan*. An agreed upon process for evaluating the acceptability of a Lot of material. It includes: Lot size and Sample (i.e. Statistical Sample) size, Quality Measures, limits for acceptance, evaluation of risks, and pay adjustment provisions.

Acceptance Sampling and Testing	Also called *Verification sampling and testing*. Sampling and testing performed by the Agency, or its Designated Agent, to measure the quality of the final product.
Accredited Laboratories	Laboratories which are recognized by a formal accrediting body as meeting quality system requirements including demonstrated competence to perform standard test procedures.
Accuracy	The degree to which a measurement, or the Mean of a distribution of measurements, tends to coincide with the true Population Mean.
Agency	Any organization, constituted under Federal, State, or Municipal laws, that is responsible for administering contracts for highway or transportation construction.
Alpha (α) Error	(See Seller's Risk)
Assignable Cause	A source of variation, usually due to error or process change, which can be detected by statistical methods and corrected within economic limits. [When Assignable Causes are identified and removed, the production process is "under control".]

Attribute	A characteristic that, by its presence or absence, classifies an item as conforming or nonconforming. [Inspection Attributes should be selected that directly relate to one of the four inspection components (i.e. equipment, environmental conditions, materials, and product workmanship). Inspection Attributes used for QC should be directly related to maintaining control of production and placement processes to ensure conformance with the requirements for each item of work. Inspection Attributes for Acceptance should relate directly to long-term product performance.]
Average	(See Mean)
Batch	A specified quantity of material produced through a uniform operation or process.
Beta (β) Error	(See Buyer's Risk)
Bias	An error, constant in direction, that causes a measurement, or the Mean of a distribution of measurements, to be offset from the true Population Mean.
Biased Sampling	A sampling procedure whereby samples obtained from a Lot do not have an equal probability of being chosen. [Conventional biased approaches to sampling which have been utilized by Agencies and Contractors include: Representative Sampling, Uniform Interval Sampling, Quota Sampling, and Selective Sampling.]

Buyer	The Agency or similar entity responsible for the acceptance and purchase of the materials and work required for the completion of a highway or transportation contract.
Buyer's Risk (β)	Also called *Agency's Risk*, *Beta (β) Error*, or *Type II Error*. It is the risk to the Agency of accepting Rejectable Quality Level (RQL) material or workmanship. [For an accept/reject Acceptance Plan, it is the probability that an Acceptance Plan will erroneously accept RQL material or workmanship with respect to a single Acceptance Quality Characteristic. For variables Acceptance Plans, it is equivalent to β_{PF}, where PF = 100. It is the probability that a variable payment Acceptance Plan will erroneously fully accept RQL material or workmanship at 100 percent pay or greater with respect to a single Acceptance Quality Characteristic.]
Central Limit Theorem	A theorem which states that given any Population with Mean (μ) and Variance (σ^2), if the Sample size (n) increases without limit, the distribution of Sample Means approaches a Normal Distribution with the Mean (μ) and Variance (σ^2). [Because of this theorem, statistical inferences can be drawn about any Population based on the Sample Mean ($\bar{x}$) and the Standard Deviation ($\sigma_{\bar{x}}$). Even if the shape of a Population is not Normal, the Means of sample groups drawn from the Population will approach a Normal Distribution as the size of the sample groups increases.

Central Tendency	The tendency of data values to cluster near the center of the distribution. It may be thought of as the single value that can be used to represent all of the values in a set of observations.
Certified Personnel	Personnel who are recognized by a formal certifying body as qualified to perform sampling, testing, inspection, or related procedures.
Chance Cause	A source of variation that is inherent in any production process and which cannot be eliminated as it is due to random, expected causes.
Class	A group of data values (measurements, observations, or test values) that all satisfy a given set of conditions associated with a Frequency Distribution.
Class Frequency	The number of data values falling into a particular Class.
Class Intervals	The difference in value between the lower and the upper limits of a given Class.
Class Limits	The upper and lower values that define a given Class.
Class Midpoint	The central value of a particular Class.
Coefficient of Variation (v)	The ratio of the Standard Deviation to the Mean, expressed as a percentage. It provides a measure of dispersion or spread relative to the Mean.

Composite Pay Factor	A multiplication factor, often expressed as a percentage that considers two or more Quality Characteristics and is used to determine the Contractor’s final Payment for a unit of Work.
Conformance	An affirmative indication or judgement that a product or process meets specified requirements.
Conformance Measure	The method used to evaluate inspection findings to determine the degree of product conformance with quality requirements. [The Conformance Measure used can be very simple and qualitative or can utilize a numeric or quantitative approach. The typical Conformance Measures applied include; Pass/Fail, Percent Conforming, and Numeric Score.]
Construction Variability	Variability that is the result of variation that is inherent in production methods and construction operations.
Contractor	All contracted parties who are involved with building an individual project, including; the Prime (General) Contractor, Subcontractors, and all Producers, Fabricators, and Manufacturers who provide construction materials for the project.
Control Chart	Also called *Statistical Control Chart*. A graphical plot of Quality Control measurements or test values used to identify variation in a production or placement process due to either Chance Causes or Assignable Causes.

Control Chart Limits	Also called *Action Limits*. Statistically derived boundaries applied to a Control Chart in controlling material production or placement. [Control Chart Limits are expressed as the Upper Control Limit (UCL) and the Lower Control Limit (LCL). When values of the material characteristics fall within these limits, the process is "under control". When values fall outside the limits, there is an indication that some Assignable Cause is present causing the process to be "out of control".]
Controlled Conditions	Consistency or uniformity in the methods of material production, placement, sampling, inspection, and testing.
Controlled Process	A production or placement process in which the Mean and Variability of a series of tests on the product remain stable, with the Variability due to Chance Causes only.
Criticality	The classification of contract requirements by the degree to which they affect safety, performance, or life-cycle cost.
Cumulative Frequency Histogram or Polygon	A Frequency Histogram or Polygon constructed by adding up the total number of occurrences of values less than or equal to a designated value.
Data	Measurements or test values organized for computation or analysis.
Deviation (from the Mean)	The difference between an individual value and the Mean of a set of measured or tested values.

D2S Limits	The maximum acceptable difference between two test values obtained for two specimens (or test portions) from the same material sample. [The difference between the two results would be equal or exceeded in the long run in only one case in twenty in the normal and correct operation of the test method.]
Disincentive	A pre-established decrease in payment to the Contractor applied to a contract bid item for which the level of materials quality and workmanship, determined by statistical means, does not meet the specified Acceptable Quality Level (AQL). The Disincentive is usually expressed as a percentage of the original contract bid price.
Dispersion	The extent to which data values are scattered about a target or central value.
Dispute Resolution	The procedure used to resolve conflicts resulting from discrepancies between the Agency's and Contractor's results of sufficient magnitude to impact payment.
End-Result Specifications	Specifications that require the Contractor to take the entire responsibility for producing and placing a product. The Agency's responsibility is to either accept or reject the final product or to apply a pay adjustment commensurate with the degree of compliance with the specifications.

Engineering Limits	The absolute limiting value(s) placed on a Quality Characteristic beyond which the test result for an individual sample is considered to be unacceptable. [Engineering Limits are established to identify material that does not provide the minimum required engineering properties. They usually have an Upper Engineering Limit (UEL), a Lower Engineering Limit (LEL), or both. The Engineering Limits may be the same as the Specification Limits.]
Expected Pay (EP) Curve	A graphical representation of an Acceptance Plan that shows the relationship between the established actual quality of a Lot and its expected pay.
Fabricator	A company which produces Fabricated Structural Materials (e.g. Precast/Prestressed Concrete Structural Elements, Fabricated Structural Steel) for either the Prime Contractor or a Subcontractor.
F-test	A Hypothesis Test involving the comparison of the Variances of two independently obtained sets of data. The Hypothesis being tested is that the Variance of one Population equals the Variance of another Population. [The F-test is used in the Validation procedure to determine whether to use the individual Variances or the pooled Variances when performing the Independent t-test.]

Fabricated Structural Materials	Major structural items produced specifically for an individual construction project by a material Fabricator. [They are generally characterized by one or more of the following conditions: a) The production process for the material occurs under controlled conditions at an established Fabricator plant typically located within State or in another State; b) The material properties are stable and have no potential for alteration under proper transportation from the Fabricator to the project site; c) The materials arrive at the project site in a solid state and require little or no additional work after installation.]
Frequency	The number of items or values that occur within a given interval (or Class).
Frequency Distribution	A grouping of data values into intervals (or Classes) showing the number of values in each interval.
Frequency Histogram	Also called *Histogram*. A type of bar chart that depicts the frequency of occurrence of each data value as a rectangle (or bar). The width of each rectangle represents the data interval, while the height represents the number of data values in the interval (or Class).
Frequency Polygon	A broken line graph constructed by drawing line segments that join the mid-points of the top of each rectangle (or bar) in a Frequency Histogram.

Frequency Table	A tabular presentation of data consisting of a minimum of two columns. One column presents the data intervals (or Classes) in some useful order and the other column presents the corresponding frequencies.
Grand Mean	The sum of the Means of sets or Subgroups of data divided by the total number of sets or Subgroups.
Histogram	(See Frequency Histogram)
Hypothesis	A tentative theory or supposition provisionally adopted to explain certain facts and to guide in the investigation of others. It is a statement concerning the value of a Population parameter which can be tested statistically to determine the validity of the statement.
Hypothesis Test	A statistical procedure based on Sample data and probability theory used to determine whether a Hypothesis is a reasonable statement and should not be rejected, or is unreasonable and should be rejected.
Incentive	A pre-established increase in payment to the Contractor applied to a contract bid item for which the level of materials quality and workmanship, determined by statistical means, exceeds the specified Acceptable Quality Level (AQL). The Incentive is usually expressed as a percentage of the original contract bid price.
Increments	Small quantities of material of equal size that are obtained from a sampling location and combined to form a sample.

Independent Assurance (IA)	Activities that are an unbiased and independent evaluation of all the sampling and testing (or inspection) procedures used in the Quality Assurance program. [IA provides an independent verification of the reliability of the Acceptance (or Verification) data obtained by the Agency and the QC data obtained by the Contractor. The results of IA testing or inspection are not to be used as a basis of material acceptance. IA provides information for Quality System management.]
Independent t-Test	A Hypothesis Test involving the comparison of the Means of two independently obtained sets of data. The Hypothesis being tested is that the Mean of one Normal Population equals the Mean of another Normal Population.
Individual Value	A single test result or measurement for a Quality Characteristic (n = 1).
Inference	A logical conclusion about a Population based on a Sample (i.e. Statistical Sample).
Inherent Variability	Variability due to random or inconsequential causes in a given process. The four components of Inherent Variability include: Sampling Variability, Testing Variability, Materials Variability, and Construction (Production & Placement) Variability.

Inspection	The process of visual examination or physical measurement of an item for comparison against applicable requirements. [Inspection activities are primarily visual in nature. The characteristics (i.e. Attributes) of a product or item are assessed using both visual observations (i.e. *examination*) and check measurements (i.e. *physical measurement*) of equipment, environmental conditions, materials, and product workmanship.]
Lot	A specific quantity of material from a single source which is assumed to be produced or placed by the same controlled process.
Lower Control Limit (LCL)	The statistically established Control Chart Limit for values below the central line (target) of a Control Chart. [The LCL for a Control Chart plotting individual values is established at minus 2 Standard Deviations from the Control Chart target. The LCL for a Control Chart plotting Subgroups of data is established at minus 3 Standard Deviations from the Control Chart target. (See Control Chart Limits)].
Lower Specification Limit (LSL)	The lower statistically based limiting value used with a Quality Measure to evaluate the quality of a Lot.
Manufacturer	A company which manufactures and supplies Standard Manufactured Materials for either the Prime Contractor, a Subcontractor, or a Fabricator.

Mass	The property of a body that is a measure of its inertia and that is commonly used as a measure of the amount of material it contains and causes it to have weight in a gravitational field. Mass (m) is measured by dividing the weight (w) of a body by the acceleration due to gravity (g). ($m = w/g$)
Material Variability	Variability due to the inherent variation that naturally exists in a given material.
Mathematics	The science of numbers and their operations, interrelationships, combinations, generalizations, and abstractions and of space configurations and their structure, measurement, transformations, and generalizations.
Mean ($\overline{X}$)	The arithmetic average of a set of measurements or test values.
Mean Range ($\overline{R}$)	The sum of the Ranges of sets or Subgroups of data divided by the total number of sets or Subgroups.
Median	For a set of data, the value for which half the data values are above and half the data values are below.
Method Specifications	Specifications that require the Contractor to produce and place a product using specified materials in definite proportions and specific types of equipment and methods under the direction of the Agency.

Military Standards	Specifications developed by the U.S. Department of Defense for Lot acceptance. Military Standard 414 provides sampling procedures and tables for inspection by variables. Military Standard 105 provides sampling procedures and tables for inspection by attributes.
Mode	The value occurring most frequently in a set of data.
Moving Average Chart	A Control Chart that plots a moving average for a predefined number of sample values or Subgroup values.
Music Bar Chart	(See Run Chart)
Normal Distribution Curve (Bell-Shaped Curve)	A curve, having a bell-shaped form that is symmetrical about the Mean. It is determined by values of $\bar{x}$ and s and is used to describe a distribution of individual sample measurements or a distribution of Sample Means.
Null Hypothesis	The Hypothesis being tested. [Contrary to intuition, the Null Hypothesis is often a research Hypothesis that the analyst would prefer to reject in favor of the alternative Hypothesis. The Null Hypothesis can never be proved true. It can, however, be shown, with specified risks of error, to be untrue. If it is not disproved (i.e. not rejected), one usually acts on the assumption that there is no reason to doubt that the Hypothesis is true.]

Operating Characteristic (OC) Curve	A graphical representation of an Acceptance Plan that shows the relationship between the actual quality of a Lot and either; (a) the probability of its acceptance or (b) the probability of its acceptance at various payment levels.
Outlier	An extreme individual sample measurement or test value, or an extreme Mean.
Paired t-test	Also called *t-test for paired measurements*. A statistical test used to compare the test values for multiple pairs of split samples. The test uses the differences between the pairs of test values and determines whether the average difference is statistically different from 0.
Partnering	An organized process to establish positive working relationships between the Contractor and the Agency. It uses a mutually-developed, formal strategy of teamwork, commitment and improved communication to prevent disputes on a project.
Pay Adjustment	The actual amount, either in dollars or in dollars per area/weight/volume, that is to be added or subtracted to the Contractor’s final payment for a unit of Work.
Pay Factor	A multiplication factor, often expressed as a percentage, that considers a single Quality Characteristic and is used to determine the Contractor’s payment for a unit of Work.

Percent Within Limits (PWL)	The cumulative area under a standard curve which represents the estimated percentage of a Lot that falls above the Lower Specification Limit (LSL), beneath the Upper Specification Limit (USL), or between the Upper and Lower Specification Limits.
Performance-Based Specifications	Quality Assurance Specifications that describe the desired levels of fundamental engineering properties (e.g. resilient modulus, creep properties, and fatigue) that are predictors of performance and appear in primary prediction relationships. [The “primary prediction relationships” contained in Performance-Based Specifications are models that can be used to predict stress, distress, or performance from combinations of predictors that represent traffic, environment, supporting materials, and structural conditions.]
Performance-Related Specifications	Specifications that use quantified Quality Characteristics and Life Cycle Cost (LCC) relationships that are correlated to product performance.
Population	A collection of all possible individuals, objects, or items that possess some common specified characteristic(s) which can be measured.
Precision	(1) The degree of agreement among a randomly selected series of measurements. (2) The degree to which tests or measurements on identical samples tend to produce the same results.

Prime (General) Contractor	The company which has the primary construction contract for an Agency project and which assumes overall responsibility for completing the work.
Probability	The relative frequency with which an event occurs or is likely to occur.
Producer	A company which produces and supplies Project Produced materials (e.g. Aggregates, HMA, PCC) for either the Prime Contractor or a Subcontractor.
Project Produced Materials	Major items produced directly for an individual construction project either by a Contractor or by a material Producer. [They are generally characterized by one or more of the following conditions: a) The production process for the material occurs either at the project site or at a Producer plant located in close proximity to the project site; b) The material properties are subject to potential contamination or segregation during transportation from the plant to the project site; c) The materials arrive and are placed at the project site in a nonsolid or loose mixture state requiring subsequent mixing, compaction, finishing, or curing.]
Q Table	A table of values that relates the Quality Indices (Q_U or Q_L) to the estimated Percent Within Limits (PWL) or Percent Defective (PD), for a Statistical Sample of a particular size (n).

Qualified Laboratories	Laboratories that are capable as defined by appropriate programs established or recognized by each Agency. [Accredited Laboratories are considered Qualified. However, a Qualified Laboratory need not be Accredited.]
Qualified Personnel	Personnel who are capable as defined by appropriate programs established or recognized by each Agency.
Quality	(1) The degree of excellence of a product or service; (2) The degree to which a product or service satisfies the needs of a specific customer; (3) The degree to which a product or service conforms with a given requirement; or (4) Conformance to requirements.
Quality Assurance	(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.
Quality Assurance Program	The core programmatic elements required for construction Quality Assurance implementation.
Quality Assurance Specifications	Specifications that require Contractor Quality Control and Agency Acceptance activities throughout production and placement of a product. Final acceptance of the product is usually based on a statistical sampling of the measured quality level for key Quality Characteristics.

Quality Characteristic	A product characteristic that is measured through testing, either for Quality Control (QC) purposes or for conformance with Acceptance requirements. [Quality Characteristics are specific material properties or product requirements which are evaluated by QC and Acceptance testing. Quality Characteristics which are specified are normally selected because they: a) Relate to initial and long-term performance; b) Are quantifiable or measurable; and c) Can be measured with good repeatability.]
Quality Control (QC)	The system used by a Contractor party to monitor, assess and adjust their production or placement processes to ensure that the final product will meet the specified level of quality. [Quality Control includes sampling, testing, inspection, evaluation, and corrective action (where required) to maintain continuous control of a production or placement process.]
Quality Control Plan	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 processes "in control" and meet the Agency specification requirements.

Quality Index (Q)	A statistic which, when used with appropriate tables, provides an estimate of either the Percent Within Limits (PWL) or the Percent Defective (PD) for a Lot. [It is typically computed from the Mean and Standard Deviation of a set of sample values. The Lower Quality Index (Q_L) is computed relative to the Lower Specification Limit (LSL). The Upper Quality Index (Q_U) is computed relative to the Upper Specification Limit (USL).]
Quality Level Analysis (QLA)	A mathematical procedure that provides an estimate of the percentage of a Lot that is either within the Specification Limits (Percent Within Limits) or outside of the Specification Limits (Percent Defective).
Quality Limits	The upper or lower limiting values provided in the specifications that are used to evaluate the acceptability of materials produced or placed. [There are three types of Quality Limits that are typically included in Quality Assurance Specifications. They include: Specification Limits, Engineering Limits, and Acceptance Limits. Each type of Quality Limit serves a different specific function in assessing the Quality of a product or work item. Quality Limits are used together to determine the quality of an individual Quality Characteristic.]

Quality Measure	Any one of several mathematical tools that are used to quantify the level of quality of an individual Quality Characteristic. [Application of a Quality Measure to a set of testing data provides an overall numeric representation of Quality for a specific Quality Characteristic. Typical Quality Measures used in Quality Assurance are selected because they quantify the average quality, the variability, or both. Examples of Quality Measures that may be used include; Mean, Standard Deviation, Percent Defective (PD), Percent Within Limits (PWL), Average Absolute Deviation (AAD), Moving Average, and Conformal Index (CI). PWL or PD are the Quality Measures that are recommended for use in Quality Assurance Specifications.]
Quality System Manual (QSM)	A written document that describes the overall Quality Control operating procedures of a Contractor party (e.g. Prime Contractor, Subcontractor, Producer, Fabricator, Manufacturer). [A QSM documents the internal policies for achieving Quality and the assignment of responsibility and accountability for Quality Control within the Contractor's organization. It may also describe the minimum QC requirements expected of upper or lower tier Contractor parties who supply constituent materials or who are involved in handling or processing of the Contractor's products.]
Quota Sampling	A non-random procedure in which samples are obtained at the discretion and convenience of the sampler to satisfy the required number of samples for a Lot.

R Chart	A Control Chart that plots the Range (R) values for Subgroups of measurements or test values against statistically derived control limits.
Random	Without aim or reason, depending entirely on chance.
Random Number	A number selected entirely by chance as from a random number table or a random number generator.
Random Number Table	A collection of digits, randomly displayed in columns and rows, that are used to determine random numbers.
Random Sampling	A sampling procedure whereby each sample obtained from the Lot has an equal probability of being selected.
Range	The difference between the highest individual value and the lowest individual value in a set of measured or tested values.
Rejectable Quality Level (RQL)	The level of established actual quality for a Quality Characteristic that is rejectable when using a particular Quality Measure. [For example, when the Quality Measure used is Percent Within Limits (PWL), the RQL is the established (not estimated) PWL at which the Quality Characteristic is rejected.]
Repeatability	The degree of variation among the test results obtained by the same operator repeating a test on the same material. [The term Repeatability is used to designate test precision under a single operator.]

Representative Sample	A single, non-random sample which, in the opinion of the sampler, represents an average condition of a material or an item of construction.
Reproducibility	The degree of variation among the test results obtained by different operators performing the same test on the same material. [It measures the human influence or human error in the execution of a test. The term Reproducibility is used to designate inter-laboratory test precision.]
Re-Sampling	The process of obtaining a <u>new</u> material sample, if warranted, to <u>replace</u> the original sample for an individual Sublot.
Re-Testing	The process of performing another test to <u>confirm</u> the initial test. Re-Testing should be performed using a second Test Portion or Specimen prepared from the <u>same</u> original sample.
Run Chart	Also called *Music Bar Chart*. A Control Chart that presents individual measurements or test values for a specific Quality Characteristic on a vertical axis and the individual sample numbers (in consecutive order) on a horizontal axis.
Rounding	The process of dropping one or more digits so that the reported value contains only those digits which are significant or necessary in subsequent computations.

Sample	(1) Also called *material sample*. A small quantity of material or measurement obtained from a Sublot or Lot. [A sample can refer to either a point of inspection (i.e. visual examination or physical measurement) or an individual material sample obtained for testing. A sample may be made up of one or more increments of equal size that have been obtained from the sampling location and combined.]; or (2) Also called *Statistical Sample*. All of the samples obtained from a Lot which provide information that may be used to quantify the quality of the entire Lot. [The context in which the word “Sample” is used determines its meaning. For example, “obtain a sample here” would mean obtain a physical quantity of material from a specific location; while “the Sample size equaled 9” means that a total of 9 individual material samples were obtained in a random manner and thus comprised the Statistical Sample of size n = 9. Each sample is included in the overall Statistical Sample for a given Lot.]
Sample Mean	The Mean of a group or Subgroup of material samples. [Used when developing a distribution of sample Means. It is not the Mean of all individual samples in a Lot.]

Sampling	The process of selecting one or more samples from a population. [Sampling is an integral part of Contractor Quality Control, as well as Agency Acceptance. Sampling procedures should be established and applied for both inspection and testing activities. An effective sampling system delineates a Population according to measurable segments. The key elements of a sampling system include; Lots, Statistical Samples, Sublots, and samples.]
Sampling Plan	(See Acceptance Plan)
Sampling Variability	Variability caused by variation that is inherent in the sampling methods or procedures used to obtain a material sample.
Selective Sampling	A non-random procedure in which a sample is obtained only for informational purposes to guide Quality Control or Acceptance actions.
Seller(s)	The Contractor or Contractor parties that provide materials and work required for the completion of a highway or transportation contract.

