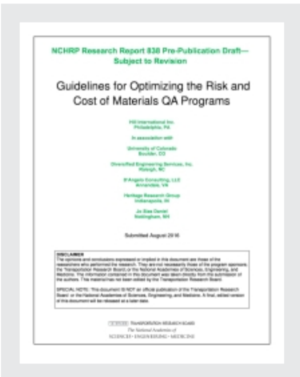
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Guidelines for Optimizing the Risk and Cost of Materials QA Programs

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DETAILS

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ABSTRACT

Materials QA has historically been a critical though resource-intensive component of project delivery for DOTs. Driven by budget and resource constraints, DOTs have begun to investigate ways to more efficiently balance the risk of poor quality against the cost of materials QA. Greater use of alternative project delivery methods that shift more responsibility to industry for managing quality, increased understanding of materials behavior, and innovations in non-destructive testing and related technologies are providing additional motivation for DOTs to revisit any existing QA practices that may be outdated or disproportionate to what is needed to ensure a quality end product. To help DOTs identify and evaluate opportunities to optimize or enhance their materials QA programs, NCHRP Project 10-92 was established with the objective of developing a rational and structured process for identifying the optimal QA investment point. As the product of this research effort, a standalone guidance document, entitled *Guidelines for Optimizing the Risk and Costs of Materials QA Programs*, was developed to present a step-by-step analytical framework that DOTs may apply to efficiently allocate their QA resources on the basis of QA costs and risks related to material nonconformance.

EXECUTIVE SUMMARY

Project Background and Objectives

In response to shrinking budgets and dramatic reductions in both the numbers and experience levels of inspectors and engineers, several state departments of transportation (DOT) are seeking ways to achieve greater efficiencies in quality management, often targeting current practices that may be either disproportionate to what is needed to ensure a quality product (e.g. does a concrete sidewalk warrant the same level of QA as a bridge deck?) or outdated given advances in testing technology (i.e., is there a more efficient or effective way to accept this material?).

The purpose of such inquiry is not to downplay the importance of QA, but to recognize that it is an inherently scalable activity driven by, among other considerations, an organization's tolerance for risk, material/product variability, and cost. A well-designed QA program can provide confidence that the materials and workmanship incorporated into a project will be in reasonably close conformance to the approved plans and specifications. Conversely, an inadequate QA plan can increase the risk of short and long-term failures, possibly leading to reduced design life, increased maintenance costs, service interruptions, and/or safety hazards. Logically, the more comprehensive and robust the QA strategy, the less risk of material failure or nonconformance; however, an overly rigorous QA plan can result in unnecessary project costs – an outcome that most agencies cannot afford in this time of flat or declining resources.

The objective of NCHRP Project 10-92 was to therefore develop a methodology to help DOTs identify and evaluate opportunities to optimize or enhance their materials QA practices to achieve a better balance between efficiency and risk reduction. For example, modifications or enhancements to an existing QA strategy might entail adopting a less rigorous plan (e.g., fewer tests, use of verified contractor test data for acceptance purposes, and/or greater reliance on certification or inspection) to achieve the same result, or incorporating more advanced, performance-oriented acceptance tests – even if at a higher cost – if such practices improve durability, reduce the risk of failure, or enhance performance.

Research Approach and Key Findings

To develop this methodology, the research team assessed the current state of practice of materials QA by performing a thorough review of relevant research, regulatory requirements, guidance manuals, and other appropriate material on QA and risk management as they relate to transportation construction projects.

This literature review effort was supplemented by an industry survey of 37 state Departments of Transportation (DOT) and individual interviews conducted with 8 DOTs. Key findings from the literature and data collection efforts include the following:

- Current material QA practices vary widely among DOTs, and what is acceptable for one DOT may not be for another. QA practices are also evolving, particularly with regard to increased use of alternative project delivery methods that shift more responsibility to industry for managing quality, and with advances in general understanding of materials/product behavior and use of more performance-based quality measures and non-destructive testing technologies that provide for continuous sampling and data collection. To appeal to a national audience of DOTs, the optimization model must be sufficiently flexible and robust to accommodate the range of materials and acceptance practices in use today as well as any new products or practices that may emerge in the future. The goal of the model is not to prescribe quality management solutions but to create a flexible framework that DOTs may customize or tailor to suit their own programs and projects.

- Several DOTs currently optimize their materials QA practices to some extent, particularly for acceptance, by modifying their standard sampling and testing schedule to reflect different tiers or levels of effort based on material criticality, quantities, type/size of project, project delivery method, and similar factors. There were no noteworthy differences in the types of optimization strategies used that could be correlated to a DOT's size, geographic location, or other factors, suggesting that these strategies could be universally applied.

- Some DOTs have developed processes to incorporate risk considerations in their materials QA practices. This is essentially an extension of DOT efforts to tier materials QA based on the criticality of materials by applying a more formal framework for risk rating materials. Although these processes are largely qualitative in nature, they suggest that a solid foundation exists for developing and implementing a more in-depth process for optimizing the costs and risks of materials QA, as contemplated under this research project.

- Although there are abundant examples of QA optimization models in the literature, related research studies suggest that real world application of quality cost calculations is not common, largely due to difficulties in identifying and tracking actual costs of quality (i.e., costs of prevention, appraisal, and failure).

Research Product

Based on the findings summarized above, the research team developed a flexible methodology, as described in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs*, for identifying an appropriate QA investment point for materials incorporated into transportation construction projects based on an analysis of risks and costs.

As QA practices vary widely among DOTs, the goal of the Guidelines is not to prescribe quality management solutions but to instead provide a flexible analytical framework that can be applied to the range of materials acceptance practices in use today, as well as to any new products or practices that may emerge in the future. Recognizing the difficulty that some users may encounter in identifying and measuring the costs of quality, a three-level optimization framework was developed that allows for both qualitative and quantitative evaluation options.

The anticipated benefits of Guidelines include:

- Enhanced understanding of the cost and value of materials QA,

- More efficient allocation of QA resources, and

- Better alignment between project risk profile, delivery method, and QA practices to help agencies deliver a quality project for the lowest overall cost.

CHAPTER 1 – INTRODUCTION

In response to shrinking budgets and dramatic reductions in both the numbers and experience levels of inspectors and engineers, several state Departments of Transportation (DOTs) are seeking ways to improve and optimize their processes to achieve greater efficiencies in resource allocation and project and program delivery. A burgeoning area for process improvement is materials quality assurance (QA) – a critical, though resource-intensive, component of project delivery.

The importance of materials QA is without question. Materials represent 50% of Federal-aid construction dollars (FHWA 2013). A well-designed QA program can provide confidence that the materials and workmanship incorporated into a project will be in reasonably close conformity to the approved plans and specifications. Conversely, an inadequate QA plan can increase the risk of short and long-term failures, leading to reduced design life, increased maintenance costs, and possibly safety concerns. Logically, the more comprehensive and robust the QA strategy, the less risk; however, an overly rigorous QA plan can result in unnecessary project costs – an outcome that agencies cannot afford in this time of flat or declining resources. This dilemma raises the following research questions:

- What are the risks and efficiencies of resource allocations associated with materials QA practices?

- How can DOTs effectively balance the risk and cost of materials QA to achieve the optimal investment point for quality management?

Background

Title 23, Code of