Seller's Risk (α)	Also called *Contractor's Risk*, *Alpha (*α*) Error*, or *Type I Error*. It is the risk to the Contractor of having Acceptable Quality Level (AQL) material or workmanship rejected. [For an accept/reject Acceptance Plan, it is the probability that an Acceptance Plan will erroneously reject AQL material or workmanship with respect to a single Acceptance Quality Characteristic. For variables Acceptance Plans, it is equivalent to α_{PF}, where PF = 100. It is the probability that a variable payment Acceptance Plan will erroneously accept AQL material or workmanship at less than 100 percent pay with respect to a single Acceptance Quality Characteristic.]
Significance Level	The probability of rejecting a Null Hypothesis when it is in fact true. This probability (often denoted by α) is generally specified before any samples are drawn, so that the results that are obtained will not influence the level selected.
Significant Digit(s)	Also called *Significant Figure*. (1) Any of the digits 0 through 9, excepting leading zeros and some trailing zeros, which is used with its place value to denote a numerical quantity to some desired approximation; or (2) The digits of the decimal form of a number beginning with the leftmost nonzero digit and extending to the right to include all digits warranted by the accuracy of measuring devices used to obtain the numbers.
Significant Figure(s)	(See Significant Digit(s))

Skewness	A measure of the symmetry of a distribution. When the distribution has a greater tendency to tail to the right, it is said to have positive skewness. When the distribution has a greater tendency to tail to the left, it is said to have negative skewness. For the normal distribution, (as well as for any other symmetrical distribution), the skewness coefficient equals 0.
Specification(s)	(1) The compilation of provisions and requirements to perform prescribed work; or (2) A document that states the requirements to which a product must conform (i.e. materials and construction procedures) and the procedures for measurement and payment of Work completed.
Specification Limits	The statistically based limiting values(s) placed on a Quality Characteristic which are applied with a particular Quality Measure (such as PWL) to evaluate the quality of a Lot. [Specification Limits are usually comprised of an Upper Specification Limit (USL), a Lower Specification Limit (LSL), or both. It is important to recognize that since Specification Limits are statistical limits, individual sample test results may fall beyond the USL or LSL and still be included in the Acceptance determination. The Specification Limits will ultimately be used for computation of Quality Levels (e.g. PWL), which will be used in calculating pay factors for a Lot.]
Specimen	Also called *Test Portion*. A portion of a material sample that is prepared and tested. Some test methods require material samples to be split into multiple Specimens for testing.

Split Sample Correlation	The comparison of split samples tested by different parties (e.g. Agency vs. Contractor) against an allowable degree of test result difference attributable to sampling and testing Variability.
Standard Deviation	A measure of the Variability of a set of values which is represented by the principal square root of the Variance.
Standard Manufactured Materials	Standard items that are produced routinely (i.e. not for a specific project) by a Manufacturer. [They are generally characterized by one or more of the following conditions: a) The materials are normally mass-produced under highly controlled and largely automated manufacturing conditions; b) The material properties are stable and have no potential for alteration under proper transportation from the Manufacturer to the project site; c) The materials arrive at the project site in a solid, finished state* and require only installation (**Note: Exceptions to this condition include materials, such as PG binder, cements, and paints/coatings that are incorporated into either Project Produced Materials or Fabricated Structural Materials*).]
Standard Normal Distribution	A mathematical construct of a continuous probability distribution having a symmetrical, asymptotic Bell-Shaped Curve that is fully defined by μ and σ, where $\mu = 0$ and $\sigma = 1$, and for which the Mean, Median, and Mode are all equal. All distribution curves having a similar shape can be modeled by the Standard Normal Distribution via the z-score transformation.

Statistical Control Chart	(See Control Chart)
Statistical Sample	(See Sample)
Statistic	A summary value calculated from a Sample (i.e. Statistical Sample) of measured or tested values. Some examples are the Mean, the Standard Deviation, and the Regression Coefficients estimated from the Sample.
Statistics	A branch of mathematics that deals with the collection, analysis, interpretation, and presentation of masses of numerical data. Statistics uses mathematical theories of probability to impose order and regularity on sets of data.
Stratified Random Sampling	A sampling procedure whereby samples are randomly obtained from each Sublot.
Student t Distribution	Also called *Student's t Distribution*. A family of continuous sampling distributions employed in small sampling theory.
Subcontractor	A company which is responsible for field placement or installation of an individual item of work under contract to the Prime Contractor.
Subgroup	A set (n > 1) of Quality Control sample values from within a Lot, whose Mean or Range are plotted on a Control Chart.

Sublot	A subdivision of a Lot. [A Sublot is an equal (usually) division or part of a Lot from which a sample of material is obtained in order to assess the Inspection Attributes or Quality Characteristics of the Lot. Sublots are established to ensure that samples of material obtained from the Lot are not all concentrated in one location. Sublots allow samples to be taken from within different segments (beginning, middle, end) of the Lot.]
Symmetry	Correspondence in size and shape of parts about a given axis. For example, the bell-shaped curve of a Standard Normal Distribution is said to be symmetrical about the Mean value.
Systematic Sampling	(See Uniform Interval Sampling)
Target Value	The value that is placed on a Quality Characteristic that represents the Mean of the expected distribution of the specified Population.
Test Portion	(See Specimen)
Testing	The application of prescribed apparatus and procedures to characterize a specified property of a material or product. [Testing is used to determine whether the physical or chemical characteristics of either a finished product or its constituent materials meet the established requirements. Testing differs from inspection (by examination) as it provides an *objective* and *quantitative* measurement tool. It provides numerical magnitude for a specified property (i.e. Quality Characteristic).

Testing Variability	Variability that is the result of variation inherent in performing a test method and variation inherent in the test equipment.
Total Quality Management	A continuous improvement process to meet customer requirements - a philosophy of doing the right thing the first time.
t-Test	(See Independent t-Test and Paired t-Test)
Type I Error	(See Seller's Risk)
Type II Error	(See Buyer's Risk)
Unbiased	Free from bias.
Uniform Interval Sampling	A non-random procedure in which samples are obtained at fixed intervals of material production or material quantity.
Upper Control Limit (UCL)	The statistically established Control Chart Limit for values above the central line (target) of a Control Chart. [The UCL for a Control Chart plotting individual values is established at plus 2 Standard Deviations from the Control Chart target. The UCL for a Control Chart plotting Subgroups of data is established at plus 3 Standard Deviations from the Control Chart target. (See Control Chart Limits)]
Upper Specification Limit (USL)	The upper statistically based limiting value used with a Quality Measure to evaluate the quality of a Lot.

Validation	The mathematical comparison of two independently obtained sets of data (e.g. Agency Acceptance data vs. Contractor QC data) to determine whether it can be assumed they came from the same Population.
Variable	A measurement that can have a series of different values.
Variability	Differences in measured test values for a given Quality Characteristic within a stable pattern due to chance, or outside this normal pattern due to assignable cause(s).
Variance	A measure of dispersion of a set of values from their Mean, expressed as a function of the sum of all squared Deviations from the Mean.
Verification Sampling and Testing	(See Acceptance Sampling and Testing)
Warning Limits (Upper, Lower)	Boundaries established within the upper and lower Control Chart Limits on Control Charts that plot Subgroups of data. They are used to warn of possible problems in the production or placement process that may lead to the process going “out of control”. [Warning Limits are established at ± 2 Standard Deviations from the Control Chart target. Warning Limits are not used with Control Charts that plot individual sample values (i.e. Run Charts).]
Weight	The force with which a body is attracted toward the earth or a celestial body by gravitation and which is equal to the product of the mass (m) of an object and the local gravitational acceleration (g). (w = m x g)

X-Bar ($\overline{X}$) Chart	A Control Chart that plots the Mean ($\overline{X}$) values for Subgroups of measurements or test values against statistically derived control limits.
Zero Defects	A TQM philosophy, aimed at preventing problems or defects from occurring, which is stated as: “Do the job right the first time”.

- END OF APPENDIX A -

APPENDIX B

Metric Conversions

Appendix B

Metric Conversions

Conversion Factors — English to Metric

Length

To Convert From	To	Multiply By
Inch	Millimeter (mm)	25.4
Inch	Centimeter	2.54
Foot	Meter (m)	0.3048
Yard	Meter (m)	0.9144
Mile (Statute)	Kilometer (km)	1.6093

Area

To Convert From	To	Multiply By
Square Inch	Square Centimeter (cm^2)	6.452
Square Foot	Square Meter (m^2)	0.0929
Square Yard	Square Meter (m^2)	0.8361

Volume (Capacity)

To Convert From	To	Multiply By
Ounce	Cubic Centimeter (cm^3)	29.57
Gallon	Cubic Meter (m^3)□	0.003785
Cubic Inch	Cubic Centimeter (cm^3)	16,39
Cubic Foot	Cubic Meter (m^3)	0.02832
Cubic Yard	Cubic Meter (m^3)□	0.7646

Mass

To Convert From	To	Multiply By
Ounce	Gram (g)	28.35
Pound	Gram (g)	453.6
Pound	Kilogram (kg)	0.4536
Ton (Metric)	Megagram (Mg)	1.000
Ton (Short 2000 lb)	Megagram (Mg)	0.9072

Temperature

To Convert From	To	Multiply By
deg Fahrenheit (F)	Deg Celsius (C)	$t_C=(t_F-32) \div 1.8$
deg Celsius (C)	deg Fahrenheit (F)	$t_F = 1.8t_C + 32$

- END OF APPENDIX B -

APPENDIX C

Agency and Industry Support for Quality Assurance

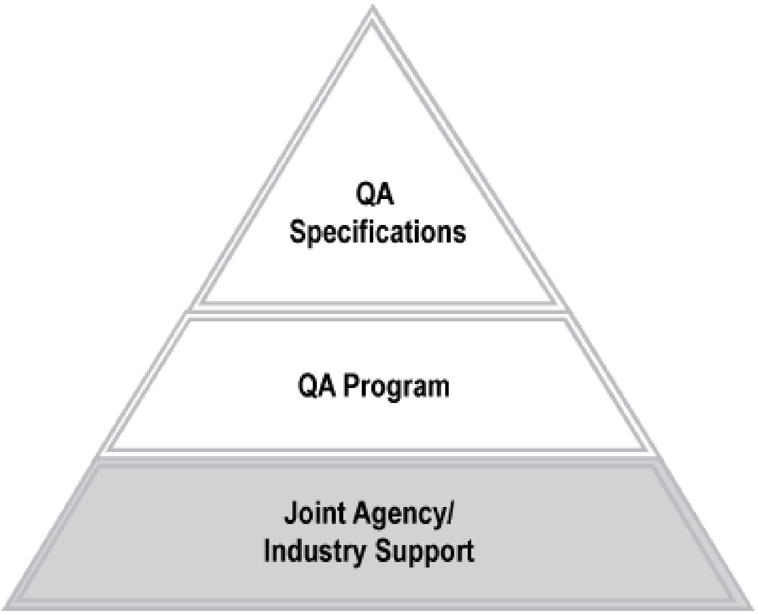
Appendix C

Agency and Industry Support for Quality Assurance

Appendix Overview

In this Appendix, the following topics will be specifically discussed:

C.1 - Joint Agency/Industry Support – The Third QA Component



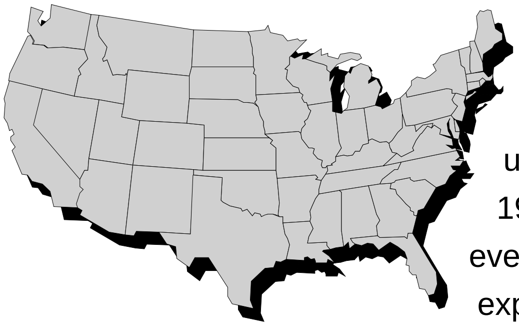
As presented in Chapter 1, QA in transportation construction is comprised of three primary components. Two other components, a Quality Assurance Program (Chapter 3) and Quality Assurance Specifications (Chapter 2) have already been discussed. However, these two components cannot be successfully implemented without the foundation component - ***Joint Agency/Industry Support*** for Quality Assurance.

This foundation component is sometimes taken for granted or overlooked. Joint Agency/Industry Support includes:

- Commitment
- Training
- Communication
- Funding

Each of these items will be addressed in this Chapter. First, however, we will take a look at how Quality Assurance implementation in transportation construction has been proceeding along with some of the feedback from Agencies and Industry.

C.2 - Quality Assurance Implementation Status



Some Transportation Agencies began implementing Quality Assurance Specifications over 30 years ago. The number of Agencies using Quality Assurance Specifications between 1960 and 1990 was initially small. Some Agencies even pulled back from using them after limited experience. The reasons for this slow climb into Quality Assurance are largely related to the absence of the other two QA Components; the six core elements of a Quality Assurance Program and joint Agency/Industry Support (i.e. Commitment, Training, Communication, Funding).

By the 1990's, in particular with a renewed focus on Quality through the NQI, many State Transportation Agencies focused on TQM in transportation construction and began to move into Quality Assurance Specifications.

A 1992 AASHTO Survey found that 42 of 50 States (84%) were either using or planning to use some type of Quality Assurance Specification. The results of the 1992 AASHTO Survey are summarized in the table below.

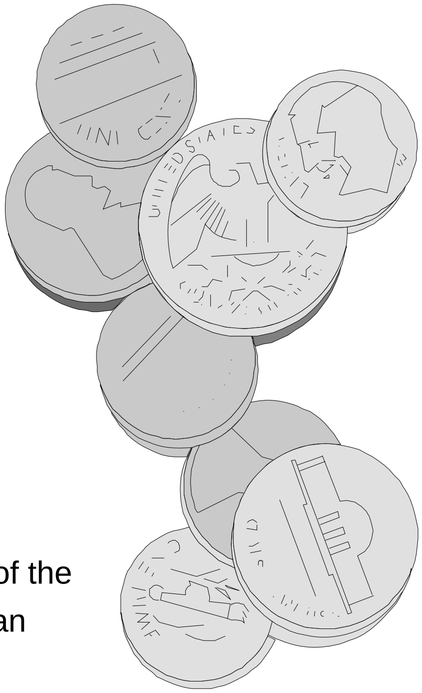
Number of State Agencies Using Quality Assurance Specifications – 1992		
Implementation Status		
Using	Not Using	Planning
29 (58%)	8 (16%)	13 (26%)

The FHWA conducted an updated Survey in 1998 of the status of Quality Assurance implementation by the 52 (50 States + DC & PR) U.S. State Highway Agencies. The 1998 FHWA Survey found that 96% of State Agencies were either using or planning to use Quality Assurance Specifications for HMA, while 75% of the Agencies were using or planning to use them for Structural PCC.

The use of Quality Assurance Specifications by State Agencies as of 1998 is summarized in the table below by Material Type.

Number of State Agencies Using Quality Assurance Specifications - 1998			
Material Type	**Implementation Status**		
	Using	Not Using	Planning
• Hot-Mix Asphalt	40 (77%)	2 (4%)	10 (19%)
• Structural PCC	21 (40%)	13 (25%)	18 (35%)
• PCC Pavement	20 (38%)	17 (33%)	15 (29%)
• Aggregate Base	18 (35%)	19 (36%)	15 (29%)
• Embankment	12 (23%)	27 (52%)	13 (25%)

C.3 - Costs of Quality Assurance



Implementing Quality Assurance requires little or no additional cost to Contractors. A study published in 1998 (Transportation Research Record No. 1632, *Summary of Current Quality Control/Quality Assurance Practices for Hot-Mix Asphalt Construction*) revealed the following findings:

- Agency-estimated Contractor Quality Assurance costs for a ton of HMA ranged from $0.27 to $1.81 per Megagram ($0.30 to $2.00 per Ton) depending on construction markets and project size.
- Contractor Quality Assurance costs, as a percentage of the total project cost, ranged from 0.5 to 10 percent, with an average of 2 percent.

C.4 - Agency and Contractor Concerns about Quality Assurance

As can be expected with any change in practice, concerns regarding Quality Assurance have been voiced by some Transportation Agencies and Contractors. In 1998, NETTCP undertook a survey of Agencies and Industry in the six New England States on the "Early Stages of Quality Assurance Implementation". Here are the main implementation difficulties and concerns reported in the NETTCP survey by New England Industry representatives:

- ***"Quality Assurance Specification limits/tolerances are still too subjective"***
  As one might expect during the early stages of Quality Assurance implementation, the historic random sampling and testing data needed to establish and validate specification targets and limits may not be available. That is why Pilot Projects are important to collect this data to determine the actual Normal Variability of various construction materials.

- ***"Agencies differ in their specifications and approaches"***
  This is a valid concern, particularly for Contractors who work in multiple States. The six New England States are working together through the NETTCP to approach Quality Assurance in a consistent and uniform manner. While this effort may not completely eliminate differences in Quality Assurance Specifications from Agency to Agency, it will hopefully eliminate most major differences.

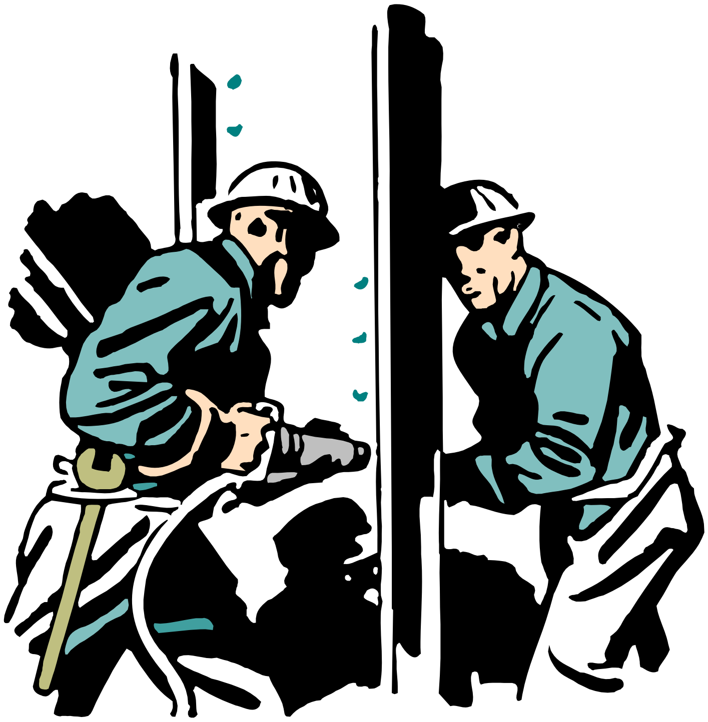
- ***"The Agency may be reluctant to give up control"***
  Working under a Quality Assurance environment requires changes in roles and responsibilities of Contractor and Agency personnel. With sufficient training and experience, personnel from both sides will hopefully come to realize that Quality Assurance doesn't really require "giving up" anything. The Agency's focus is simply shifted to Acceptance inspection, sampling and testing, rather than trying to run the Contractor's Quality Control operations.

- ***"Process Control testing is mandated"***
  Yes, as discussed in Chapter 2, Quality Control is one of the six core elements of a Quality Assurance Program. Placing responsibility for Quality Control inspection, sampling and testing with the Contractor is consistent with the approach followed in most business sectors that manufacture or produce products. It is much more effective for the Contractor to take ownership for controlling the quality of construction materials production and placement.

- ***"Increases the QC layers in an organization"***
  Depending upon the management structure of an individual Contractor or Producer, Quality Assurance may create additional levels of personnel. However, those organizations that embrace modern management philosophies which embrace empowerment of the individual "closest to the work", should not find a need to "increase layers". It will require personnel responsible for Quality Control (Superintendents, Foremen, Operators, QC Plan Administrators, Technicians) who are properly trained and who have a solid understanding of Quality Assurance principles and practices.

- ***"Difficulty using multiple Subcontractors on the same project to assign monetary disincentive responsibility"***
  This issue is not unique to Quality Assurance. The assignment of "ownership" to individual Subcontractors for lesser quality materials should be clearly delineated in each Subcontract. Quality Characteristics which are sampled and tested at the point of materials production (i.e. Plant) should be the responsibility of the Supplier or Producer, while Quality Characteristics sampled and tested from in place material should be the responsibility of the individual Subcontractor that place the material. Contractors should also provide for a sharing of incentive money with each Subcontractor to enlist their attention to providing a high level of quality.

The following challenges were reported in the 1998 NETTCP Survey by New England Agency representatives:



- ***"More work for everyone*!
(*But it's worth it)"***

  Virginia DOT reported a similar statement but said that after the initial pain of implementation, things began to settle down. After sufficient experience with Quality Assurance, most Agencies will find that it does not really require any extra work.

- ***"Higher risk initially"***

  The level of Agency risk will be dependent upon how well specification targets and limits have been set along with corresponding Pay Factors. This is why it is prudent to use a phased approach using only partial incentives and disincentives during initial Pilot Projects. Risk will also be balanced as long as the Agency provides proper levels of Acceptance sampling, testing, and inspection to verify QC data.

- ***"Steep learning curve"***

  The "learning curve" is largely a function of Agency Commitment to Quality Assurance. As will be discussed further below, proper support through training, communication, and funding are key items required to lessen the "learning curve".

C.5 - Positive Comments and Findings on Quality Assurance

OK, it is best to report the good with the bad, so here is some positive feedback related to Quality Assurance obtained by AASHTO, NETTCP, the Transportation Research Board (TRB), and a few States beyond New England.

A 1992 AASHTO Survey of Industry reported the following feedback:

- Quality Assurance is less inspector (plant) intensive
- Responsibility for process Quality Control and Acceptance is separated and clearly defined
- Permits the optimizing and timing of sampling
- Risks are quantified, which means that both the Contractor and Agency share the same risks in product Acceptance
- The quality improvement attributed to their use is documented by governmental Agencies
- Quality Assurance Specifications can be performance-related
- Pay Factors can be related to performance
- Quality Assurance is the only way to assure a 100% pay factor
- Permits obtaining premium prices for premium quality work

The 1998 NETTCP Survey of Agencies and Industry in the six New England States on the “Early Stages of Quality Assurance Implementation” revealed a number of positive findings. Here are the positive comments reported in the NETTCP survey by New England Industry representatives:

- The effect of Quality Assurance is evident in increasing quality aids such as Material Transfer Devices and slowing down the paving ‘train’
- In order to obtain ride quality, all aspects of the project must be concentrated on
- Quality Assurance allows creativity and deviation from the ‘standard operating procedures’ of Method Specifications – Gives the Contractor power over their own destiny

The following positive findings were reported in the 1998 NETTCP Survey by both Agency and Industry representatives in New England:

- Quality Assurance means more working together; Increased communication with focus on details
- Everyone including the owners have a stake in a good outcome; It requires all parties to work together
- It increases Contractor awareness of their capabilities and inabilities
- Quality Assurance increases quality with more emphasis on consistency of production, construction, sampling, and testing

Excerpts taken from the 1998 Transportation Research Board (TRB) NCHRP Synthesis 263 entitled “State DOT Management Techniques for Materials and Construction Acceptance” follow:

- The quality from Contractors has improved
- The Contractors are more aware of their product

- The Contractors provide smoother pavements
- The Contractor is rewarded for work exceeding the specification
- State DOT has increased conformance with specifications
- User delays are reduced
- Reduced Contractor litigation is anticipated
- The disincentives capture the attention of the Contractor to enlist their fullest cooperation

An Arizona DOT Survey on Quality Assurance reported the following findings:

- Increased confidence in Contractor’s testing program
- Timely turnaround of test results
- Improved relations between the Agency and the Contractor – No more ‘We versus Them’

Indiana DOT also found from a survey of their construction and testing personnel, as well as from Contractors and Suppliers, the following positive feedback on the use of Quality Assurance Specifications:

- 73% of the responders feel that Quality Assurance Specifications are better than conventional (Method) specifications
- 76% of responders feel that a Quality Assurance Program is more effective in producing better products
- 62% of the Suppliers responding prefer supplying to Quality Assurance projects
- 69% of responders feel that a Quality Assurance Program is cost effective

C.6 - Use of Pay Adjustments in Quality Assurance

As briefly discussed in Chapter 4, the use of pay adjustments that are directly tied to the measured quality level of individual Quality Characteristics is an important part of most Quality Assurance Specifications. Many State Agencies provide reduced payment for lesser quality work through disincentives that typically range from 0% to 99%. To complement this, a number of State Agencies also reward superior quality work by the Contractor with incentives ranging from 101% to 115%.

A 1992 AASHTO Survey of State Transportation Agencies using Quality Assurance revealed the following information regarding the use of pay adjustments:

- 78% of the Agencies use specified pay adjustment clauses
- 35% of the Agencies use positive pay factors

As noted in Chapter 2, one of the key quality principles supported by the NQI, as specified through the National Policy on the Quality of Highways, is support for the use of incentives linked to quality. Accordingly, the application of positive pay adjustments by Agencies did grow through the 1990’s.

In 1996, FHWA conducted an updated survey of State Agencies to determine the use of incentives and disincentives. The results of the 1996 FHWA Survey are summarized as follows:

- 29 out of the 36 States responding to this survey (81%) use some type of pay adjustment (incentives and/or disincentives)

- 27 out of the 36 States responding (75%) use incentives for at least one Material Quality Characteristic

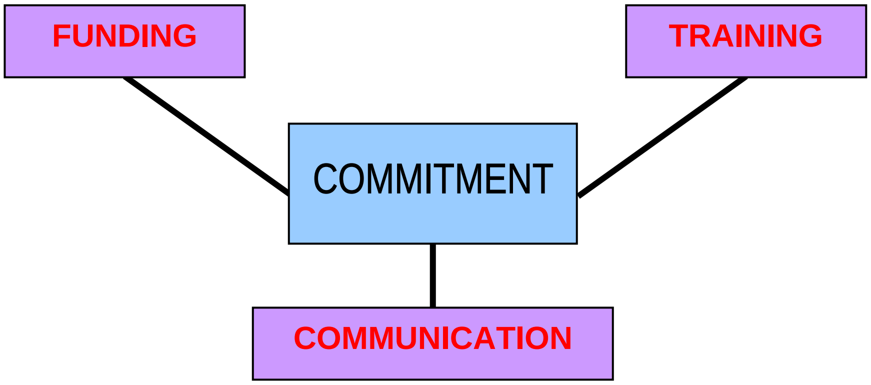
The widespread use of pay adjustments for HMA construction was noted in a 1998 TRB report. The study, published by the University of Wisconsin in Transportation Research Record No. 1632, is titled "Summary of Current Quality Control/Quality Assurance Practices for Hot-Mix Asphalt Construction". The following finding was reported in the study:

- 39 out of the 41 States responding to the Study Survey (95%) indicated they are implementing some type of pay adjustment

C.7 - Commitment to Quality Assurance

At the core of Joint Agency/Industry Support for Quality Assurance lies ***Commitment***. There must be commitment from personnel at all levels of each organization (Agency, Industry Associations, Contractors, Suppliers). It begins with top management and must extend to all front-line personnel responsible for construction quality.

This commitment to Quality Assurance must be demonstrated not only in words but through continuous tangible actions. Each organization needs a "Champion" to ensure that the required elements of a Quality Assurance Program are put in place and to coordinate the development and updating of Quality Assurance Specifications.
The other required tangible actions of Joint Agency/Industry Support, which the "Champion" should lead for their organization, include training, communication, and funding as further discussed below. The absence of any of these items will weaken the commitment to the implementation and continued application of Quality Assurance.



C.8 - Quality Assurance Training

Some of the concepts and requirements of Quality Assurance present a significantly different approach to transportation construction for Agency and Industry personnel alike. Accordingly, ***Training*** is an essential tool to assist in supporting successful Quality Assurance implementation. Here are the key approaches to Quality Assurance training that should be utilized:

- ***Joint Agency/Industry training is most effective***
  There is a need to produce a common understanding of Quality Assurance throughout Transportation Agencies as well as Industry partners. It is Important that personnel from each organization hear the “Same Thing” at the “Same Time”. Joint training allows each party to better understand the concerns of the other and it can improve communication and cooperation.

- ***Training is needed at all levels***
  Quality Assurance training should be provided for top management as well for front-line personnel. One State Transportation Agency in the Northeast learned that having only a few well-trained Quality Assurance “gurus” in the Agency did not facilitate effective implementation of Quality Assurance. Front-line project-level personnel must be adequately trained to have sufficient understanding of the basic concepts as well as the detailed application of specification requirements.

- ***Training must be geared to the target audience***
  Obviously, top managers need to have a solid grasp of the fundamentals of Quality Assurance (such as is contained in Module I of this course), but do not really need more in-depth training. Front-line Agency personnel (Resident Engineers, Inspectors, Technicians) and Contractor personnel (Superintendents, Foremen, Operators, QC Plan Administrators, Technicians) must have a full understanding of Quality Assurance principles and practices as well as the detailed requirements of Quality Assurance Specifications. Training and certification courses such as this Quality Assurance Technologist Course are designed to address these front-line personnel.

- ***Continuous training is necessary***
  Quality Assurance training must not be viewed as a "One-Time" thing. Initial training should be followed by periodic update training, particularly after personnel have had some hands-on experience working with Quality Assurance Specifications. This enables personnel to confirm and/or clear up their understanding of Quality Assurance in light of their actual experience. Continuous training also ensures that new personnel are brought into the Quality Assurance environment equipped with the same knowledge as their more experienced peers.

C.9 - Communication in Quality Assurance

The next essential tool to support Quality Assurance implementation is ***Communication***.

- ***Communication must begin within each organization***
  The intent and plans for applying Quality Assurance must be communicated from management to front-line personnel within each organization (Agency, Industry Associations, Contractors, Suppliers).

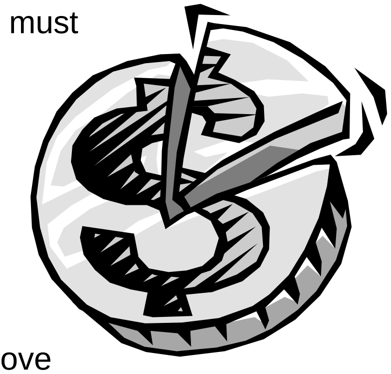
- ***Communication between Agency and Industry is vital***
  Communication between an Agency and their Industry partners is also vital during early program development. The Agency needs to share information with Industry when developing the first two pieces of the TQM pie (Quality Assurance Program + Quality Assurance Specifications). Open communication under a partnership approach will help allay fears between organizations by allowing input and consideration of each partner's interests.

- ***Project level communication is needed***
  Continuous project level communication within and between Contractor and Agency personnel is necessary to the successful application of Quality Assurance. Communication must continue with day-to-day project level activities, especially through timely feedback and sharing of inspection and testing information for QC and Acceptance.

- ***Joint Agency/Industry workshops improve communication***
  Periodic workshops for both Agency and Industry personnel should be held to present Quality Assurance Program and Specification status, progress, and issues. This allows an opportunity for joint Agency/Industry Continuous Quality Improvement (CQI). Other forums (e.g. Industry meetings, Conferences) should be used as well to communicate progress and issues associated with Quality Assurance implementation.

C.10 - Funding for Quality Assurance

Last, but by no means least, ***Funding*** by Agencies and Industry is necessary to support the implementation of Quality Assurance. Each organization must commit to provide adequate funding for the resources (personnel, equipment, training) required for a succesful Quality Assurance Program. Investing in Quality Assurance should not be viewed as a “Luxury” but rather a “Necessity”.



- ***Contractor Investment***
  Contractors may need to invest in new equipment to improve their materials production and placement operations. Other Contractor needs may include new laboratories and laboratory equipment. Additional qualified personnel (typically QC Plan Administrators, Technicians, and Inspectors) may also be needed.

- ***Agency funding needs***
  On the Agency side, there is obviously a need to ensure an adequate number of qualified Engineers, Technicians, and Inspectors, as well as equipment for testing and inspection.

- ***Funding for Training***
  Training must obviously be provided for both Agency and Industry as discussed above. Quality Assurance training and workshops might be jointly funded by Agency and Industry.

C.11 - Partnering

The Support Component of Partnering

[s]

In addition to the six Quality Assurance Program core elements presented, there is one additional component that may be used to support these elements. ***Partnering*** is a key ingredient to support a Quality Assurance Program. Partnering is defined as follows:

> **Partnering** - "An organized process to establish positive working relationships between the Contractor and the Agency. It uses a mutually-developed, formal strategy of teamwork, commitment and improved communication to prevent disputes on a project."

Partnering Function

[s]

Partnering can help facilitate the implementation of Contractor Quality Control and Agency Acceptance procedures. It should never be used as a substitute for Dispute Resolution as a core QA Program element. However, Partnering can assist in minimizing the need to utilize the formal Dispute Resolution process or make the Dispute Resolution process less confrontational when implemented. Partnering is a tool that can help to link the Quality Control and Acceptance systems and support the other QA Program elements to keep them up and running smoothly.

The concept of "Partnering" is not a new way of doing business – many Agency and Contractor personnel have always utilized an informal partnering approach. As it has come to be used today, Partnering is a formal, organized method of improving communications and enhancing the resolution of conflicts on a project. The parties to a contract voluntarily agree to adopt a different method of interacting on a project. The parties agree to utilize a team-based cooperative approach to the management of the project. It requires an attitude on the part of participants to approach the job with an open mind and a willingness to listen to and work with other people.

Background of Formal Partnering

[s]

Partnering had its origins in private industry during the early 1980's where management saw a need to develop more efficient ways for groups of people to work together. The U.S. Army Corps of Engineers turned to Partnering in 1988 in an effort to turn back the tide of litigation that had characterized the construction industry in the 1980's. Too often, the Army Corps' and Contractors' efforts were focused on posturing and documentation preparation related to claims and lawsuits. The Army Corps recognized that this was not a cost-effective manner in which to conduct business and deliver the end product.

By 1991, many Transportation Agencies began to use Partnering with encouragement from the Associated General Contractors of America (AGCA). A 1993 survey conducted by Bowling Green State University for the Ohio DOT revealed that Partnering has been implemented by forty-two State Transportation Agencies. The National Partnership for Highway Quality, AASHTO, AGCA, and FHWA have encouraged the use of Partnering as an effective tool to strengthen a Quality Assurance Program.

Implementing Partnering Activities

[s]

While the contract establishes the legal relationships between the Agency and Contractor, Partnering seeks to establish positive working relationships among the project personnel (stakeholders) through a mutually developed, formal strategy of commitment and communication. It attempts to create an environment of trust and teamwork between the Agency and the Contractor. Partnering also promotes the importance of shared goals by the Agency and the Contractor and establishes a shared commitment to solve problems in a timely and cost-effective manner. For the most effective results on a project, it is recommended that a Partnering Workshop be held, ideally at the early stage of the project. The Partnering Workshop is usually conducted at a neutral site, away from the project and outside of the respective offices of the Agency and the Contractor. Structured discussions and team-building exercises are used to identify and develop the following:

- Individual and shared goals
- Key project issues and concerns
- A formal conflict resolution process
- A joint Evaluation Process
- A Partnering Charter

The AGCA publication titled *Partnering – A Concept for Success* (September 1991) provides excellent information on and guidelines for implementing Partnering.

Benefits of Partnering

[s]

The benefits of partnering are numerous and many Agencies have adopted partnering as standard practice, including Arizona and Washington State. Some of the benefits which can be realized by Agencies and Contractors through Partnering include the following:

- Litigation is reduced and schedules are improved
- Safety records are generally better
- Contract growth is contained
- Administrative costs are reduced (since the amount of documentation required is lessened due to the reduced risk of litigation)
- Communications are clear and the need for re-work is minimized
- All stakeholders can enjoy a productive atmosphere where the emphasis is on mutual problem solving and goals

C.12 - Support for Quality Assurance Summary

Joint Agency/Industry Support is one of the primary ingredients for the implementation of QA in transportation construction. It requires a continuous commitment from personnel at all levels of each organization.

The other tangible actions which demonstrate Joint Agency/Industry Support include training, communication, and funding. These support activities will ensure the successful implementation of a Quality Assurance Program and the proper development and application of Quality Assurance Specifications.

Today, most State Transportation Agencies have Quality Assurance Programs in place for construction. The number of Agencies using Quality Assurance Specifications increased during the 1990's. Additionally, pay adjustments (incentives and/or disincentives) have become a key component of most Agency Quality Assurance Specifications.

Concerns have been expressed about Quality Assurance implementation by some Agency and Contractor representatives. However, most feedback obtained through recent surveys has been very positive. Quality Assurance is generally perceived as a "Win-Win" approach by both Industry and Agencies.

- END OF APPENDIX C -

APPENDIX D

Example Laboratory Qualification Program

Appendix D

Example Laboratory Qualification Program

Appendix Overview

In this Appendix, an example of a Laboratory Qualification Program from the New England Transportation Technician Certification Program is provided. The document includes the following topics:

- ☐ Requirements for Laboratory Accreditation or Qualification
- ☐ Program Description and Participating Agencies
- ☐ NETTCP Laboratory Certification Program Criteria
- ☐ Laboratory Decertification From NETTCP LCP
- ☐ NETTCP Laboratory Certification Program Inspection Summary Report

NETTCP LABORATORY CERTIFICATION PROGRAM

May 17, 2007

I. Requirements for Laboratory Accreditation or Qualification:

The Federal regulation for Quality Assurance Procedures for Construction (23 CFR 637) identifies the following three requirements for the accreditation and qualification of laboratories:

- Transportation Agency Central Laboratory - Must be accredited through the AASHTO Accreditation Program (AAP) by June 30, 1997.

- Consultant Laboratories performing Independent Assurance (IA) or Dispute Resolution - Must be AAP accredited by June 29, 2000.

- Contractor, Consultant & Other Transportation Agency Laboratories (other than the Agency Central Laboratory) performing sampling & testing utilized in the Agency acceptance determination - Must be "qualified" through appropriate programs established by each Transportation Agency by June 29, 2000.

The New England Transportation Technician Certification Program (NETTCP) has established the following Laboratory Certification Program (LCP) to address the requirement for "qualified" laboratories (See third bullet above). Laboratories that are certified through the NETTCP LCP are considered to be "qualified" as defined in 23CFR637 and should not be confused with an "accredited" laboratory.

II. Program Description and Participating Agencies:

The criteria herein established have been agreed upon by the six New England Transportation Highway Agencies (CT, MA, ME, NH, RI, VT), their corresponding Federal Highway Administration (FHWA) Division Offices, and the Federal Aviation Administration (FAA). This Laboratory Certification Program will be administered by the NETTCP and implemented by each Transportation Agency in accordance with procedures established under the auspices of the NETTCP. The following five Laboratory Categories have been established for the NETTCP LCP:

1-P - Permanent Transportation Agency (Satellite/District/Regional/Consultant) laboratories performing Acceptance testing (*See Note 1 below*)

1-T - Temporary Transportation Agency (Project/Consultant) laboratories performing Acceptance testing (*See Note 1*)

2-P - Permanent Contractor (Plant/Consultant) laboratories that:
Perform Quality Control (QC) testing that is incorporated in the Acceptance decision (*See Note 1*); or
Are utilized by Agency personnel to perform Acceptance testing

2-T - Temporary Contractor (Project) laboratories that:
Perform QC testing that is incorporated in the Acceptance decision (*See Note 1*); or
Are utilized by Agency personnel to perform Acceptance testing

3 - Contractor laboratories (Permanent or Temporary) performing only QC testing (*See Note 2 below*)

Note 1: *The criteria established herein for Laboratory Categories 1-P, 1-T, 2-P, & 2-T are minimum criteria for the purposes of compliance with the Federal Regulation. Transportation Agencies may elect to utilize additional certification requirements, for any type of laboratory, in order to meet their particular needs.*

Note 2: *Category 3 Laboratory certification is not required for compliance with the Federal Regulations. This category is provided for Transportation Agencies requiring minimum qualifications for all QC Laboratories.*

A. Transportation Agency Responsibilities

Each Transportation Agency will be responsible for implementing the NETTCP Laboratory Certification Program as follows:

- Each Transportation Agency will be responsible for inspecting all Transportation Agency, Contractor, and Consultant laboratories within their state, which fall under Laboratory Categories 1-P, 1-T, 2-P, & 2-T above. If a Transportation Agency so elects, it may also inspect Category 3 laboratories. Each laboratory inspection will be conducted by either the Transportation Agency or NETTCP in accordance with the NETTCP LCP Criteria contained in Section III below.

- Each laboratory inspection will be documented on the NETTCP LCP Inspection Summary Report (See Attached Summary Report). Each Transportation Agency will utilize appropriate detailed Inspection Checklists (acceptable to NETTCP) to augment the LCP Inspection Summary Report (Note: Inspection Checklists are available from NETTCP). The completed LCP Inspection Summary Report will indicate whether or not the laboratory meets the NETTCP LCP Criteria.

- A copy of the LCP Inspection Summary Report will be forwarded to NETTCP for their records and entry into the NETTCP Laboratory Certification Database. The original copy of all completed inspection documentation (LCP Inspection Summary Report and the Inspection Checklists) will be retained by the entity performing the inspection.

- Each Transportation Agency Category 1-P and 1-T Laboratory is responsible for ensuring continuous compliance with all NETTCP LCP requirements. The Transportation Agency or NETTCP may at anytime perform a follow-up inspection of any laboratory to determine conformance with the LCP. Laboratories determined not to be in compliance with the NETTCP LCP shall have their laboratory certification suspended. If identified deficiencies are not corrected within 30 days, the laboratory certification will be revoked.

- IA personnel from the Transportation Agency Central Laboratory will provide random checks of personnel and equipment in each Category 1-P, 1-T, 2-P, and 2-T certified laboratory at a minimum frequency as determined by the Transportation Agency's approved Independent Assurance Program.

B. Contractor/Consultant Laboratory Responsibilities

Each Contractor or Consultant Laboratory (Category 2-P, 2-T, or 3) requiring certification through the NETTCP Laboratory Certification Program is responsible for the following:

- Each Contractor/Consultant Laboratory is required to contact either the appropriate Transportation Agency or NETTCP to request a laboratory inspection a minimum of 30 calendar days prior to the date of the desired inspection. In the event the Transportation Agency is not able to provide laboratory inspection, NETTCP can provide personnel to conduct the inspection of the laboratory (See Section IIC below).

- Each Contractor/Consultant Laboratory is required to pay the NETTCP laboratory inspection fee as indicated in the NETTCP Policies and Procedures Manual.

- Each Contractor/Consultant Laboratory is responsible for ensuring continuous compliance with all NETTCP LCP requirements.

C. NETTCP Responsibilities

NETTCP will be responsible for administering the NETTCP Laboratory Certification Program as follows:

- When a Transportation Agency is not able to provide inspection of a laboratory seeking NETTCP Laboratory Certification, NETTCP will provide personnel to conduct the inspection of the laboratory.

- NETTCP will maintain an NETTCP Laboratory Certification Database and will be responsible for entering basic information (Laboratory Name, Location, Lab Category, Laboratory Manager, Date Inspected, Materials Qualified to Test, AASHTO/ASTM Test Methods Qualified to Perform) obtained from the LCP Inspection Summary Reports for each laboratory that is inspected.

- Upon receipt of the completed LCP "Inspection Summary Report", completed Inspection Checklists, and the specified fee from the laboratory, NETTCP will issue a "Certificate of Laboratory Certification" to each laboratory which has been inspected and which meets the NETTCP LCP Criteria (*See Note 3 below*). The certification Certificate will be valid for a maximum period of one year and will indicate:

  (1) The name of the Laboratory
  (2) The location of the Laboratory
  (3) The Laboratory Category (1-P, 1-T, 2-P, 2-T, or 3)
  (4) The materials (Soils, Agg., HMA, PCC) the laboratory is qualified to test
  (5) The specific AASHTO/ASTM test methods qualified to perform
  (6) The name of the entity (Transportation Agency or NETTCP) that performed the certification inspection
  (7) The date of Inspection

- NETTCP will respond to questions or inquiries related to the status of certification for individual registered laboratories and will provide the name and phone number for the Laboratory Manager/Supervisor.

Note 3: *A laboratory possessing a "NETTCP Certificate of Laboratory Certification" has demonstrated that it meets the criteria contained in this LCP only, and not any more stringent criteria a Transportation Agency may elect to use for a given type of laboratory.*

III. NETTCP Laboratory Certification Program Criteria:

A. General Requirements (All Laboratories)

The following criteria apply to all (Category 1-P, 1-T, 2-P, 2-T, & 3) laboratories requiring certification under this Program:

- The Laboratory Supervisor will have a minimum of 3 years of relevant experience in testing of construction materials for which the laboratory is seeking certification.
- All Laboratory Technicians performing testing on Agency projects, unless working in an interim status under the direct supervision of a NETTCP certified technician, will possess a valid NETTCP certification, or be qualified through another FAA approved certification program, for the sampling and testing they perform.
- The laboratory facility must adequately house and allow proper operation of all required testing equipment in accordance with applicable test procedures.
- All laboratory test equipment shall be calibrated/verified at least once every 12 months per AAP approved Transportation Agency calibration procedures. Complete documentation of calibration for all laboratory test equipment shall be kept by the laboratory and made available for review.
- All laboratory test equipment must be determined to be in proper working order and kept in working order at all times the laboratory is performing testing.
- The laboratory must maintain a record of all Transportation Agency IA reviews received which evaluated the laboratory testing personnel and equipment, including appropriate follow-up actions taken.
- The laboratory must maintain current Reference Manuals, which contain AASHTO/NETTCP standard testing procedures and Transportation Agency/NETTCP policies for the handling, identification, conditioning, storage, retention, and disposal of test samples for all tests performed.
- All laboratory test results will be recorded using the NETTCP standard Test Report Forms (TRFs) or equivalent forms acceptable to the responsible Transportation Agency(s).

B. Category 1-P Laboratories

In addition to the “General Requirements” listed in Section IIIA above, each permanent Transportation Agency (Satellite/District/Regional/Consultant) laboratory shall meet the following criteria:

- Each Transportation Agency shall establish an internal program to assure the quality of the results being obtained by each Category 1-P Laboratory. This internal program must include the following activities as a minimum:

  (1) All Laboratory Technicians and equipment in each Category 1-P Laboratory shall be evaluated at a minimum frequency as determined by the Transportation Agency’s approved Independent Assurance Program.

  (2) Each Category 1-P Laboratory shall participate in a proficiency testing program administered by the Transportation Agency. The Agency Central Laboratory shall provide proficiency samples at a frequency not to exceed 12 months for all Acceptance tests being performed by each laboratory.

  Alternatively, each Category 1-P Laboratory may participate in the AMRL/CCRL proficiency sampling program for all Acceptance tests being performed by the laboratory.

  All proficiency sample results shall be documented and causes for unacceptable discrepancies identified. Corrective actions taken by each Category 1-P Laboratory shall be documented.

C. Category 1-T Laboratories

In addition to the “General Requirements” listed in Section IIIA above, each temporary Transportation Agency (Project/Consultant) laboratory shall meet the following criteria:

- Each Transportation Agency shall establish an internal program to assure the quality of the results being obtained by each Category 1-T Laboratory. This internal program must include the following activities as a minimum:

  (1) All Laboratory Technicians and equipment in each Category 1-T Laboratory shall be evaluated at a minimum frequency as determined by the Transportation Agency’s approved Independent Assurance Program.

D. Category 2-P Laboratories

In addition to the "General Requirements" listed in Section IIIA above, each permanent Contractor (Plant/Consultant) laboratory shall meet the following criteria:

- Each Transportation Agency shall establish an internal program to assure the quality of the results being obtained by each Category 2-P Laboratory. This internal program must include the following activities as a minimum:

  (1) All Laboratory Technicians and equipment in each Category 2-P Laboratory shall be evaluated at a minimum frequency as determined by the Transportation Agency's approved Independent Assurance Program.

  (2) Each Category 2-P Laboratory must undergo proficiency testing to verify continuing acceptable performance. This can be accomplished in one of the following ways:

    (a) The Transportation Agency's Independent Assurance Program can be used, if it incorporates procedures to evaluate the results obtained at a frequency approved by the FHWA Division Office as part of the overall Independent Assurance Program.

    (b) The laboratory may participate in all AMRL/CCRL proficiency testing programs relevant to the testing being performed by the laboratory. The laboratory shall investigate to determine the cause(s) for any proficiency rating of "2" or less and shall implement indicated corrective action. Copies of all AMRL/CCRL reports, along with laboratory responses, shall be provided to the Transportation Agency for review and approval.

    (c) The laboratory may participate in a proficiency testing program established and operated by an independent AASHTO-accredited laboratory. The program shall be similar in nature to the AMRL/CCRL proficiency testing program and be approved by both the Transportation Agency and the FHWA Division Office.

E. Category 2-T Laboratories

In addition to the "General Requirements" listed in Section IIIA above, each temporary Contractor (Project) laboratory shall meet the following criteria:

- Each Transportation Agency shall establish an internal program to assure the quality of the results being obtained by each Category 2-T Laboratory. This internal program must include the following activities as a minimum:

  (1) All Laboratory Technicians and equipment in each Category 2-T Laboratory shall be evaluated at a minimum frequency as determined by the Transportation Agency's approved Independent Assurance Program.

F. Category 3 Laboratories (Optional)

Any Contractor laboratory (Permanent or Temporary) performing only Quality Control testing shall be deemed qualified if it has met the "General Requirements" listed in section IIIA above.

IV. Laboratory Decertification From NETTCP LCP:

All laboratories which become certified in accordance with the NETTCP LCP must ensure that the laboratory facilities, personnel, and sampling and testing activities are in continuous conformance with the applicable requirements of Section III above. As determined by the applicable Transportation Agency or NETTCP, a certified laboratory found to not be in compliance with the above requirements will have its NETTCP certification status suspended. If the identified deficiencies are not corrected within 30 days, the laboratory certification will be revoked.. The Transportation Agency shall notify the affected laboratory and forward a letter of explanation to NETTCP, detailing the reason(s) for revocation of the NETTCP certification. NETTCP shall amend its records within 5 working days after receipt of such letter. Appeals of such revocation shall be handled by the Transportation Agency and NETTCP.

NETTCP Laboratory Certification Program
Inspection Summary Report

LABORATORY INFORMATION

Laboratory Name:	**Lab Certification No.:**

Laboratory Location

Street Address

City/Town	State	Zip
Phone #	Fax #	

Laboratory Manager/Supervisor:	**Certification Number??**

Laboratory Category:	1-P ☐	1-T ☐	2-P ☐	2-T ☐	3 ☐

Materials Qualified to Test:	Soils ☐	Agg. ☐	HMA ☐	PCC ☐

AASHTO/ASTM Test Methods Qualified to Perform: (Please Attach Inspection Checklist)

GENERAL REQUIREMENTS (All Laboratory Categories)

♦ The Laboratory Manager/Supervisor has a minimum of 3 years relevant experience in testing of construction materials.	YES ☐	NO ☐
♦ All Laboratory Technicians performing testing on Transportation Agency projects, unless working in an interim status under the direct supervision of a NETTCP certified technician, possess a valid NETTCP certification, or are qualified through another FHWA-approved certification program, for the sampling and testing they perform.	YES ☐	NO ☐
♦ The laboratory facility adequately houses and allows proper operation of all required testing equipment in accordance with applicable test procedures.	YES ☐	NO ☐
♦ All laboratory test equipment has been calibrated/verified at least once in the past 12 months per AAP approved Transportation Agency calibration procedures. Complete documentation of calibration for all laboratory test equipment is kept by the laboratory and available for review.	YES ☐	NO ☐
♦ All laboratory test equipment was determined to be in proper working order and is kept in working order at all times the laboratory is performing testing.	YES ☐	NO ☐
♦ The laboratory maintains a record of all Transportation Agency IA reviews received which evaluated the laboratory testing personnel and equipment, including appropriate follow-up actions taken.	YES ☐	NO ☐

GENERAL REQUIREMENTS (- Continued -)		
♦ The laboratory maintains current Reference Manuals, which contain AASHTO/NETTCP standard testing procedures and Transportation Agency/NETTCP policies for the handling, identification, conditioning, storage, retention, and disposal of test samples.	YES ☐	NO ☐
♦ All laboratory test results are recorded using the NETTCP standard Test Report Forms (TRFs) or equivalent forms acceptable to the responsible Transportation Agency(s).	YES ☐	NO ☐
CATEGORY 1-P, 1-T, 2-P, & 2-T LABORATORY REQUIREMENTS		
♦ All Laboratory Technicians and equipment in the laboratory have been evaluated at a minimum frequency as determined by the Transportation Agency's approved Independent Assurance Program.	YES ☐	NO ☐
CATEGORY 1-P LABORATORY REQUIREMENTS		
♦ The laboratory has participated in a proficiency testing program administered by the Transportation Agency Central Laboratory, <u>or</u> has participated in the AMRL/CCRL proficiency sample testing program, at a frequency not to exceed 12 months for all Acceptance tests being performed by the laboratory. All proficiency sample results are documented and causes for unacceptable discrepancies are identified. Corrective actions taken by the laboratory are documented.	YES ☐	NO ☐
CATEGORY 2-P LABORATORY REQUIREMENTS		
♦ The laboratory participates in <u>one</u> of the following proficiency testing approaches: (a) Through FHWA approved procedures in the Transportation Agency's Independent Assurance Program. (b) All AMRL/CCRL proficiency testing programs relevant to the testing performed by the laboratory. The laboratory has investigated to determine the cause(s) for any proficiency rating of "2" or less and has implemented indicated corrective action. Copies of all AMRL/CCRL reports, along with laboratory responses, are provided to the Transportation Agency. (c) Through a proficiency testing program established and operated by an independent AASHTO-accredited laboratory. The program is similar to the AMRL/CCRL program and is approved by both the Transportation Agency and FHWA.	YES ☐	NO ☐
CERTIFICATION DETERMINATION		
Inspecting Agency:		
Inspected By:	**Inspection Date:**	
♦ This Laboratory meets all relevant NETTCP LCP requirements	YES ☐	NO ☐

- END OF APPENDIX D -

APPENDIX E

Typical Quality Assurance Specification Requirements

Appendix E

Typical Quality Assurance Specification Requirements

Typical requirements for various aspects of Quality Assurance specifications are described throughout Chapters 5 and 6. Specific examples of QA specification requirements are contained within individual Agency specifications. The National Highway Specifications website (http://fhwapap04.fhwa.dot.gov/nhswp/index.jsp), established and maintained by FHWA, provides a searchable database of specifications issued by:

- AASHTO
- FHWA
- Individual State Transportation Agencies

- END OF APPENDIX E -

APPENDIX F

Typical Model Quality Control Plan

Appendix F

Typical "Model Quality Control Plan"

Appendix Overview

The ***NETTCP Model Quality Control Plan*** provided in this Appendix is intended to serve as a generic tool to assist Contractors in preparing complete and useful QC Plans. The Model QC Plan follows a recommended standard format that includes ten separate Sections plus Appendices. Each Section addresses one of the major QC Plan items presented in Chapter 5 (Section 5.4). These Sections are:

- ☐ **Terms and Definitions (optional)**
- ☐ **1.0 Scope and Applicable Specifications**
- ☐ **2.0 Quality Control Organization**
- ☐ **3.0 Quality Control Laboratories**
- ☐ **4.0 Materials Control**
- ☐ **5.0 Quality Control Sampling and Testing**
- ☐ **6.0 Production Facilities**
- ☐ **7.0 Field Operations**
- ☐ **Appendices**

It is recommended that Transportation Agencies adopt the format (Section and Subsection headings) provided in the NETTCP Model QC Plan as a standard for Contractors to follow.

The Model QC Plan presented here is an example of a completed Earthwork QC Plan for a fictitious major transportation construction project. QC Plans for other materials (e.g., HMA, PCC, etc.) can be developed following the same standard format (Section and Subsection headings) provided in the Model QC Plan.

The level of detailed information in any QC Plan will obviously change depending upon the size and complexity of the individual construction project. As a minimum, all text highlighted in yellow (shaded grey) throughout the Model QC Plan will require replacement or deletion to address the specific Quality Control information related to a given project.

Note

Every QC plan should include examples of forms and reports that the contractor will use to document and report the results of QC monitoring to the transportation agency. These sample documents can appear as appendices to the QC plan. The samples included will differ from plan to plan depending on the type of project. For example, in the fictitious model presented here for Earthworks, several sample documents are named as appendices to the plan:

- Project Drawings List
- Material Source Characterization Sampling and Testing Forms
- Standard Test Report Forms
- Weekly Schedule of Production Operations
- Standard Inspection Report Forms for Production Quality Control
- Weekly Schedule of Materials Placement Operations
- Control Charts Used for Materials Placement
- Standard Inspection Report Forms for Field Quality Control

Each QC plan should include samples of forms and reports that are appropriate to the project type.

State Route 99 Construction Project
Anytown, USA
Transportation Agency Contract #54321

ABC Contractors, Inc.

NETTCP
MODEL QC PLAN

Construction Quality Control Plan

Section 1 - Earthwork

December 2, 2003

Submitted By:	____________________ **ABC Contractors, Inc.**	________ **Date**
Approved By:	____________________ **Transportation Agency**	________ **Date**

Section 1 - Earthwork

This Quality Control Plan (QC Plan) identifies the specific resources and procedures which will be utilized by ABC Contractors to control the quality of all Earthwork materials and ensure that all associated Work is completed in accordance with Project Specifications.

TERMS & DEFINITIONS

The following terms and definitions are applicable to this QC Plan:

- **Contractor Information Testing (CIT)** – Testing that is performed at the discretion of the QC Inspector (non-random) for information to guide Production or Field Placement of material.

- **Control Strip** – An area of Earthwork placed at the beginning of each new Earthwork operation which is used to establish the rolling pattern and compactive effort required to achieve the in-place Target Density at Optimum Moisture Content.

- **Control Strip Section** – One of 3 approximately equal parts of a Control Strip which are sequentially placed and tested for In-Place Density and Moisture Content.

- **Crushed Stone** – Processed Earthwork material used for “Embankment Under Bridge Foundations” which meets the materials specification requirements contained in Subsection M2.01.0.

- **Earth Excavate** – Earthwork material, obtained from On-Site excavation (cut) activity, which is used for “Roadway Embankment Material”, and which meets the materials specification requirements contained in Section M1.01.0 (Ordinary Borrow) and contains up to 50% boulders or rock fragments with a maximum size of 600 millimeters largest dimension.

- **Field Quality Control (FQC)** – All sampling, testing, and inspection activity performed to control the quality of Field Placement operations.

- **Gravel Borrow** – Earthwork material, obtained either from On-Site excavation (cut) activity or from Off-Site Borrow Producers, which is used for “Roadway Embankment Material”, “Embankment Under Bridge Foundations”, or “Backfill Material for Structures and Pipes”, and which meets the materials specification requirements contained in Subsection M1.03.0.

- **Ordinary Borrow** – Earthwork material, obtained either from On-Site excavation (cut) activity or from Off-Site Borrow Producers, which is used for “Roadway Embankment Material”, and which meets the materials specification requirements contained in Subsection M1.01.0.

- **Producer** – A Subcontractor who supplies either “project produced” materials or “commercially manufactured” materials for incorporation into the Work.

- **Production Quality Control (PQC)** – All sampling, testing, and inspection activity performed by ABC Contractors or their Producers to control the quality of material produced at the Production facility.

- **Rock Excavate** – Earthwork material, obtained from On-Site excavation (cut) activity, which is used for “Backfill Material for Muck Excavation” or “Roadway Embankment Material”, and which is comprised of boulders or rock fragments with a maximum size of 1 meter largest dimension.

- **Source Characterization (SC)** – Sampling and testing performed to determine the specific “Earthwork Material Type” which an individual material source location (On-Site or Off-Site) contains.

- **Source Quadrant** – An area of defined boundaries at an individual Earthwork material source location (On-Site or Off-Site) which has been evaluated by Source Characterization sampling and testing.

- **Special Borrow** – Earthwork material, obtained either from On-Site excavation (cut) activity or from Off-Site Borrow Producers, which is used for “Backfill Material for Muck Excavation” or “Roadway Embankment Material”, and which meets the materials specification requirements contained in Subsection M1.02.0.

1.0 SCOPE AND APPLICABLE SPECIFICATIONS

The relevant specifications for all Earthwork activities are as indicated below.

1.1 – Standard Specifications

This QC Plan applies to all Work covered by the following sections of Transportation Agency Standard Specifications for Highways and Bridges, 1995 Metric Edition:

- Division II - Section 150: Embankment
- Division II - Section 170: Grading
- Division III - Section M1: Soils and Borrow Materials, limited to:
    - Subsection M1.01.0 Ordinary Borrow
    - Subsection M1.02.0 Special Borrow
    - Subsection M1.03.0 Gravel Borrow (Type a)
    - Subsection M1.04.0 Sand Borrow (Type b)
    - Subsection M1.08.0 Impervious Soil Borrow
- Division III - Section M2: Aggregates and Related Materials, limited to:
    - Subsection M2.01.0 Crushed Stone
    - Subsection M2.01.1 Grading Requirements (37.5 mm)

1.2 – Supplemental Specifications

Transportation Agency Supplemental Specifications, December 23, 1998 Metric Edition, applicable to Work addressed by this QC Plan include:

- ❖ Division II - Section 150: Embankment
- ❖ Division II - Section 170: Grading

1.3 – Project Special Provisions

Special Provisions applicable to Work addressed by this QC Plan include:

- ❖ Division II - Section 150: Embankment (June 26, 2001)
    - o Subsection 150.20 General
    - o Subsection 150.66 Gravel Borrow for Bridge Foundations
    - o Subsection 150.69 Crushed Stone for Stabilized Construction Entrances
    - o Subsection 150.70 Gravel Borrow for Sidewalk
    - o Subsection 150.72 Sedimentation Control

1.4 – Project Drawings

A current listing of drawings applicable to all Work addressed by this QC Plan will be maintained by ABC Contractors. The "Project Drawings List" will be updated and submitted monthly to Transportation Agency in electronic format. An example copy of the "Project Drawing List: Section 1 – Earthwork" is contained in Appendix __ (See Note, Page F-3).

1.5 – Standard Drawings

All Standard Drawings related to Earthwork contained in the Transportation Agency Construction and Traffic Standard Details (1996) are applicable to Work addressed by this QC Plan.

2.0 QUALITY CONTROL ORGANIZATION

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

2.1 – QC Plan Manager

The QC Plan Manager is Mr. “Plan Manager”, P.E. He is employed by ABC Contractors, Inc. (ABC Contractors). Mr. “Plan Manager” is located at the ABC Contractors State Route 99 Project Office in Anytown, USA and can be contacted as follows:

Office Phone: (508) 123-4567
Cell Phone: (508) 123-4568
Pager: (508) 123-4500

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

- Development and submission of this QC Plan for 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
- Ensure that Producers have required certifications and qualified personnel and laboratories
- Complete adherence to all QC requirements and activities contained in this QC Plan
- Initiating Work suspension and determining appropriate corrective action when testing or inspection identifies nonconforming materials or construction as outlined under Section 6.5 and Section 7.6 below
- Review and evaluation of all QC documentation for content and completeness
- Maintaining the “QC Record System – Earthwork” in accordance with Section 5.5 below
- Preparing and submitting a “Weekly QC Summary Report” to Transportation Agency within 7 Calendar Days following the end of 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 Earthwork 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".

Project Segment	QC Position	Personnel - Company	Qualifications
1, 2, 3	Soils Inspector	Various – Producers (See Weekly QC Summary Report)	NETTCP Soils & Agg. Inspector (See Weekly Report)

Off-Site Production QC activities by ABC Contractors will be scheduled as necessary and will generally involve the collection of samples for Source Characterization testing from potential Earthwork material Producers.

Where Earthwork materials Producers possess their own qualified QC personnel and laboratories, the results of the Producer's QC inspection and testing may be used by ABC Contractors. In such instances, the Producer will perform Source Characterization sampling and testing in accordance with the required test methods and frequencies outlined in Section 4.0 below.

Off-Site Production Facility QC personnel have responsibility and authority for the following items:

- Obtaining random Source Characterization samples of Earthwork materials at each Production Facility
- Inspecting Earthwork Production operations at each Production Facility
- Preparing and signing standard QC Inspection report forms for each Production location
- Identifying Production Facility practices or materials which do not conform with the requirements of the relevant specifications and this QC Plan, and discussing appropriate corrective action with the Production Facility Superintendent and the QC Manager
- Suspending the transport of Earthwork materials to On-Site placement locations when materials are not in conformance with the relevant specification requirements or when corrective actions have been determined necessary and are not implemented

2.3 – Qualified QC Laboratory Personnel

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

Project Segment	QC Position	Personnel – Company	Qualifications
1, 2, 3	Laboratory Supervisor (ABC Contractors Anytown, USA)	Bob Supervisor – XYZ	NETTCP Soils & Agg. Technician # SAT 100
1, 2, 3	Laboratory Technician	Cathy Technician – XYZ	NETTCP Soils & Agg. Technician # SAT 190
1, 2, 3	Laboratory Technician	Mike Technician – XYZ	NETTCP Soils & Agg. Inspector # SAI 450

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

- Sampling of Earthwork materials
- Laboratory testing of Earthwork materials
- Preparing and signing standard Test Report Forms (TRFs) for each test completed
- Properly storing all Earthwork material samples
- Identifying Earthwork materials test results which do not conform with the requirements of the relevant specifications and this QC Plan, and discussing with the QC Manager

2.4 – Qualified On-Site Field QC Personnel

Personnel assigned to perform On-Site Field QC sampling, testing, and inspection of Earthwork 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".

Project Segment	QC Position	Personnel - Company	Qualifications
1	Lead QC Inspector	Kevin Boulder – XYZ	NETTCP Soils & Agg. Inspector # SAI 491
2	Lead QC Inspector	George Troxler – XYZ	***Not Currently NETTCP Certified***
3	Lead QC Inspector	Mike Gravel – XYZ	***Not Currently NETTCP Certified***
1, 2, 3	Soils Inspector	Various – XYZ (See Weekly QC Summary Report)	NETTCP Soils & Agg. Inspector (See Weekly QC Summary Report)

On-Site Field QC personnel have responsibility and authority for the following items:

- Obtaining random Field samples of Earthwork materials for laboratory testing
- Performing In-Place sampling and testing of Earthwork
- Preparing and signing standard Test Report Forms (TRFs) for each test completed
- Inspecting On-Site Earthwork production and placement operations
- Preparing and signing standard QC Inspection report forms for each placement location
- Identifying On-Site Field placement practices or materials which do not conform with the requirements of the relevant specifications and this QC Plan, and discussing appropriate corrective action with the Segment Field Superintendent and the QC Manager
- Suspending the placement of Earthwork materials when materials are not in conformance with the relevant specification requirements or when corrective actions have been determined necessary and are not implemented

3.0 QUALITY CONTROL LABORATORIES

The Quality Control Laboratories to be used for all Earthwork 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 Earthwork materials is identified in the table below.

Project Segment	Laboratory	Location	Qualifications
1, 2, 3	ABC Contractors State Route 99 Project Laboratory	Anytown, USA	NETTCP Laboratory Qualification Program – Category 2-T: Soils, Aggregates (***MM/DD/YY***)

The ABC Contractors State Route 99 Project Laboratory is responsible for performing testing of all On-Site Earthwork materials as well as testing of any Off-Site Borrow material. The following tests will be performed on Earthwork materials by this laboratory:

❖ Soil Classification	AASHTO M145
❖ Gradation	AASHTO T11 and T27
❖ Liquid Limit	AASHTO T89
❖ Plastic Limit/Plasticity Index	AASHTO T90
❖ Optimum Moisture Content	AASHTO T99 and AASHTO T180
❖ Maximum Dry Density	AASHTO T99 and AASHTO T180
❖ Coarse Particles Correction	AASHTO T224
❖ Grain-Size Analysis	AASHTO T311

3.2 – Qualified Subcontractor or Consultant Laboratories

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

Project Segment	Laboratory	Location	Qualifications
1, 2, 3	XYZ Company Laboratory	Soil City, USA	AASHTO Accreditation Program: Soils (08/15/00)

The XYZ Company Laboratory in Soil City, USA will serve as a backup to assist the Primary QC Laboratory in performing testing of all On-Site Earthwork materials as well as testing of any Off-Site Borrow for Embankment. The following tests will be performed on Earthwork materials by this laboratory:

❖ Soil Classification	AASHTO M145
❖ Gradation	AASHTO T11 and T27
❖ Liquid Limit	AASHTO T89
❖ Plastic Limit/Plasticity Index	AASHTO T90
❖ Maximum Wear (LA Abrasion)	AASHTO T96
❖ Optimum Moisture Content	AASHTO T99 and AASHTO T180
❖ Maximum Dry Density	AASHTO T99 and AASHTO T180
❖ Coarse Particles Correction	AASHTO T224
❖ Grain-Size Analysis	AASHTO T311

4.0 MATERIALS CONTROL

The types, sources, properties, and procedures for storing of materials to be used for each Earthwork category are as indicated below.

4.1 – Material Types and Source(s) of Supply

Earthwork material will be classified according to the following Earthwork Item categories:

- Backfill Material for Muck Excavation
- Roadway Embankment Material
- Embankment Material under Bridge Foundations
- Backfill Material for Structures
- Backfill Material for Pipes

4.1.1 – Backfill Material for Muck Excavation

The types and potential sources of material currently identified for use as Backfill Material for Muck Excavation are listed in the table below.

Backfill Material for Muck Excavation	
Material Type	**Material Source**
Rock Excavate	• On-Site, Segment 1, Rte 99 Median • On-Site, Segment 3, Rte 99 Median
Special Borrow	• On-Site, Segment 1 • On-Site, Segment 2 • Borrow Producer **(*TBD*)**

ABC Contractors will submit updated information on the types and sources of Backfill Material for Muck Excavation as part of the “Weekly Schedule of Earthwork Materials Production Operations” as outlined under Section 6.1 below.

4.1.2 – Roadway Embankment Material

The types and sources of material currently identified for use as Roadway Embankment are listed in the table below. At this time, sufficient quantities of Earth Excavate, Rock Excavate, Ordinary Borrow, and Gravel Borrow appear to be available On-Site for Roadway Embankment construction. If Off-Site sources of these materials are determined necessary by ABC Contractors, the table will be updated to reflect these sources.

Roadway Embankment Material	
Material Type	**Material Source**
Rock Excavate	• On-Site, Segment 1, Rte 99 Median • On-Site, Segment 3, Rte 99 Median
Earth Excavate	• On-Site, Segment 1, Rte 99 Median • On-Site, Segment 3, Rte 99 Median
Ordinary Borrow	• On-Site, Segment 1 • On-Site, Segment 2 • On-Site, Segment 3 • Borrow Producer ***(TBD)***
Gravel Borrow	• On-Site, Segment 1 • On-Site, Segment 3 • Borrow Producer **(*TBD*)**
Special Borrow	• On-Site, Segment 1 • On-Site, Segment 2 • Borrow Producer **(*TBD*)**

ABC Contractors will submit updated information on the types and sources of Roadway Embankment Material as part of the “Weekly Schedule of Earthwork Materials Production Operations” as outlined under Section 6.1 below.

4.1.3 – Embankment Material Under Bridge Foundations

The types and potential sources of material currently identified for use as Embankment Material under Bridge Foundations are listed in the table below.

Embankment Material Under Bridge Foundations	
Material Type	**Material Source**
Gravel Borrow	• ***Borrow Producer (TBD)***
Crushed Stone	• ***Borrow Producer (TBD)***

ABC Contractors will submit updated information on the types and sources of Embankment Material under Bridge Foundations as part of the "Weekly Schedule of Earthwork Materials Production Operations" as outlined under Section 6.1 below.

4.1.4 – Backfill Material for Structures

The types and potential sources of material currently identified for use as Backfill Material for Structures are listed in the table below.

Backfill Material for Structures	
Material Type	**Material Source**
Gravel Borrow	• **Borrow Producer (TBD)**

ABC Contractors will submit updated information on the types and sources of Backfill Material for Structures as part of the "Weekly Schedule of Earthwork Materials Production Operations" as outlined under Section 6.1 below.

4.1.5 – Backfill Material for Pipes

The types and potential sources of material currently identified for use as Backfill Material for Pipes are listed in the table below.

Backfill Material for Pipes	
Material Type	**Material Source**
Ordinary Borrow	• On-Site, Segment 1 • On-Site, Segment 2 • On-Site, Segment 3 • Borrow Producer **(*TBD*)**
Gravel Borrow	• ***Borrow Producer (TBD)***

ABC Contractors will submit updated information on the types and sources of Backfill Material for Pipes as part of the “Weekly Schedule of Earthwork Materials Production Operations” as outlined under Section 6.1 below.

4.2 – Material Properties

Earthwork material Source Characterization and Mix Designs will be performed as described below.

4.2.1 – Material Source Characterization Sampling & Testing

Earthwork materials will be fully characterized by ABC Contractors prior to their use in the intended location. Grids will be established and maintained at each Earthwork source location identifying “Quadrants”. Each Quadrant will be numbered for Source Characterization identification (e.g., SC-1, SC-2, SC-99, etc.) ABC Contractors will submit the results of Source Characterization testing for each Source Quadrant of Earthwork material to Transportation Agency a minimum of two (2) calendar days prior to placement of any material from the Source Quadrant. The following table identifies the specific Source Characterization testing that will be performed on all Earthwork materials.

Material Source Characterization Sampling & Testing			
Material Type	**Characteristic tested**	**Test Method**	**Test Frequency**
Rock Excavate	Maximum Size (< 1m)	Visual/Tape	Minimum 4/Day/Quadrant
Earth Excavate (M1.01.0 Modified) (Contains Boulders < 600mm)	Soil Classification	AASHTO M 145	Minimum 4/Quadrant
	Liquid Limit	AASHTO T89	Minimum 4/Quadrant
	Plastic Limit/ PI	AASHTO T90	Minimum 4/Quadrant
	Maximum Dry Density	AASHTO T 180 (Method D)	Minimum 4/Quadrant
	Optimum Moisture Content	AASHTO T 180 (Method D)	Minimum 4/Quadrant
	Coarse Particles Correction	AASHTO T 224	Minimum 4/Quadrant
	Grain-Size Analysis	AASHTO T 311	Minimum 4/Quadrant
Ordinary Borrow (M1.01.0)	Soil Classification	AASHTO M 145	Minimum 4/Quadrant
	Liquid Limit	AASHTO T89	Minimum 4/Quadrant
	Plastic Limit/ PI	AASHTO T90	Minimum 4/Quadrant
	Maximum Dry Density	AASHTO T 99 (Method C)	Minimum 4/Quadrant
	Optimum Moisture Content	AASHTO T 99 (Method C)	Minimum 4/Quadrant
	Coarse Particles Correction	AASHTO T 224	Minimum 4/Quadrant
	Grain-Size Analysis	AASHTO T 311	Minimum 4/Quadrant
Gravel Borrow (M1.03.0)	Soil Classification	AASHTO M 145	Minimum 4/Quadrant
	Gradation	AASHTO T 11, T27	Minimum 4/Quadrant
	Maximum Dry Density	AASHTO T 180 (Method D)	Minimum 4/Quadrant
	Optimum Moisture Content	AASHTO T 180 (Method D)	Minimum 4/Quadrant

Material Source Characterization Sampling & Testing (-Continued-)			
Material Type	**Characteristic tested**	**Test Method**	**Test Frequency**
Special Borrow (M1.02.0)	Soil Classification	AASHTO M 145	Minimum 4/Quadrant
	Gradation	AASHTO T 11, T27	Minimum 4/Quadrant
	Plastic Limit/ PI	AASHTO T90	Minimum 4/Quadrant
	Maximum Dry Density	AASHTO T 180 (Method D)	Minimum 4/Quadrant
	Optimum Moisture Content	AASHTO T 180 (Method D)	Minimum 4/Quadrant
	Maximum Percentage of Wear (LA Abrasion)	AASHTO T 96	Minimum 4/Quadrant
Crushed Stone (M2.01.0)	Soil Classification	AASHTO M 145	Minimum 1/10,000 m^3
	Gradation	AASHTO T 11, T27	Minimum 1/10,000 m^3
	Maximum Percentage of Wear (LA Abrasion)	AASHTO T 96	Minimum 1/10,000 m^3
	Flat & Elongated Particles	ASTM D 4791	Minimum 1/10,000 m^3

All Earthwork Source Characterization samples will be obtained randomly in accordance with ASTM D3665. The random sample locations within each Source Quadrant will be determined by Station, Offset, and elevation within the Quadrant. All random sample locations will be documented on NETTCP Standard Test Report Form D3665 or D3665RNG. A copy of these Random Sampling forms is located in Appendix __ (See Note, Page F-3).

All Earthwork Source samples will be obtained following AASHTO T2 and split in accordance with AASHTO T248.

All Source Characterization sampling and testing results will be documented on the following standard Test Report Forms (TRFs):

Source Characterization Standard Test Report Forms	
Form No.	Form Title
M145-T89-T90	Classification of Soils (Includes Liquid Limit & Plastic Limit)
NETTCP T27	Sieve Analysis Test Report
NETTCP T96	Resistance to Degradation of Aggregate by Abrasion Test Report
T99	Moisture-Density Relations of Soils (Standard)
T180	Moisture Density Relations of Soils (Modified)
T311	Grain-Size Analysis of Granular Soil Materials
Rock Size	Evaluation of Maximum Rock Size in Earthwork Materials

A copy of the standard TRF's used for Source Characterization sampling and testing is located in Appendix __ (See Note, Page F-3).

4.2.2 – Mix Designs

Earthwork Materials "Mix Designs" are generally not required. Source Characterization testing will determine whether specific Earthwork Materials sources meet the specification requirements for a particular material type required (i.e., Ordinary Borrow, Gravel Borrow, Special Borrow, etc.).

4.3 – Processing of Existing Materials

Where On-Site excavate proposed to be used for Earthwork is found to not meet specification requirements, the following procedures will be used to process or blend the material to meet the requirements of a specific Earthwork Material Type:

- A blended material "Mix Design" will be developed by the Project Laboratory.
- A stockpile of the excavate, not to exceed one day's production, will be blended with other material per the "Mix Design".
- At the completion of blending of the stockpile, samples will be obtained and Source Characterization testing will be performed to confirm that the blended material meets the specification requirements.

4.4 – Material Storage & Stockpiling

All Earthwork materials will be properly stored and maintained to prevent contamination or commingling of different materials. Storage and stockpiling procedures will be as follows:

- The limits of each storage or stockpile location will be clearly marked by grade stakes legibly marked indicating the corresponding Source Characterization sample number (i.e., SC-1, SC-2, etc.) contained in the Project "Soils Source Characterization Log".
- All active/working stockpiles of Earthwork materials will be characterized in accordance with Section 4.2.1 above a minimum of once per week.

5.0 QUALITY CONTROL SAMPLING AND TESTING

The requirements and procedures to be used for QC sampling and testing of Earthwork are as indicated below.

5.1 – Lot and Sublot Sizes

Each Lot of Earthwork 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 Earthwork Item is identified in the following table.

Earthwork Lot and Sublot Sizes			
Earthwork Item	**Material Type(s)**	**Lot Size**	**Sublot Size**
Backfill Material for Muck Excavation (Section 150.65)	• Rock Excavate • Special Borrow	Total Quantity (m^3) of Backfill material type, per material Source, per Project Segment	(See Table 5.4.1)
Roadway Embankment Material (Section 150.62 & Section 150.63)	• Rock Excavate • Earth Excavate • Ordinary Borrow • Gravel Borrow • Special Borrow	Total Quantity (m^3) of Embankment Material Type, per Material Source, per Project Segment	(See Table 5.4.2)
Embankment Material Under Bridge Foundations (Section 150.66 & Section 150.67)	• Gravel Borrow • Crushed Stone	Total Quantity (m^3) of Embankment material type, per material Source, per Project Segment	(See Table 5.4.3)
Backfill Material for Structures (Section 150.64)	• Gravel Borrow	Total Quantity (m^3) of Backfill material type, per material Source, per Project Segment	(See Table 5.4.4)
Backfill Material for Pipes (Section 150.64)	• Gravel Borrow • Ordinary Borrow	Total Quantity (m^3) of Backfill material type, per material Source, per Project Segment	(See Table 5.4.5)

5.2 – Random Sampling Plan

ABC Contractors will establish a Random Sampling Plan for QC sampling and testing for each Lot of Earthwork material prior to placement of the Lot. All Earthwork 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 NETTCP Standard Test Report Form D3665 or D3665RNG. A copy of the Random Sampling Forms is located in **Appendix *xxx***. (See Note, page F-3.) ABC Contractors will provide Transportation Agency a copy of the Random Sampling locations (i.e., completed NETTCP Form D3665) for each Earthwork placement operation, during the start of the placement operation each day.

5.3 – Sample Identification System

All Earthwork material samples will be clearly identified as follows:

- Project Segment (i.e.,, 1, 2, 3)
- Material Type (i.e., Rock Excavate, Earth Excavate, Ordinary Borrow, etc.)
- Sample Type (QC, CIT) and Random/Non-Random
- Lot Number and Sublot Number
- Sample Location (i.e., Rte 99 Median, Borrow Subcontractor, etc.)
- Station, Offset, and Depth
- Sample Date
- Technician or Inspector

5.4 – QC Sampling & Testing Requirements

The specific requirements (Quality Characteristics, frequency, location, methods) for QC sampling and testing of each Earthwork item are outlined in the tables below.

5.4.1 – Backfill Material for Muck Excavation

QC Sampling & Testing Requirements					
Quality Characteristic	**Test Method(s)**	**Lot Size**	**Sublot Size/ Test Frequency**	**Point of Sampling**	**Sampling Method**
Gradation	AASHTO T11 AASHTO T27	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/ 5,000 m^3 for 1^{st} 50,000 m^3 and 1 Sample/ 10,000 m^3 thereafter	From In-Place Lift of Backfill	Random T2, T248
Maximum Dry Density & Optimum Moisture Content	AASHTO T99 (Method C) AASHTO T180 (Method D)	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/ 5,000 m^3 for 1^{st} 50,000 m^3 and 1 Sample/ 10,000 m^3 thereafter	From In-Place Lift of Backfill	Random T2, T248
Maximum Rock Size (< 1 m)	Visual/Tape	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
Maximum Lift Thickness (< 300 mm)	Rod/Grade Stake	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
In-Place Density & Moisture Content (Per Targets)	AASHTO T310 (Method B)	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/1,000 m^3, but not less than 1/Placement Location/Day	From Compacted Backfill	Random T310

5.4.2 – Roadway Embankment Material

QC Sampling & Testing Requirements					
Quality Characteristic	**Test Method(s)**	**Lot Size**	**Sublot Size/ Test Frequency**	**Point of Sampling**	**Sampling Method**
Gradation	AASHTO T11 AASHTO T27	Total Quantity of Embankment Material Type / Source / Project Segment	1 Sample/ 5,000 m^3 for 1st 50,000 m^3 and 1 Sample/ 10,000 m^3 thereafter	From In-Place Lift of Embankment	Random T2, T248
Maximum Dry Density & Optimum Moisture Content	AASHTO T99 (Method C) AASHTO T180 (Method D)	Total Quantity of Embankment Material Type / Source / Project Segment	1 Sample/ 5,000 m^3 for 1st 50,000 m^3 and 1 Sample/ 10,000 m^3 thereafter	From In-Place Lift of Embankment	Random T2, T248
Maximum Rock Size (< 1 m)	Visual/Tape	Total Quantity of Embankment Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
Maximum Lift Thickness (< 600 mm for Earth Excavate)	Rod/Grade Stake	Total Quantity of Embankment Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Embankment	Random Visual
Maximum Lift Thickness (< 300 mm for Ordinary Borrow & Gravel Borrow)	Rod/Grade Stake	Total Quantity of Embankment Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Embankment	Random Visual
Maximum Lift Thickness (< 200 mm for Special Borrow)	Rod/Grade Stake	Total Quantity of Embankment Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Embankment	Random Visual
In-Place Density & Moisture Content (Per Targets)	AASHTO T310 (Method B)	Total Quantity of Embankment Material Type / Source / Project Segment	1 Sample/1,000 m^3, but not less than 1/Placement Location/Day	From Compacted Embankment	Random T310

5.4.3 – Embankment Material Under Bridge Foundations

QC Sampling & Testing Requirements					
Quality Characteristic	**Test Method(s)**	**Lot Size**	**Sublot Size/ Test Frequency**	**Point of Sampling**	**Sampling Method**
Gradation	AASHTO T11 AASHTO T27	Total Quantity of Embankment Material Type / Source / Project Segment	1 Sample/ Placement Location	From In-Place Lift of Embankment	Random T2, T248
Maximum Dry Density & Optimum Moisture Content	AASHTO T99 (Method C) AASHTO T180 (Method D)	Total Quantity of Embankment Material Type / Source / Project Segment	1 Sample/ Placement Location	From In-Place Lift of Embankment	Random T2, T248
Maximum Stone Size (< 75 mm)	Visual/Tape	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
Maximum Lift Thickness (< 300 mm)	Rod/Grade Stake	Total Quantity of Embankment Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Embankment	Random Visual
In-Place Density & Moisture Content (Per Targets)	AASHTO T310 (Method B)	Total Quantity of Embankment Material Type / Source / Project Segment	Gravel Borrow: 1 Sample/ Each Lift/ Placement Location/Day Crushed Stone: N/A	From Compacted Embankment	Random T310

5.4.4 – Backfill Material for Structures

QC Sampling & Testing Requirements					
Quality Characteristic	**Test Method(s)**	**Lot Size**	**Sublot Size/ Test Frequency**	**Point of Sampling**	**Sampling Method**
Gradation	AASHTO T11 AASHTO T27	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/1,000 m^3	From In-Place Lift of Backfill	Random T2, T248
Maximum Dry Density & Optimum Moisture Content	AASHTO T99 (Method C) AASHTO T180 (Method D)	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/1,000 m^3	From In-Place Lift of Backfill	Random T2, T248
Maximum Stone Size (< 75 mm)	Visual/Tape	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
Maximum Lift Thickness (< 150 mm)	Rod/Grade Stake	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
In-Place Density & Moisture Content (Per Targets)	AASHTO T310 (Method B)	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/100 m^3, but not less than 1/Lift/Day	From Compacted Backfill	Random T310

5.4.5 – Backfill Material for Pipes*

QC Sampling & Testing Requirements					
Quality Characteristic	**Test Method(s)**	**Lot Size**	**Sublot Size/ Test Frequency**	**Point of Sampling**	**Sampling Method**
Gradation	AASHTO T11 AASHTO T27	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/1,000 m^3	From In-Place Lift of Backfill	Random T2, T248
Maximum Dry Density & Optimum Moisture Content	AASHTO T99 (Method C) AASHTO T180 (Method D)	Total Quantity of Backfill Material Type / Source / Project Segment	1 Sample/1,000 m^3	From In-Place Lift of Backfill	Random T2, T248
Maximum Stone Size (< 75 mm)	Visual/Tape	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
Maximum Lift Thickness (< 150 mm)	Rod/Grade Stake	Total Quantity of Backfill Material Type / Source / Project Segment	Minimum 4/Lift/Day	From In-Place Lift of Backfill	Random Visual
In-Place Density & Moisture Content (Per Targets)	AASHTO T310 (Method B)	Total Quantity of Backfill Material Type / Source / Project Segment	Gravel Borrow: 1 Sample/100 m of Trench, but not less than 1/Lift/Day Ordinary Borrow: 1 Sample/100m of trench, but not less than 1/Placement Location/Day	From Compacted Backfill	Random T310

(*)**Backfill Material for Pipes** will include Gravel Borrow and Ordinary Borrow to be placed as follows:

Gravel Borrow – Gravel Borrow shall be used for bedding and backfilling of pipe to a point 600mm above the top of pipe.

Ordinary Borrow – Ordinary Borrow shall be used to backfill the remaining depth of trench from the top of the Gravel Borrow to the top of the finished subgrade.

5.5 – QC Test Result Reporting

All QC sampling and testing of In-Place Earthwork materials will be documented on the following Standard Test Report Forms (TRFs):

Form No.	Form Title
NETTCP T27	Sieve Analysis Test Report
T99	Moisture-Density Relations of Soils (Standard)
T180	Moisture Density Relations of Soils (Modified)
T310	Soils In-Place Density & Moisture Content Test Report
Rock Size & Lift	Maximum Rock Size and Lift Thickness Test Report

A copy of the Standard TRFs used for QC sampling and testing of Earthwork materials is located in **Appendix *xxx***. (See Note, page F-3.)

ABC Contractors will retain a complete record of all completed Earthwork testing and inspection in accessible files which will be labeled as the “QC Record System – Earthwork”. The QC Record System will contain the following QC documents:

- The approved Earthwork QC Plan
- Original copies of all completed Earthwork QC Standard Test Report Forms (including Random Sampling Forms)
- Earthwork Control Charts
- Summaries of all Earthwork test results
- Records of Earthwork Daily Production quantity information

ABC Contractors will also submit copies of all completed QC sampling and testing Report Forms to Transportation Agency with each “Weekly QC Summary Report”.

5.6 – QC Sample Storage and Retention Procedures

All physical QC samples of Earthwork material will be split prior to testing in accordance with relevant AASHTO and NETTCP procedures.

The split sample portion of Earthwork material 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 which performed the test for a minimum of 60 Days following testing.

6.0 PRODUCTION FACILITIES

The activities and procedures to be followed for QC during production of Earthwork materials are as indicated below.

6.1 – Schedule of Production Operations

ABC Contractors will provide Transportation Agency with a “Weekly Schedule of Earthwork Materials Production Operations” on each Friday prior to the week of production. A copy of the “Weekly Schedule of Earthwork Materials Production Operations” is located in **Appendix *xxx***. (See Note, page F-3.)

The weekly schedule of Production Operations will identify the following:

- Material Type
- Material Source
- Production Location
- Estimated Production Quantity

ABC Contractors will track the actual production quantities on a daily basis and maintain a “Record of Earthwork Production” for each week. Copies of the “Record of Earthwork Production” will be made available to Transportation Agency in the “Weekly QC Summary Report”.

6.2 – Production Facilities & Equipment

ABC Contractors and their Subcontractors and Suppliers will utilize conventional facilities and equipment for the production of all Earthwork materials. The major types of facilities and equipment to be utilized for On-Site and Off-Site production are summarized below.

Material Source Production Facility	Production Equipment
On-Site, Segment 1, 2, & 3	• Crawler Drills (Multiple, Various Make)
	• Explosives & Blasting Mats
	• Backhoes (Multiple, Various Make)
	• Tractor/Dozers (Multiple, Various Make)
	• Front End Loaders (Multiple, Various Make)
	• End Dump Trucks (Multiple, Various Make)
Bedrock Industries, Bedrock, MA	
	• Tractor/Dozers (Multiple, Various Make)
	• Rock Crusher
	• Conveyor Belt
	• Front End Loaders (Multiple, Various Make)
	• End Dump Trucks (Multiple, Various Make)
Borrow Producer(s) (TBD)	
	• Tractor/Dozers (Multiple, Various Make)
	• Front End Loaders (Multiple, Various Make)
	• End Dump Trucks (Multiple, Various Make)

6.3 – Production Quality Control Activities

Production Quality Control (PQC) personnel will perform the following inspection, sampling, and testing activities at the frequencies indicated:

6.3.1 – Pre-Production QC Activities

- Conduct a Pre-Production Quality Control Audit at each Earthwork Source facility or location in accordance with CQMP Part XIII prior to the start of Earthwork production
- Maintain a reference grid system (Stations, Offsets) and boundaries for each Earthwork Source facility or location
- Determine and document random sampling locations of Earthwork materials at Production Facility in accordance with Section 4.2.1 above
- Obtain and properly label all Source Characterization (SC) samples of Earthwork materials at the frequencies indicated in Section 4.2.1 above
- Transport Earthwork Source Characterization samples to the appropriate laboratory for testing
- Ensure that Source Characterization sampling and testing is completed for each Source Quadrant prior to production/removal of material from the Source Quadrant
- Inspect stockpiles to ensure that different Earthwork material types are not commingled or contaminated

6.3.2 – Production QC Activities

- Visually monitor Earthwork materials production to ensure no change in material type within the Source Quadrant
- Determine and document random sampling locations for each Sublot of Earthwork material produced.
- Obtain and properly label all PQC Field samples of Earthwork materials.
- Transport Earthwork PQC Field samples to the appropriate laboratory for testing.
- Perform PQC sampling and testing of Earthwork in accordance with the required test methods and frequencies outlined in Section 5.0 above.
- Prepare and sign standard Test Report Forms (TRFs) for each test completed.
- Maintain Production Facility Control Charts per Section 6.4 below.
- Monitor loading and transportation of Earthwork materials to ensure that the correct materials are being transported to the correct Project location
- Ensure that all Borrow Pits are neatly trimmed and finished to the minimum grades and dimensions required under Section 150.21 of the Standard Specifications
- Document Off-Site and On-Site Earthwork Production QC inspection activities and findings on standard QC Inspection Report Forms (IRFs) for each production location in accordance with Section 6.6 below

- Identify Production Facility practices or materials which do not conform with the requirements of the relevant specifications and this QC Plan, and discuss appropriate corrective action with the Production Facility Superintendent and the QC Manager

6.4 – Production Facility Control Charts

Control Charts may be used by ABC Contractors and their Earthwork material Producers to control production operations as described below.

6.4.1 – Off-Site Production Control Charts

Off-Site Earthwork material Producers will use Control Charts as needed to provide adequate control of their production operations. Prior to production, ABC Contractors will request each Earthwork material Producer to identify and submit examples of any Control Charts to be used. ABC Contractors will monitor and discuss the Control Charts with the Producer during Earthwork production.

6.4.2 – On-Site Production Control Charts

At this time, the application of Control Charts does not appear necessary for the production of On-Site Earthwork materials (i.e., Earth Excavate). However, in the event that Rock Crushing operations are established to produce Earthwork materials from On-Site Rock Excavate, Control Charts will be maintained to monitor control of the operation.

6.5 – Procedures for Corrective Action of Non-Conforming Materials

The following procedures will be followed for corrective action of non-specification materials encountered at the Source/Production facility:

- If contaminated materials are encountered, the limit of contaminated material will be identified. The contaminated material will be clearly marked off by signs labeled "**No Use On Rte 99**".

- If a change in material type is encountered within a Source Lot, additional sampling and testing will be performed to characterize the material. The disposition of such material will be as follows:

    - If the material meets specification requirements for another Project Material Type, then the material will be approved for use at an appropriate location for that Material Type.

    - If the material can be blended with other material and subsequently meet specification requirements for a Project Material Type, then the material will be approved for use at an appropriate location for that Material Type.

    - If the material does not meet specification requirements for a Project Material Type, the material will not be permitted for use on the Project. ABC Contractors will prepare a Non-Conformance Report (NCR) for such material in accordance with Part X of the CQMP. If the source of such material is On-Site (e.g., Rte 99 Median), ABC Contractors will dispose of the material Off-Site at an approved disposal site. If the source of such material is Off-Site (e.g., Borrow), the material will be clearly marked off by signs labeled "**No Use On Rte 99**".

6.6 – Production QC Inspection Reporting

All PQC inspection activities will be documented on the following standard QC Inspection Report Forms (IRFs):

Form No.	Form Title
PQC-PPA	Production QC - Pre-Production Audit Report
PQC-IDR	Production QC – Inspectors Daily Report

A copy of the Standard IRFs used for Production QC inspection of Earthwork materials is located in **Appendix *xxx***. (See Note, page F-3.)

7.0 FIELD OPERATIONS

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

7.1 – Schedule of Field Placement Operations

ABC Contractors will provide Transportation Agency with a "Weekly Schedule of Earthwork Materials Placement Operations" on each Friday prior to the week of placement. A copy of the "Weekly Schedule of Earthwork Materials Placement Operations" is located in **Appendix *xxx***. (See Note, page F-3.)

(Note to Plan Preparer: A sample Weekly Report may look like the example, below.)

Weekly Schedule of Earthwork Materials Production Operations

Week Beginning: ______________________

Material Type	**Material Source**	**Production Location** **(STA to STA, Stockpile, Pit, etc.)**	**Estimated Production Quantity**
Ordinary Borrow	**Rte 99 On-Site Borrow Pit**	Quadrant SC-234	5,000 m^3
Ordinary Borrow	Rte 99 On-Site Borrow Pit	Quadrant SC-240	**4,000 m^3**
Ordinary Borrow	Rte 99 On-Site, Segment 1	Rte 99 Median, STA 114+10 to STA 116+50	4,000 m^3
Ordinary Borrow	Rte 99 On-Site, Segment 1	Rte 99 Median	4,000 m^3
Ordinary Borrow	Rte 99 On-Site, Segment 1	Rte 99 Median	4,000 m^3
Ordinary Borrow	Rte 99 On-Site, Segment 1	Rte 99 Median	4,000 m^3
Ordinary Borrow	Rte 99 On-Site, Segment 1	Rte 99 Median	4,000 m^3
Rock Excavate	Rte 99 Segment 1, 2, 3	Rte 99 Median, Outboard	2,200 m^3
Earth Excavate	Rte 99 Segment 1, 2, 3	Rte 99 Median, Outboard	4,000 m^3
Ordinary Borrow	Borrow Producer (TBD)	Stockpile	6,000 m^3
Gravel Borrow	Borrow Producer (TBD)	Stockpile	3,000 m^3

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)

ABC Contractors will track the actual placement quantities on a daily basis and maintain a “Record of Earthwork Placement” for each week. Copies of the “Record of Earthwork Placement” will be made available to Transportation Agency.

7.2 – Field Placement Facilities & Equipment

ABC Contractors will utilize conventional facilities and equipment for the placement of all Earthwork materials. The major types of facilities and equipment to be utilized for Earthwork placement are summarized below for each type of Earthwork Item.

Earthwork Item	Placement Equipment
Backfill Material for Muck Excavation & Roadway Embankment Material	• End Dump Trucks (Multiple, Various Make)
	• Tractor/Dozers (Multiple, Various Make)
	• Vibratory Rollers - 50 Ton (Multiple, Various Make)
	• Sheepsfoot Rollers (Multiple, Various Make)
	• Water Trucks (Multiple, Various Make)
Embankment Material Under Bridge Foundations	• End Dump Trucks (Multiple, Various Make)
	• Tractor/Dozers (Multiple, Various Make)
	• Vibratory Rollers - 50 Ton (Multiple, Various Make)
Backfill Material for Structures and Pipes	• End Dump Trucks (Multiple, Various Make)
	• Backhoes (Multiple, Various Make)
	• Front End Loaders (Multiple, Various Make)
	• Vibratory Sled Compactors (Various Make)

7.3 – Establishment of Compaction Rolling Pattern (Control Strips)

Control Strips will be constructed at the start of each Earthwork placement operation. A new Control Strip will be constructed whenever one of the following occurs:

- A new Earthwork Lot
- A change in weather
- A change in environment
- A PWL < 85% for 3 or more consecutive QC Test Results

The Control Strips will be used to establish an effective rolling pattern and the corresponding compactive effort required to achieve the in-place Target Density (Maximum Dry Density) at Optimum Moisture Content. The procedure to be followed for developing a Control Strip is outlined as follows:

7.3.1 - Earthwork Compacted by Rollers

Step A. – The Control Strip will be established on the first lift to be constructed within an area not to exceed 30m long by 15m wide. The Strip will be divided longitudinally into 3 approximately equal Control Strip Sections.

Step B. – Material will be loose placed in the first Control Strip Section. The Field Superintendent, Roller Operator(s) and QC Field Inspector will visually assess the moisture content of Earthwork placed and determine whether additional moisture is needed to achieve Optimum Moisture Content.

Step C. – The Field Superintendent, Roller Operator(s) and QC Field Inspector will discuss and agree upon the proposed number and sequence of passes and compactive mode(s) (static, vibratory) to be used for the particular Earthwork being placed.

Step D. – The Roller Operator(s) will compact Control Strip Section #1 following the agreed upon number and sequence of passes and compactive mode(s).

Step E. – After compacting Control Strip Section #1, the Roller Operator will suspend operation. The QC Inspector will perform Contractor Information Testing (CIT) within Control Strip Section #1and obtain a minimum of three separate (Random or Non-Random) In-Place Density and Moisture Content readings.

Step F. – The Field Superintendent, Roller Operator(s) and QC Field Inspector will review the In-Place Density and Moisture Content readings for Control Strip Section #1 and determine any necessary adjustment to the number and sequence of passes and compactive mode(s).

Step G. - The Roller Operator will move on to Control Strip Section #2 and compact the material following the agreed upon number and sequence of passes and compactive mode(s).

Step H. – After compacting Control Strip Section #2, the Roller Operator will suspend operation and permit the QC Inspector to obtain a minimum of three separate random In-Place Density and Moisture Content readings in Control Strip Section #2.

Step I. – The CIT results for Control Strip Section #2 will be evaluated by the QC Inspector using Quality Level Analysis (QLA). The QLA must indicate a Percent Within Limits (PWL) of 85% or more for the In-Place Density and Moisture Content as indicated in Section 8.1 below.
Step J. – If the PWL for Control Strip Section #2 is 85% or greater, then the number and sequence of passes and compactive mode(s) used in Control Strip Section #2 will be established as the approved "Compaction Pattern" for the remainder of the placement operation on that day.
Step K. – If the PWL for Control Strip Section #2 is less than 85%, then Steps **F** through **I** above will be repeated on segment #3.

7.3.2 - Earthwork Compacted by Hand Operated Compacters

Step A. – The Control Strip will be established on the first lift to be constructed within an area not to exceed 24m long by 1m wide. The Strip will be divided longitudinally into 3 approximately equal Control Strip Sections.
Step B. – Material will be loose placed in the first Control Strip Section. The Field Superintendent, Compactor Operator and QC Field Inspector will visually assess the moisture content of Earthwork placed and determine whether additional moisture is needed to achieve Optimum Moisture Content.
Step C. – The Field Superintendent, Compactor Operator(s) and QC Field Inspector will discuss and agree upon the proposed number and sequence of passes and compactive mode to be used for the particular Earthwork being placed.
Step D. – The Compactor Operator will compact Control Strip Section #1 following the agreed upon number and sequence of passes and compactive mode.
Step E. – After compacting Control Strip Section #1, the Compactor Operator will suspend operation. The QC Inspector will perform Contractor Information Testing (CIT) within Control Strip Section #1and obtain a minimum of three separate (Random or Non-Random) In-Place Density and Moisture Content readings.
Step F. – The Field Superintendent, Compactor Operator and QC Field Inspector will review the In-Place Density and Moisture Content readings for Control Strip Section #1 and determine any necessary adjustment to the number and sequence of passes and compactive mode.
Step G. - The Compactor Operator will move on to Control Strip Section #2 and compact the material following the agreed upon number and sequence of passes and compactive mode(s).
Step H. – After compacting Control Strip Section #2, the Compactor Operator will suspend operation and permit the QC Inspector to obtain a minimum of three separate random In-Place Density and Moisture Content readings in Control Strip Section #2.

Step I. – The CIT results for Control Strip Section #2 will be evaluated by the QC Inspector using Quality Level Analysis (QLA). The QLA must indicate a Percent Within Limits (PWL) of 85% or more for the In-Place Density and Moisture Content as indicated in Section 8.1 below.
Step J. – If the PWL for Control Strip Section #2 is 85% or greater, then the number and sequence of passes and compactive mode(s) used in Control Strip Section #2 will be established as the approved “Compaction Pattern” for the remainder of the placement operation on that day.
Step K. – If the PWL for Control Strip Section #2 is less than 85%, then Steps **F** through **I** above will be repeated on segment #3.

7.4 – Field Quality Control Activities

Field Quality Control (FQC) personnel will perform inspection, sampling, and testing of Earthwork as described below.

7.4.1 – Pre-Placement QC Activities

- Check Earthwork line and grade for conformance to the design documents.
- Ensure that all erosion control measures are in place per approved plans and specifications.
- Ensure that the existing ground has been cleared, grubbed and stripped as specified in Section 101 and 120 of the Standard Specifications, prior to the placing of any Earthwork materials.
- Verify that all vegetation and other organic material is removed within and immediately adjacent to Earthwork placement location.
- Determine that excavations have been conducted to suitable founding material and grade.
- Where Earthwork material is to be placed against existing earth slopes steeper than 1 Veritical: 3 Horizontal, ensure that the slope is broken up into steps of random width in order to provide a suitable bond between the existing ground and the new material.

7.4.2 – Placement QC Activities

- Ensure that Control Strips are constructed at the start of each Earthwork placement operation and as required thereafter per Section 7.3 above.
- Ensure that stumps, rubbish, sod, or other unsuitable materials are not incorporated in the Earthwork.
- Ensure that frozen Earthwork materials are not placed and that Earthwork is not placed on material frozen to a depth of over 75 millimeters.
- Ensure that correct Earthwork material type, per Section 4.1 above, is being delivered/received at the intended placement location.

- Ensure that Earthwork is placed in successive layers of uniformly distributed material and compacted over the full width of the cross section.
- Monitor lift placement to ensure that maximum lift thicknesses specified in Section 5.4 above are not exceeded.
- Ensure that each lift of compacted Earthwork materials is visibly crowned to allow drainage of surface water and rainwater off the surface.
- Monitor maximum Rock Size and maximum Stone Size in Earthwork materials for conformance with the requirements of Section 5.4 above.
- Ensure that where Rock Excavate is placed, all voids and interstices are filled with an appropriate clean, granular Earthwork material type identified in Section 4.1 above.
- Ensure that the placed Earthwork moisture content is near the optimum moisture content established through Source Characterization testing (Section 4.2 above) and through the Control Strip (Section 7.3 above).
- Ensure that moisture is added when Earthwork material is too dry and that Earthwork which is too wet is dried by disking, harrowing, blading, rotary mixing, or other approved means so that proper compaction can be achieved.
- Monitor compaction patterns against the approved Control Strip “Compaction Pattern” and perform Contractor Information Testing (CIT) to ensure that the in-place density is near the target (100%) in-place density.
- Ensure that no rock in excess of 150 millimeters in its largest dimension is incorporated in the top 600-millimeter layer of Earthwork immediately below the finished Subgrade elevation.
- Perform check measurements during placement of Roadway Embankment Material final Subgrade Course (Special Borrow) in accordance with Section170.61 of the Standard Specifications to ensure proper depth and elevations of finished Subgrade within +/-15 millimeters.
- Ensure that Roadway Embankment Material 3 meters or more in height from the elevation of the Subgrade to the original ground elevation is constructed to the elevation of the proposed Subgrade and then allowed to settle for 60 days (or other period as specified by the Design Engineer) before the pavement structure is constructed thereon.
- Ensure that Embankment Material under Bridge Foundations is placed in embankment prior to driving piles.
- Determine and document random sampling locations for each Sublot of Earthwork material placed.
- Obtain and properly label all Field samples of Earthwork materials.
- Transport Earthwork Field samples to the appropriate laboratory for testing.
- Perform In-Place QC sampling and testing of Earthwork in accordance with the required test methods and frequencies outlined in Section 5.0 above.
- Prepare and sign standard Test Report Forms (TRFs) for each test completed.
- Maintain Control Charts per Section 7.5 below.

- Document On-Site Earthwork QC inspection activities and findings on standard QC Inspection Report Forms (IRFs) for each On-Site placement location per Section 7.7 below.
- Identify On-Site Field placement practices or materials which do not conform with the requirements of the relevant specifications and this QC Plan, and discuss appropriate corrective action with the Segment Field Superintendent and the QC Manager.

7.5 – Placement Control Charts

Control Charts may be used by ABC Contractors to control placement operations for each of the five Earthwork Item categories as described below.

7.5.1 – Control Charts for Backfill Material for Muck Excavation

Since the placement of Backfill Material for Muck Excavation will generally involve smaller Earthwork quantities at sporadic locations, the application of Control Charts as a tool to provide field control for this Earthwork Item will yield limited QC information. Accordingly, Control Charts will not be used for placement of Backfill Material for Muck Excavation.

7.5.2 – Control Charts for Roadway Embankment Material

The placement of Roadway Embankment Material will involve large quantities of Earthwork within each Project Segment. Accordingly, Control Charts will be used as a tool to assist in the field control for placement of this Earthwork Item. Control Charts will be maintained for each Lot of Roadway Embankment Material by the QC Field Inspection staff. Control Charts will monitor the In-Place Density and Moisture Content of each Lot. The Mean QC Test results will be plotted according to daily subgrouping.

7.5.3 – Control Charts for Embankment Material under Bridge Foundations

The placement of Embankment Material under Bridge Foundations will involve large quantities of Earthwork within each Project Segment. Accordingly, Control Charts will be used as a tool to assist in the field control for placement of this Earthwork Item. Control Charts will be maintained for each Lot of Embankment Material under Bridge Foundations by the QC Field Inspection staff. Control Charts will monitor the In-Place Density and Moisture Content of each Lot. The Mean QC Test results will be plotted according to daily subgrouping.

7.5.4 – Control Charts for Backfill Material for Structures

Since the placement of Backfill Material for Structures will generally involve smaller Earthwork quantities at various locations, the application of Control Charts as a tool to provide field control for this Earthwork Item will yield limited QC information. Accordingly, Control Charts will not be used for placement of Backfill Material for Structures.

7.5.5 – Control Charts for Backfill Material for Pipes

Since the placement of Backfill Material for and Pipes will generally involve smaller Earthwork quantities at various locations, the application of Control Charts as a tool to provide field control for this Earthwork Item will yield limited QC information. Accordingly, Control Charts will not be used for placement of Backfill Material for Pipes.

An example of the types of Control Charts which will be used for Earthwork placement is contained in **Appendix *xxx***. (See Note, page F-3.)

7.6 – Procedures for Corrective Action of Non-Conforming Materials

The following procedures will be followed for corrective action of non-specification materials encountered during placement of Earthwork Items:

- If the Earthwork material delivered/received at the placement location is not the correct Material Type (i.e., Earth Excavate, Ordinary Borrow, Special Borrow, etc.), it will be removed (if placed) and returned to the material source.
- If the Earthwork material delivered/received at the placement location is determined to be the correct Material Type, but does not meet specification requirements (e.g., gradation), the limits of such material will be determined and it will be removed from the Project. Further receipt and placement of Earthwork material from the source will be suspended until Quality Control personnel have determined and corrected the cause of non-specification material.
- If new Earthwork material delivered/received at the placement location is commingled with existing On-Site non-specification material (e.g., Organic material, Other), the limits of the commingled area will be determined and the commingled material will be removed and disposed of at an approved Off-Site location.
- If rock contained in Earthwork material is determined to exceed the specified size limits (e.g., Earth Excavate: <600mm), appropriate equipment will be used to break the rock to conform to the maximum size requirements, or the rock will be removed and disposed of at an approved Off-Site location.
- If the percentage of rock contained in Earthwork material is determined to exceed the specified limit (e.g., Earth Excavate: <50%), the material will either be spread and blended with other material to conform with requirements or it will be removed.
- If the lift thickness of Earthwork material is determined to exceed the specified limits, the lift will be cut using appropriate equipment and regraded to conform to the maximum lift thickness requirements.
- If an individual QC test result for in-place density or in-place moisture content is outside the Engineering Limits contained in Section 8.6 below, placement of Earthwork material in the corresponding Sublot will be stopped. The following steps will be taken:

- A Re-Test within 300mm of the original random test location may be performed only if the cause of the results is believed to be due to sampling/testing error.

- If a Re-Test is not warranted, or if a Re-Test is performed and the test results of the Re-Test are also outside the Engineering Limits, then three (3) additional random QC tests may be performed within the Sublot. The results of the 3 additional random QC tests will be evaluated as follows:

    - If all three tests are above the Lower Engineering Limit (95%), then the Sublot will be accepted and all of the test results (The original failing result + the 3 passing results) will be included for Quality Level Analysis.

    - If any one of the 3 additional random QC tests is below the Lower Engineering Limit (95%), then the Sublot will not be accepted. Field QC personnel will troubleshoot to determine if the failing results are due to:

        - Improper compaction procedure
        - Inadequate moisture content
        - Other

    - Once the cause of the failing test results is determined, appropriate corrective action will be taken (e.g., Add moisture, Regrade and compact. The failing Earthwork material will be reworked and three additional random QC tests will be performed for the Sublot. The results of the 3 additional random QC tests will be evaluated in accordance with the steps above until all 3 additional test results are within the Engineering Limits and the overall Percent Within Limits (PWL) for the Sublot equals or exceeds 85%.

- Earthwork material that cannot be reworked to achieve the specified in-place density and in-place moisture content will be disposed of Off-Site.

7.7 – Field QC Inspection Reporting

All FQC inspection activities will be documented on the following standard QC Inspection Report Forms (IRFs):

Form No.	Form Title
FQC-MRIR	Field QC – Material Receiving Inspection Report
FQC-IDR	Field QC – Inspectors Daily Quality Surveillance Report
FQC-EBIR	Field QC – Embankment & Backfill Inspection Report

(* For Off-Site Earthwork Producer material only)

A copy of the Standard IRFs used for Field QC inspection of Earthwork materials is located in **Appendix *xxx***. (See Note, page F-3.)

- END OF APPENDIX F -

APPENDIX G

Example Standard Test Report Forms

Appendix G

Example Standard Test Report Forms

Appendix Overview

This Appendix provides a summary of ***NETTCP Standard Test Report Forms*** that are available for use by Contractor and Agency personnel. The Standard Test Report Forms (TRFs) are available in electronic form (Microsoft Excel®) on the NETTCP website (http://www.nettcp.com).

Each TRF includes a standard "Header" section for entry of project and sample specific information, line by line data entry cells and built in function cells that automatically calculate test values, and a standard "Footer" section for signoff by the tester and a reviewer. The data reporting and calculation line items on each TRF have been designed to follow the steps required by the specific AASHTO or ASTM test procedure.

The NETTCP Standard TRFs include the following:

Soils & Aggregate Test Report Forms

- Random Sampling Test Report (D3665)
- Coarse Aggregate Angularity & Flat and Elongated Particles Test Report (D5821, D4791)
- Soundness of Coarse Aggregate Test Report (T104)
- Soundness of Fine Aggregate Test Report (T104)
- Deleterious Materials Test Report (T112)
- Plastic Fines By Sand Equivalent Test Report (T176)
- Density By Sand Cone Test Report (T191)
- Sieve Analysis Test Report (T27, T11, T255)
- Fine Aggregate Angularity Test Report (T304)
- Fine Aggregate Specific Gravity Test Report (T84)
- Coarse Aggregate Specific Gravity Test Report (T85)
- Resistance to Degradation of Aggregate By Abrasion Test Report (T96)

Portland Cement Concrete (PCC) Test Report Forms

- Random Sampling Test Report (D 3665)
- PCC Cover Over Reinforcing Steel Test Report (ACI & NETTCP)
- PCC Slump, Air Content & Unit Mass Test Report (T119, T152, T196, T121, C1064)
- PCC Field Tests and Cylinder Strength Test Report (T23, T119, T152, T196, C1064, T231, T22)

Hot Mix Asphalt (HMA) Test Report Forms

- HMA Pavement Nuclear Density Test Report (D 2950)
- Random Sampling Test Report (D 3665)
- Pavement Ride Quality Test Report (E 1489)
- HMA Field Tests Summary Report
- HMA Plant Tests Summary Report
- HMA Field Temperatures Test Report (Sub-Base, Air, Mix
- HMA Ash Correction Test Report (T 111)
- HMA Asphalt Content and Gradation Test Report (T 110, T164, T 30)
- HMA Asphalt Content, Gradation & Marshall Volumetrics Test Report (T 110, T 164, T 30, T 166, T 209, PP 19, T 245)
- HMA Theoretical Maximum Specific Gravity Test Report (T 209)
- HMA Pavement Thickness and Compaction Test Report (D 3549, T 166, T 230, T 269)
- HMA Marshall Volumetric Properties Test Report (T 166, PP 19, T 245)
- HMA Moisture Sensitivity Test Report (T 283)
- Asphalt Binder Sample Record (T 40)
- HMA Gyratory Volumetric Properties Test Report (T 166, TP 4, PP 19)
- HMA Asphalt Content and Gradation Test Report (T 110, TP 53, T 30)
- HMA Asphalt Content, Gradation & Marshall Volumetrics Test Report (T 110, TP 53, T 30, T 166, T 209, PP 19, T 245)

Test Report Form Header Section Key

Date/Time Date and time, in military format, when the sample was taken (*5/1/97 1330*).

Weather Brief description of weather *(sunny & hot, light rain, windy & cool, etc.)*.

Project Description of project including town, roadway and type of work (*West Springfield/I91 Resurfacing*).

Contract # State contract Number.

Contractor Contractor who is performing work.

Pay Item # Contract Item number for which the material is being tested.

Source Name and location of source of material.

Plant Type Type of plant being used to produce material *(batch plant, drum plant, etc).*

Lab/Location Name and location of testing laboratory performing material testing.

Date Rec'd. Lab number to be assigned by the testing laboratory and the date which the lab received the sample.

Lab Login # Number assigned to sample by testing laboratory.

Material ID Description of material type, which is being sampled, examples include, but are not limited to the following: 12.5*mm HMA Surface, coarse ag., fine ag.*

Material # Specification number, which corresponds to the material, listed under the Material ID or Producer's Mix Number.

Sample # Unique number to be assigned in order to clearly identify the sample being tested.

Sample Type Indicate why the sample was taken: **QA** – quality acceptance, **QC** – quality control, **IA** – independent assurance, **AV** – acceptance verification, **PC** – process control, **Other**. Select one of the 6 choices.

Sampled By/Cert. # Name and Certification No. of the person who obtained the sample.

Random Sample: Is the sample random? (select one)

Lot # A unique sequential number, starting with 1, assigned to represent a specific quantity spelled out in the specifications for each Pay Item No.

Sublot # A unique sequential number, starting with 1, assigned to represent a specific quantity spelled out in the specifications within each specific Lot. Sublot numbers should not be repeated within a Lot. Sublot numbers start with 1 and progress as needed, they do not start over with each day's production. *If Sublot numbers 1 to 4 were used on the first day of production the Sublot numbers would start with 5 on the second day of production.*

Sample Location Location from which the sample was taken. Depending on the type of sample the following would be appropriate locations: *hopper, stockpile, conveyor belt, truck, behind paver, center lane I91SB , bridge deck, footing*. This is not meant to be a complete list of locations, location should be descriptive enough so that it clearly defines where the sample came from.

Station Standard roadway baseline stationing which is established on the project site (*Sta.134+50*)

Offset Offset, right or left from the base line of the project stationing (*4m left*).

Test Report Form Footer Section Key

Comments Comments on anything relative to taking or testing of the sample.

Tested By Name of the person who performed test or tests on the sample.

Certification # Certification No. of person who performed test or tests on the sample.

Date Date which the test or tests were performed

Reviewed By Name of the person who has reviewed the test results and is responsible for acceptance of results

Certification # Certification No. of person who has reviewed the test results and is responsible for acceptance of results.

Date Date which the test results were reviewed

Results within Specification Limits Check box to provide clear summary of outcome of test results, simply check the box that applies.

Results outside Specification Limits Check box to provide clear summary of outcome of test results, simply check the box that applies.

Fonts and Color Schemes Used on Test Report Forms

Yellow Shading & Black text Text in black followed by cells shaded yellow indicates that user data entry is required. All user input is in cells shaded yellow.

Blue text Blue text indicates intermediate calculations performed by the spreadsheet.

Red-Bold text, within a bold box Red-Bold text, within a bold box indicates final results that are calculated by the spreadsheet.

- END OF APPENDIX G -

APPENDIX H

Reprint of: FHWA RD-02-095
Optimal Procedures for Quality Assurance Specifications
(Appendix F only)

F–test and *t*–test Method for Comparing Two Sets of Data

Introduction

In comparing two sets of data, such as contractor and agency test results, what is involved is two hypothesis tests, where the H_0 for each test is that the data sets are from the same population. In other words, the null hypotheses are that the variabilities of the two data sets are equal, for the *F*–test, and that the means of the two data sets are equal, for the *t*–test.

When comparing two data sets, it is important to compare both the means and the variances. A different test is used for each of these comparisons. The ***F*–test** provides a method for comparing the **variances** (standard deviation squared) of the two sets of data. Differences in **means** are assessed by the ***t*–test**. Construction processes and material properties usually follow a normal distribution. For normal distributions, the ratios of variances follow an *F*–distribution, while the means of relatively small samples follow a *t*–distribution. Hypothesis tests for equal variances and means can therefore be conducted using these distributions.

For samples from the same normal population, the statistic *F*, which is the ratio of the two sample variances, has a sampling distribution called the *F*–distribution. Tables are available for the *F*–distribution just like they are for the normal distribution. For process verification testing, the *F*–test is based on the ratio of the sample variance of the contractor's test results, s_c^2, and the sample variance of the agency's test results, s_a^2.

Similarly, the *t*–statistic and the *t*–test can be used to test whether the sample mean of the contractor's test results, $\overline{X}_c$, and that of the agency's test results $\overline{X}_a$, came from populations with the same mean.

The equations for the *F*–test and *t*–test are presented conceptually in the following sections, but it is recommended that a computer program be used in practice to perform the calculations. Spreadsheet programs, such as Microsoft® Excel, have both *F*–tests and *t*–tests. Agencies may also wish to develop their own computer packages. Also, the program DATATEST, which was developed for FHWA Demonstration Project 89, is demonstrated at the end of this appendix. (18)

When comparing contractor and agency samples, it is important that **random sampling** was used when obtaining the samples. Also, because sources of variability influence the population parameters, the two sets of test results must have been sampled over the **same time period**, and the **same sampling and testing procedures** must have been used. If it is determined that a significant difference is likely between either the variances or the means, the source of the difference should be identified. The identification of a difference is just that, i.e., notice that a difference exits. The reason for the difference must still be determined.

Before comparing contractor and agency samples, **a level of significance, α, must be selected**. While α values of 0.10, 0.05, and 0.01 are common, many agencies select a value of 0.01 to minimize the likelihood of incorrectly concluding that the results are different when they actually came from the same population. However, it should be recognized that selecting a low α value reduces the chance of detecting a real difference when one actually exists.

F–test for Sample Variances

Since the values used for the *t*–test are dependent upon whether or not the variances are assumed equal for the two data sets, it is necessary to **test the variances before the means**. The intent is to determine whether the difference in the variability of the contractor's tests and the agency's tests is larger than might be expected by chance if they came from the same population. It does not matter which variance is larger. After comparing the *F*–test results, one of the following will be concluded:

- The two sets of data have different variances because the difference between the two sets of test results is greater than is likely to occur from chance if their variances are actually equal.
- There is no reason to believe the variances are different because the difference is not so great as to be unlikely to have occurred from chance if the variances are actually equal.

Steps Involved in the *F*–test

The first step is to compute the variance for the contractor's tests, s_c^2, and the agency's tests, s_a^2. Then use the simple ratio equation to compute F, where $F = s_c^2 / s_a^2$ or $F = s_a^2 / s_c^2$. *Always use the larger of the variances in the numerator so the ratio will be greater than 1.*

Next, choose α, the level of significance for the test. For this discussion α = 0.01 is used.

The next step is to determine the critical F value, F_{crit}, from the *F*–table (see table 35 at the end of this appendix) for the α level of significance chosen, and using the degrees of freedom $(n - 1)$ associated with each set of test results. Thus, the degrees of freedom associated with the contractor's variance, s_c^2, is $(n_c - 1)$ and the degrees of freedom associated with the agency's variance, s_a^2, is $(n_a - 1)$. The values in this *F*–table are tabulated to test if there is a difference (either larger or smaller) between the two variance estimates. This is known as a two–sided or two–tailed test. Care must be taken when using other tables of the *F*–distribution, since they are usually based on a one–tailed test, i.e., testing whether one variance is larger than another is. This means that the F_{crit} values in table 35 are the same values that would be listed at the 99.5 percentile (even though the 99.0 percentile would normally be associated with α = 0.01) for a one–sided test.

Once the value for F_{crit} is determined from the table (making sure the appropriate degrees of freedom for the numerator and denominator are used), if $F \geq F_{crit}$, then decide that the two sets of tests have significantly different variabilities. If $F < F_{crit}$ then decide that there is no reason to believe that the variabilities are significantly different.

F–test Example Problem 1

A contractor has run 12 asphalt content tests and the agency has run 6 tests over the same period of time using the same sampling and testing procedure. The results are shown below. Based on their variabilities, is it likely that the tests came from the same population?

Table 33. Asphalt Content Tests

Contractor Tests	Agency Tests
6.41	5.42
6.23	5.78
6.08	6.23
6.55	5.38
6.11	5.62
5.97	5.79
6.28	—
6.07	—
5.92	—
5.76	—
6.06	—
5.71	—
$\overline{X} = 6.10$	$\overline{X} = 5.70$
$s_c^2 = 0.061$	$s_c^2 = 0.097$

Use the F–test to determine whether or not to assume the variance of the contractor's tests differs from the variance of the agency's tests.

Step 1. Compute the variance, s^2, for each set of tests.

$$s_c^2 = 0.061 \qquad s_a^2 = 0.097 \qquad (44, 45)$$

Step 2. Compute F:

$$F = \frac{s_a^2}{s_c^2} = \frac{0.097}{0.061} = 1.59 \qquad (46)$$

Step 3. Determine F_{crit} from the F–distribution table making sure to use the correct degrees of freedom for the numerator ($n_a - 1 = 6 - 1 = 5$) and the denominator ($n_c - 1 = 12 - 1 = 11$). From table 35, $F_{crit} = 6.42$.

Conclusion: Since $F < F_{crit}$ (i.e., $1.59 < 6.42$), there is no reason to believe that the two sets of data have different variabilities. That is, they could have come from the same population.

F–test Example Problem 2

A contractor has run 10 air void tests from cores and the agency has run 5 air void tests over the same period of time using the same sampling and testing procedure. The results are shown below. Based on their variabilities, is it likely that the tests came from the same population?

Table 34. Air Void Tests

Contractor Tests	Agency Tests
6.42	7.52
7.18	11.38
5.04	9.20
4.56	5.32
7.12	3.18
7.98	—
6.32	—
6.08	—
5.92	—
5.78	—
$\overline{X} = 6.24$	$\overline{X} = 7.32$
$s_c^2 = 1.036$	$s_c^2 = 10.299$

Step 1. Compute the variance, s^2, for each set of tests.

$$s_c^2 = 1.036 \qquad s_a^2 = 10.299 \qquad (47, 48)$$

Step 2. Compute *F*:

$$F = \frac{s_a^2}{s_c^2} = \frac{10.299}{1.036} = 9.94 \qquad (49)$$

Step 3. Determine F_{crit} from the *F*–distribution table making sure to use the correct degrees of freedom for the numerator ($n_a - 1 = 5 - 1 = 4$) and the denominator ($n_c - 1 = 10 - 1 = 9$). From table 35, $F_{crit} = 7.96$.

Conclusion: Since $F > F_{crit}$ (i.e., $9.94 > 7.96$), it is unlikely that the two data sets came from the same population. Therefore, conclude that the contractor and agency results are different.

t–test for Sample Means

Once the variances have been tested and assumed to be either equal or not equal, the means of the test results can be tested to determine whether they differ from one another or can be assumed to be equal. The desire is to determine whether it is reasonable to assume that the contractor's tests came from the same population as the agency's tests. A ***t*–test** is used to **compare the sample means**. Two approaches for the *t*–test are necessary. If the sample variances are assumed equal (*F*–test example problem 1 above), then the *t*–test is conducted based on the two samples using a **pooled** estimate for the variance and the **pooled** degrees of freedom. This approach is *t*–test example 1 described below. If the sample variances are assumed to be different (*F*–test example problem 2 above), then the *t*–test is conducted using the individual sample variances, the individual sample sizes, and the **effective** degrees of freedom (estimated from the sample variances and sample sizes). This approach is *t*–test example 2 below.

In either of the two cases discussed in the previous paragraph, one of the following decisions is made:

- The two sets of data have different means because the difference in the sample means is greater than is likely to occur from chance if their means are actually equal.
- There is no reason to believe that the means are different because the difference in the sample means is not so great as to be unlikely to have occurred from chance if the means are actually equal.

Conceptually, for the *t*–test in which the **sample variances are equal**, the equation used to calculate the *t*–value divides the difference between two means by the pooled standard deviation. The pooled standard deviation is the square root of the pooled variance that is the weighted average of the two variances, using the degrees of freedom for each sample as the weighting factor. (Again, conceptually, this is similar to the *Z*–equation in which the difference between the mean and a point of interest is expressed in standard deviation units. But because small sample sizes are used, the *t*–distribution is used.)

To determine the critical *t* value, t_{crit}, against which the computed *t*–value is compared, it is necessary to select the level of significance, α. Again, a value of $\alpha = 0.01$ is recommended. Next, the critical *t*–value, t_{crit}, is obtained from the *t*–table (see table 36 at the end of this appendix) for the pooled degrees of freedom. The pooled degrees of freedom for the case where the sample variances are assumed equal are $(n_c + n_a - 2)$. If $t \geq t_{crit}$, then decide that the two sets of tests have significantly different means. If $t < t_{crit}$, then decide that there is no reason to believe the means are significantly different.

t–test Example Problem 1: Sample Variances Assumed to Be Equal.

Use *F*–test example problem 1 above in which a contractor has run 12 asphalt content tests and the agency has run 6 tests over the same period of time using the same sampling and testing procedures. Based on their means, is it likely that the tests came from the same population?

Use the *t*–test for the case of equal variances (determined above in *F*–test example problem 1) to determine whether or not to assume the mean of the contractor's tests differs from the mean of the agency's tests.

In *F*–test example problem 1, it was determined that $s_c^2 = 0.061$ and $s_a^2 = 0.097$.

Step 1. Compute the sample mean, $\overline{X}$, for each set of tests.

$$\overline{X}_c = 6.10 \qquad \overline{X}_a = 5.70 \qquad (50, 51)$$

Step 2. Compute the pooled variance, s_p^2, using the sample variances from above.

$$s_p^2 = \frac{s_c^2(n_c - 1) + s_a^2(n_a - 1)}{n_c + n_a - 2} \qquad (52)$$

$$s_p^2 = \frac{0.061(12-1) + 0.097(6-1)}{12+6-2} = 0.072$$

Step 3. Compute the t–statistic, t, using the equation for equal variances.

$$t = \frac{\left|\overline{X}_c - \overline{X}_a\right|}{\sqrt{\frac{s_p^2}{n_c} + \frac{s_p^2}{n_a}}} \qquad (53)$$

$$t = \frac{|6.10 - 5.70|}{\sqrt{\frac{0.072}{12} + \frac{0.072}{6}}} = 2.981$$

Step 4. Determine the critical t value, t_{crit}, for the pooled degrees of freedom.

Degrees of freedom = $(n_c + n_a - 2) = (12 + 6 - 2) = 16$.

From table 36, for $\alpha = 0.01$ and 16 degrees of freedom, $t_{crit} = 2.921$.

Conclusion: Since 2.981 > 2.921, we reject the null hypothesis, and assume that the sample means are not equal. We therefore assume that they came from different populations. We therefore conclude that it is unlikely (but not impossible) that the contractor and agency test results represent the same process. In other words, the agency tests do not verify the contractor tests.

t–test Example Problem 2: Sample Variances Assumed to be Different

The *F*–test example problem 2 above in which a contractor has run 10 air void tests from cores and the agency has run 5 tests over the same period of time using the same sampling and testing procedure is used. Based on their means, is it likely that the tests came from the same population?

In *F*–test example problem 2, it was determined that $s_c^2 = 1.036$ and $s_a^2 = 10.299$.

Step 1. Compute the mean, $\overline{X}$, for each set of tests.

$$\overline{X}_c = 6.24 \qquad \overline{X}_a = 7.32 \qquad (54, 55)$$

Step 2. Compute the *t*–statistic, *t*, using the equation for unequal variances.

$$t = \frac{\left|\overline{X}_c - \overline{X}_a\right|}{\sqrt{\frac{s_c^2}{n_c} + \frac{s_a^2}{n_a}}} \qquad (56)$$

$$t = \frac{\left|6.24 - 7.32\right|}{\sqrt{\frac{1.036}{10} + \frac{10.299}{5}}} = 0.734$$

Step 3. Determine the critical *t* value, t_{crit}, for the effective degrees of freedom, f'.

$$f' = \frac{\left(\frac{s_c^2}{n_c} + \frac{s_a^2}{n_a}\right)^2}{\left[\frac{\left(\frac{s_c^2}{n_c}\right)^2}{n_c + 1} + \frac{\left(\frac{s_a^2}{n_a}\right)^2}{n_a + 1}\right]} - 2 \qquad (57)$$

$$f' = \frac{\left(\frac{1.036}{10} + \frac{10.299}{5}\right)^2}{\left[\frac{\left(\frac{1.036}{10}\right)^2}{10 + 1} + \frac{\left(\frac{10.299}{5}\right)^2}{5 + 1}\right]} - 2 = 4.61 \rightarrow 5$$

The calculated value for effective degrees of freedom is rounded to the closest integer in this example. The critical value could also be obtained by interpolation or by truncating to the lowest integer. This equation is an approximation and there is not a universally accepted method for arriving at the effective degrees of freedom. In general, rounding to a smaller value for degrees of freedom gives a larger critical value, thereby making it less likely to reject the null hypothesis of equal means.

Note that the value for effective degrees of freedom is less than would have been used if the variances had been assumed to be equal.

From the *t*–table, table 36, for $\alpha = 0.01$ and 5 degrees of freedom, $t_{crit} = 4.032$.

Conclusion: Since 0.734 < 4.032, there is no reason to reject the assumption that the means are equal. Therefore, we assume that it is possible (but not certain) that they came from the same population.

Note: The difference in sample means is much greater in this example (7.32 – 6.24 = 1.08) than in the previous example (6.10 – 5.70 = 0.40). However, in the previous example it was concluded that the means were different, while in this example it was not concluded that the means were different. The larger ratio of variance values in this example is the reason that it was not possible to conclude that the means were different.

Computer Programs for the *F*–test and *t*–test Calculations

As can be seen from the example problems, the required computations can be quite complex and time consuming. This introduces the possibility of human error.

Using Microsoft Excel.

As noted above, spreadsheet programs such as Microsoft Excel often have built–in functions for conducting both *F*–tests and *t*–tests. These tests can be performed by anyone with a basic knowledge regarding how to use spreadsheet functions. Excel has a function for conducting *F*–tests. Excel can also conduct paired *t*–tests, as well as two–sample *t*–tests for the cases of both equal and unequal variances.

To illustrate the use of spreadsheets for conducting *F*–tests and *t*–tests, Excel was used to compare the data sets used in Example Problem 1 above. The following paragraphs show the steps necessary in using Excel for these calculations.

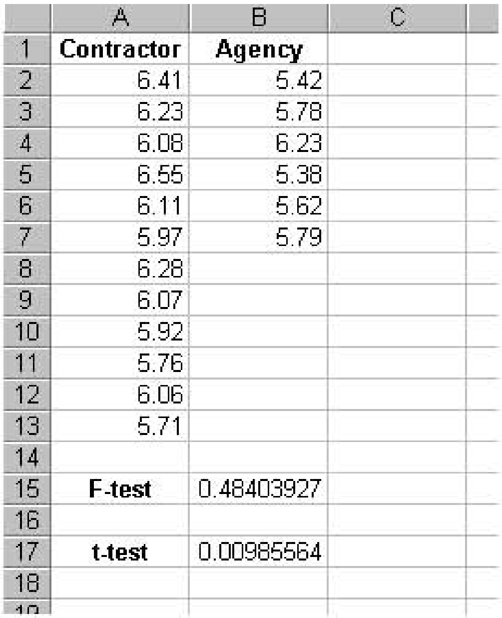
The first step is to input the contractor and agency data into two different columns in Excel. The data for this example are shown in figure 48.

The *F*–test is then conducted before the *t*–test. This is done by using the Excel function

FTEST(array1,array2)

where: array1 is the array representing one set of data
array2 is the array representing the other set of data.

For the example in figure 48, the contractor data are in array1, and it is input as A2:A13, while the agency data are in array2 and it is input as B2:B7. The function that is entered into cell B15 is therefore =FTEST(A2:A13,B2:B7).



	A	B	C
1	**Contractor**	**Agency**	
2	6.41	5.42	
3	6.23	5.78	
4	6.08	6.23	
5	6.55	5.38	
6	6.11	5.62	
7	5.97	5.79	
8	6.28		
9	6.07		
10	5.92		
11	5.76		
12	6.06		
13	5.71		
14			
15	**F-test**	0.48403927	
16			
17	**t-test**	0.00985564	
18			

Figure 48. Excel Results for Data from Example Problem 1

The test that is conducted by Excel is a one sided *F* test. The value that is displayed in cell B15 is the probability of getting an *F* value as large as the one for these data sets if the two data sets have the same variance. In other words, the lower the probability value returned by this function, the less likely it is that the two sets of data have the same variance. For example, if the level of significance for the test were selected as 0.05, for a one tailed test you would reject the assumption of equal variances whenever the probability value that is returned by the function is less than 0.05.

To compare the results of function FTEST with the critical values in table 35, which is based on a two sided *F* test and $\alpha - 0.01$ therefore, you would reject the assumption of equal variances whenever the Excel FTEST function returned a probability value less than 0.005. Figure 48 shows that for the example data a probability value of 0.484 is returned by the FTEST function. Therefore, the conclusion would be to assume that the variances are equal.

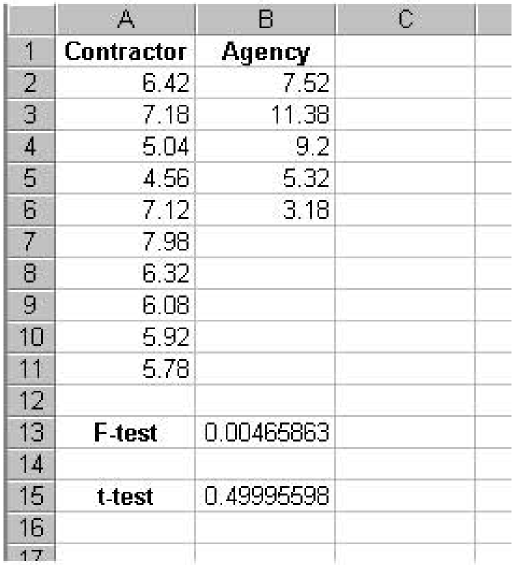
Once the results of the *F* test are known, the *t* test can then be conducted using the Excel function

TTEST(array1,array2,tails,type)

Where: array1 is the array representing one set of data.
array2 is the array representing the other set of data.
tails is either 1 for a one sided test or 2 for a two sided test.
type is 1 for a paired t test, 2 for an equal variance t test, and 3 for an unequal variance t test.

For the example in figure 48, the contractor data are in array1, and it is input as A2:A13, while the agency data are in array2 and it is input as B2:B7. Since a two tailed is desired, tails is input as 2, and, since from the F test the variances were assumed to be equal, type is input as 2. The function that is entered into cell B17 is therefore −TTEST(A2:A13,B2:B7,2,2). Figure 48 shows that for the example data a probability value of 0.00986 is returned by the TTEST function. Therefore, at the α − 0.01 level of significance, the conclusion would be to assume that the means are not equal since the probability value is less than 0.01.

Similarly, Excel can be used to perform the F test and t test on the data sets from Example Problem 2 above. This is illustrated in figure 49.



	A	B	C
1	**Contractor**	**Agency**	
2	6.42	7.52	
3	7.18	11.38	
4	5.04	9.2	
5	4.56	5.32	
6	7.12	3.18	
7	7.98		
8	6.32		
9	6.08		
10	5.92		
11	5.78		
12			
13	**F-test**	0.00465863	
14			
15	**t-test**	0.49995598	
16			

Figure 49. Excel Results for Data from Example Problem 2

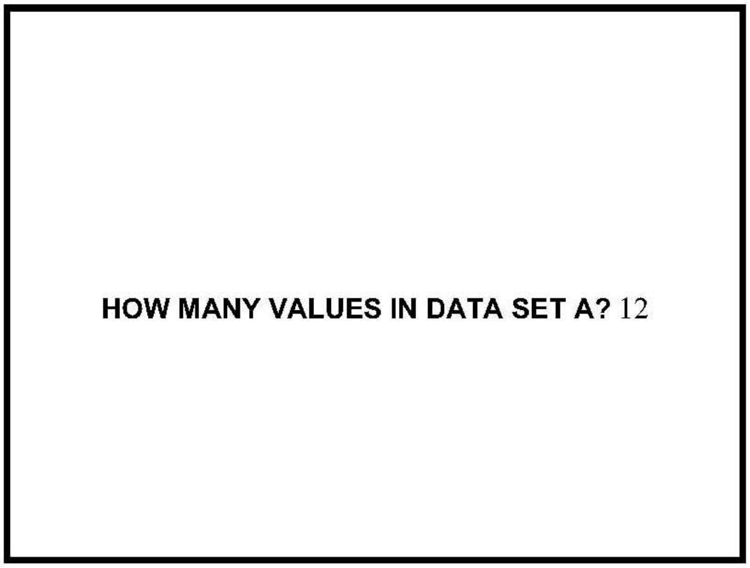
The results in figure 49 (see cell B13) indicate that the variances are assumed to be not equal. This means that the type input for the TTEST function will be 3, for an unequal variance t test. The tails input will still be 2 for a two tailed test. The results in figure 49 (see cell B15) indicate that the means are assumed to be equal since the probability in cell B15 is much greater than the level of significance of α − 0.01.

Using Program DATATEST

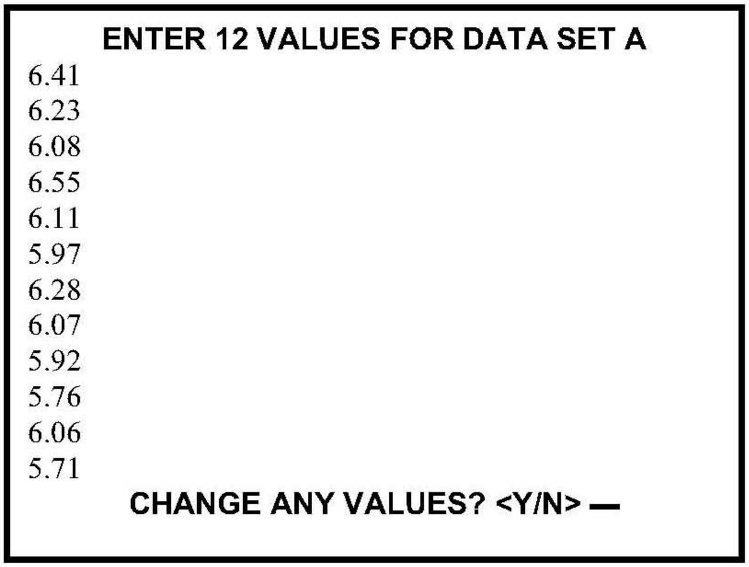
Another software program that can be used for performing F test and t test comparisons is the FHWA Demonstration Project No. 89 program DATATEST.(18) This program demonstrates how simply the F tests and t tests can be performed with a personal computer. To illustrate this, the DATATEST program was used to compare the data sets used in the example problems above. To illustrate the use of the program, the input and output screens for these examples are presented in the figures beginning on the next page.

DATATEST Screens for the Data from Example Problem 1

The program first asks for the number of values and then allows the user to input the values for the first set of data.

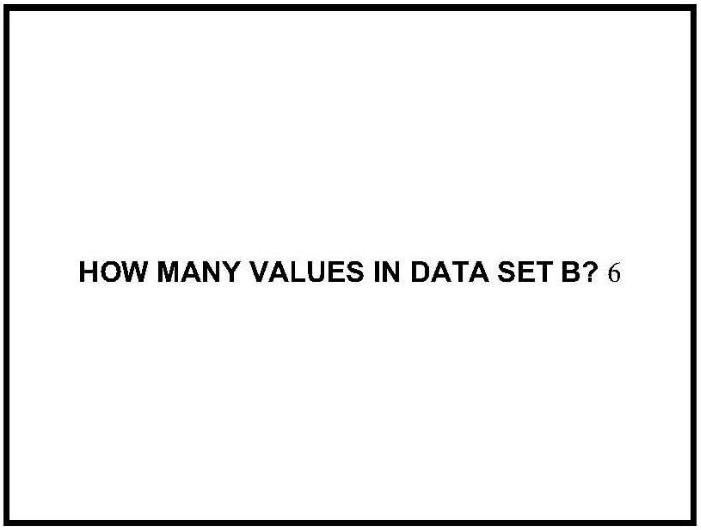


```
HOW MANY VALUES IN DATA SET A? 12
```

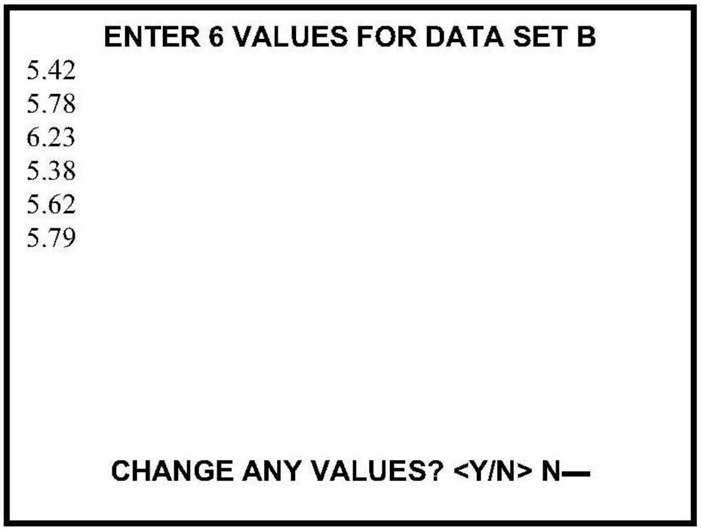


```
ENTER 12 VALUES FOR DATA SET A
6.41
6.23
6.08
6.55
6.11
5.97
6.28
6.07
5.92
5.76
6.06
5.71
CHANGE ANY VALUES? <Y/N> —
```

The program then asks for the number of values and then allows the user to input the values for the second set of data.



```
HOW MANY VALUES IN DATA SET B? 6
```

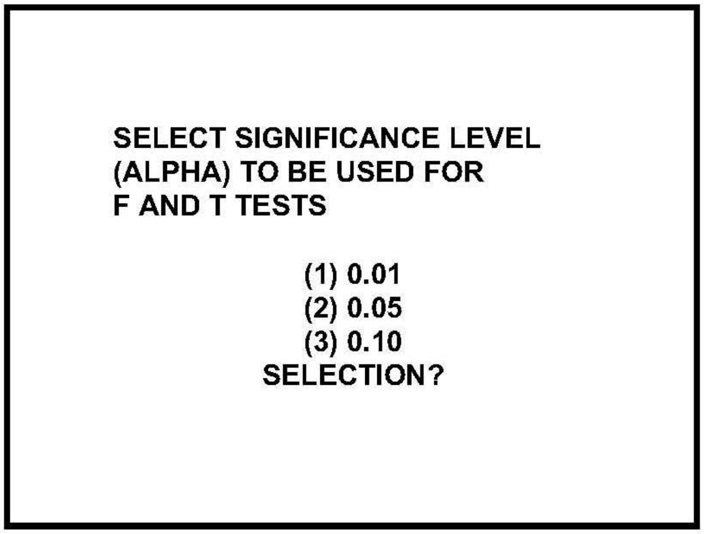


```
        ENTER 6 VALUES FOR DATA SET B
5.42
5.78
6.23
5.38
5.62
5.79




        CHANGE ANY VALUES? <Y/N> N—
```

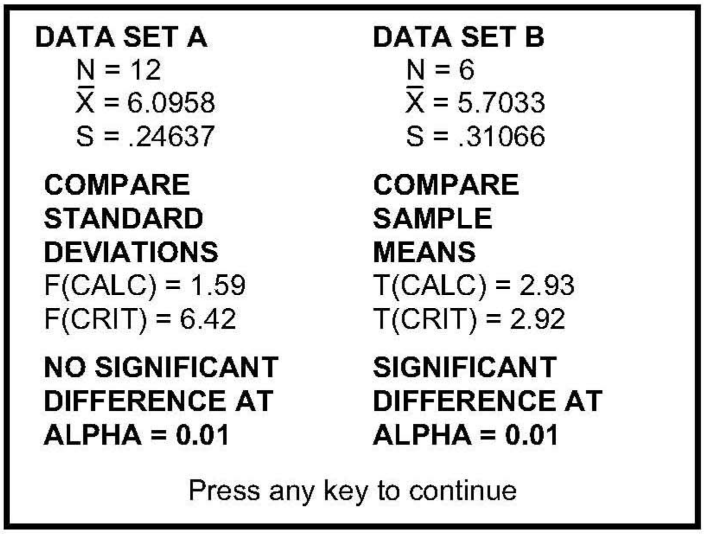
The program then asks the user to select a level of significance, α.



```
SELECT SIGNIFICANCE LEVEL
(ALPHA) TO BE USED FOR
F AND T TESTS

        (1) 0.01
        (2) 0.05
        (3) 0.10
       SELECTION?
```

Finally, the program conducts the *F*–test and then, based on the *F*–test results, the appropriate form of the *t*–test, and displays the results.

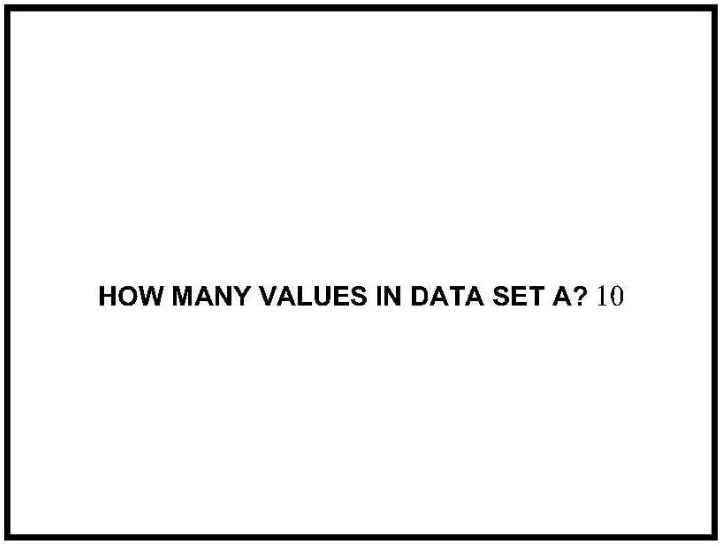


```
DATA SET A              DATA SET B
   N = 12                  N = 6
   X̄ = 6.0958              X̄ = 5.7033
   S = .24637              S = .31066
COMPARE                 COMPARE
STANDARD                SAMPLE
DEVIATIONS              MEANS
F(CALC) = 1.59          T(CALC) = 2.93
F(CRIT) = 6.42          T(CRIT) = 2.92
NO SIGNIFICANT          SIGNIFICANT
DIFFERENCE AT           DIFFERENCE AT
ALPHA = 0.01            ALPHA = 0.01
          Press any key to continue
```

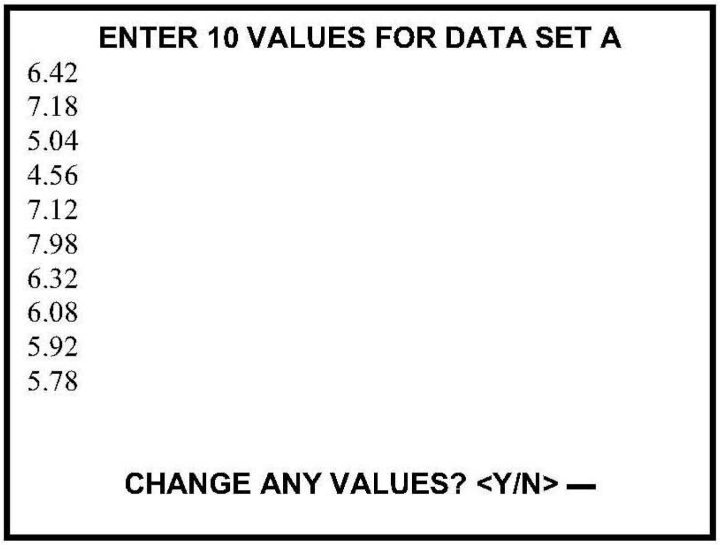
The values obtained by the DATATEST program are consistent with those calculated in Example Problem 1 above. The slight difference in the calculated *t*– value stems from the number of decimal places that are used in the computer's calculation. The results from the DATATEST program, i.e., the variances not assumed different and the means assumed different, are consistent with those from Example Problem 1.

DATATEST Screens for the Data from Example Problem 2

The program first asks for the number of values and then allows the user to input the values for the first set of data.



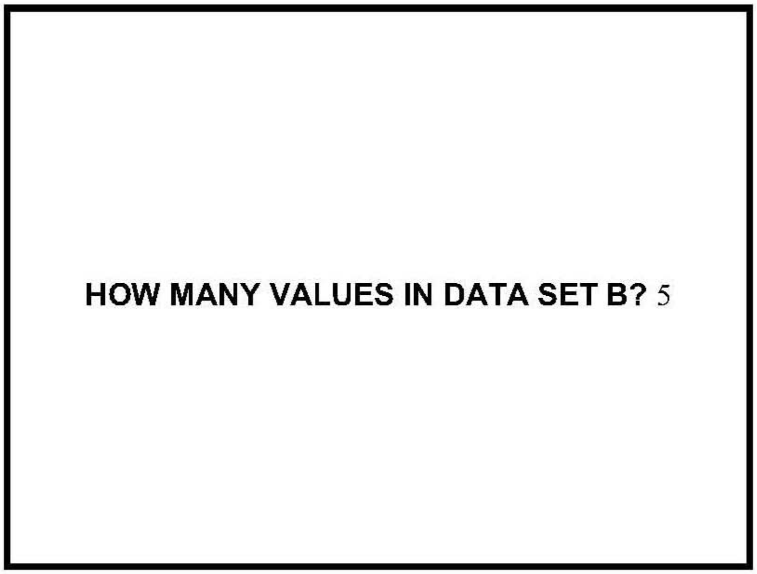
```
HOW MANY VALUES IN DATA SET A? 10
```



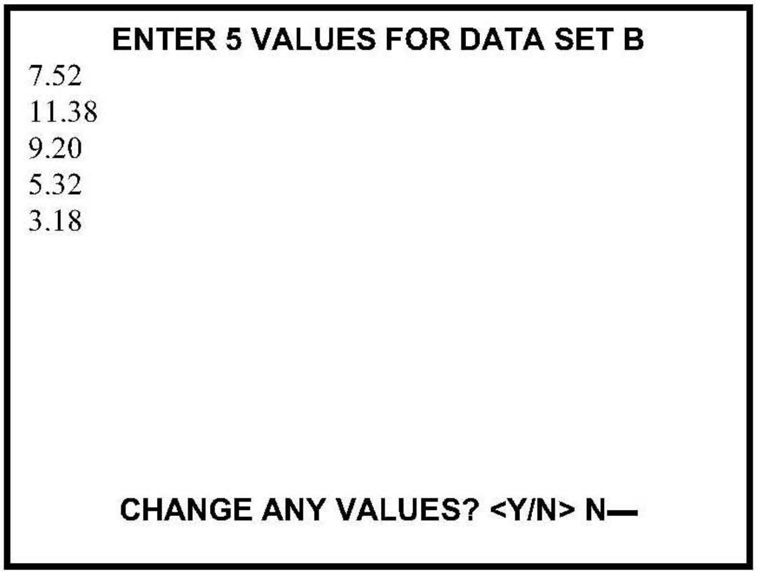
```
ENTER 10 VALUES FOR DATA SET A
6.42
7.18
5.04
4.56
7.12
7.98
6.32
6.08
5.92
5.78

CHANGE ANY VALUES? <Y/N> —
```

The program then asks for the number of values and then allows the user to input the values for the second set of data.



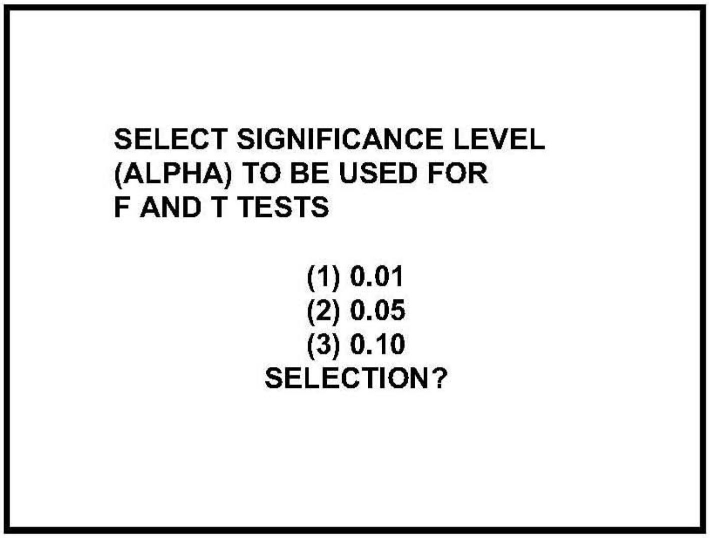
```
HOW MANY VALUES IN DATA SET B? 5
```



```
ENTER 5 VALUES FOR DATA SET B
7.52
11.38
9.20
5.32
3.18

CHANGE ANY VALUES? <Y/N> N—
```

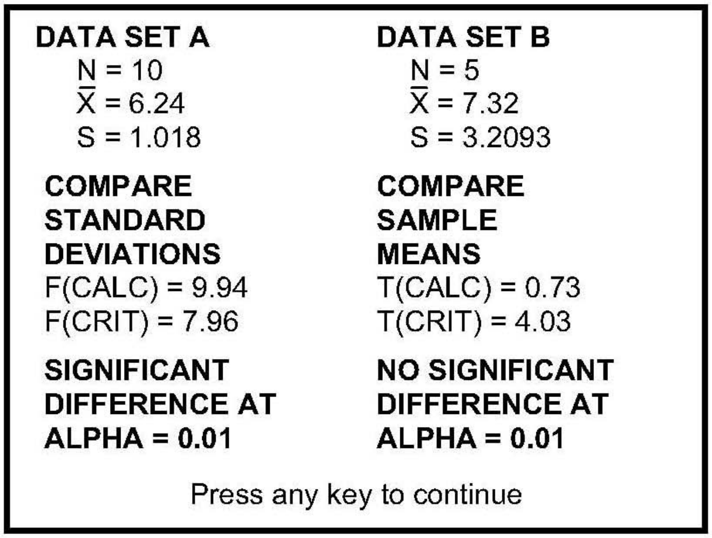
The program then asks the user to select a level of significance, α.



```
SELECT SIGNIFICANCE LEVEL
(ALPHA) TO BE USED FOR
F AND T TESTS

            (1) 0.01
            (2) 0.05
            (3) 0.10
          SELECTION?
```

Finally, the program conducts the *F*–test and then, based on the *F*–test results, the appropriate form of the *t*–test, and displays the results.



```
DATA SET A                 DATA SET B
   N = 10                     N = 5
   X̄ = 6.24                   X̄ = 7.32
   S = 1.018                  S = 3.2093

 COMPARE                   COMPARE
 STANDARD                  SAMPLE
 DEVIATIONS                MEANS
 F(CALC) = 9.94            T(CALC) = 0.73
 F(CRIT) = 7.96            T(CRIT) = 4.03

 SIGNIFICANT               NO SIGNIFICANT
 DIFFERENCE AT             DIFFERENCE AT
 ALPHA = 0.01              ALPHA = 0.01

          Press any key to continue
```

The values obtained by the DATATEST program are consistent with those calculated in Example Problem 2 above. The results from the DATATEST program, i.e., the variances assumed different and the means not assumed different, are consistent with those from Example Problem 2.

Table 35. Critical Values, F_{crit}, for the F–test for a Level of Significance, $\alpha = 0.01$[1]

DEGREES OF FREEDOM FOR NUMERATOR

DEGREES OF FREEDOM FOR DENOMINATOR

	1	2	3	4	5	6	7	8	9	10	11	12
1	16200	20000	21600	22500	23100	23400	23700	23900	24100	24200	24300	24400
2	198	199	199	199	199	199	199	199	199	199	199	199
3	55.6	49.8	47.5	46.2	45.4	44.8	44.4	44.1	43.9	43.7	43.5	43.4
4	31.3	26.3	24.3	23.2	22.5	22.0	21.6	21.4	21.1	21.0	20.8	20.7
5	22.8	18.3	16.5	15.6	14.9	14.5	14.2	14.0	13.8	13.6	13.5	13.4
6	18.6	14.5	12.9	12.0	11.5	11.1	10.8	10.6	10.4	10.2	10.1	10.0
7	16.2	12.4	10.9	10.0	9.52	9.16	8.89	8.68	8.51	8.38	8.27	8.18
8	14.7	11.0	9.60	8.81	8.30	7.95	7.69	7.50	7.34	7.21	7.10	7.01
9	13.6	10.1	8.72	7.96	7.47	7.13	6.88	6.69	6.54	6.42	6.31	6.23
10	12.8	9.43	8.08	7.34	6.87	6.54	6.30	6.12	5.97	5.85	5.75	5.66
11	12.2	8.91	7.60	6.88	6.42	6.10	5.86	5.68	5.54	5.42	5.32	5.24
12	11.8	8.51	7.23	6.52	6.07	5.76	5.52	5.35	5.20	5.09	4.99	4.91
15	10.8	7.70	6.48	5.80	5.37	5.07	4.85	4.67	4.54	4.42	4.33	4.25
20	9.94	6.99	5.82	5.17	4.76	4.47	4.26	4.09	3.96	3.85	3.76	3.68
24	9.55	6.66	5.52	4.89	4.49	4.20	3.99	3.83	3.69	3.59	3.50	3.42
30	9.18	6.35	5.24	4.62	4.23	3.95	3.74	3.58	3.45	3.34	3.25	3.18
40	8.83	6.07	4.98	4.37	3.99	3.71	3.51	3.35	3.22	3.12	3.03	2.95
60	8.49	5.80	4.73	4.14	3.76	3.49	3.29	3.13	3.01	2.90	2.82	2.74
120	8.18	5.54	4.50	3.92	3.55	3.28	3.09	2.93	2.81	2.71	2.62	2.54
∞	7.88	5.30	4.28	3.72	3.35	3.09	2.90	2.74	2.62	2.52	2.43	2.36

---

[1] **NOTE:** This is for a **two-tailed test** with the null and alternate hypotheses shown below:

$$H_0\colon s_c^2 = s_a^2$$
$$H_a\colon s_c^2 \neq s_a^2$$

Table 35. Critical Values, F_{crit}, for the F–test for a Level of Significance, α = 0.01[1] *(continued)*

DEGREES OF FREEDOM FOR NUMERATOR

DEGREES OF FREEDOM FOR DENOMINATOR

	15	**20**	**24**	**30**	**40**	**50**	**60**	**100**	**120**	**200**	**500**	**∞**
1	24600	24800	24900	25000	25100	25200	25300	25300	25400	25400	25400	25500
2	199	199	199	199	199	199	199	199	199	199	199	200
3	43.1	42.8	42.6	42.5	42.3	42.2	42.1	42.0	42.0	41.9	41.9	41.8
4	20.4	20.2	20.0	19.9	19.8	19.7	19.6	19.5	19.5	19.4	19.4	19.3
5	13.1	12.9	12.8	12.7	12.5	12.5	12.4	12.3	12.3	12.2	12.2	12.1
6	9.81	9.59	9.47	9.36	9.24	9.17	9.12	9.03	9.00	8.95	8.91	8.88
7	7.97	7.75	7.65	7.53	7.42	7.35	7.31	7.22	7.19	7.15	7.10	7.08
8	6.81	6.61	6.50	6.40	6.29	6.22	6.18	6.09	6.06	6.02	5.98	5.95
9	6.03	5.83	5.73	5.62	5.52	5.45	5.41	5.32	5.30	5.26	5.21	5.19
10	5.47	5.27	5.17	5.07	4.97	4.90	4.86	4.77	4.75	4.71	4.67	4.64
11	5.05	4.86	4.76	4.65	4.55	4.49	4.45	4.36	4.34	4.29	4.25	4.23
12	4.72	4.53	4.43	4.33	4.23	4.17	4.12	4.04	4.01	3.97	3.93	3.90
15	4.07	3.88	3.79	3.69	3.59	3.52	3.48	3.39	3.37	3.33	3.29	3.26
20	3.50	3.32	3.22	3.12	3.02	2.96	2.92	2.83	2.81	2.76	2.72	2.69
24	3.25	3.06	2.97	2.87	2.77	2.70	2.66	2.57	2.55	2.50	2.46	2.43
30	3.01	2.82	2.73	2.63	2.52	2.46	2.42	2.32	2.30	2.25	2.21	2.18
40	2.78	2.60	2.50	2.40	2.30	2.23	2.18	2.09	2.06	2.01	1.96	1.93
60	2.57	2.39	2.29	2.19	2.08	2.01	1.96	1.86	1.83	1.78	1.73	1.69
120	2.37	2.19	2.09	1.98	1.87	1.80	1.75	1.64	1.61	1.54	1.48	1.43
∞	2.19	2.00	1.90	1.79	1.67	1.59	1.53	1.40	1.36	1.28	1.17	1.00

[1] **NOTE:** This is for a **two-tailed test** with the null and alternate hypotheses shown below:

$$H_0\colon s_c^2 = s_a^2$$
$$H_a\colon s_c^2 \neq s_a^2$$

Table 36. Critical Values, t_{crit}, for the t–test [1]

Degrees of Freedom	$\alpha = 0.01$	$\alpha = 0.05$	$\alpha = 0.10$
1	63.657	12.706	6.314
2	9.925	4.303	2.920
3	5.841	3.182	2.353
4	4.604	2.776	2.132
5	4.032	2.571	2.015
6	3.707	2.447	1.943
7	3.499	2.365	1.895
8	3.355	2.306	1.860
9	3.250	2.262	1.833
10	3.169	2.228	1.812
11	3.106	2.201	1.796
12	3.055	2.179	1.782
13	3.012	2.160	1.771
14	2.977	2.145	1.761
15	2.947	2.131	1.753
16	2.921	2.120	1.746
17	2.898	2.110	1.740
18	2.878	2.101	1.734
19	2.861	2.093	1.729
20	2.845	2.086	1.725
21	2.831	2.080	1.721
22	2.819	2.074	1.717
23	2.807	2.069	1.714
24	2.797	2.064	1.711
25	2.787	2.060	1.708
26	2.779	2.056	1.706
27	2.771	2.052	1.703
28	2.763	2.048	1.701
29	2.756	2.045	1.699
30	2.750	2.042	1.697
40	2.704	2.021	1.684
60	2.660	2.000	1.671
120	2.617	1.980	1.658
∞	2.576	1.960	1.645

[1] **NOTE:** This is for a two-tailed test with the null and alternate hypotheses shown below:

$$H_0: \overline{X}_c = \overline{X}_a$$
$$H_a: \overline{X}_c \neq \overline{X}_a$$

- END OF APPENDIX H -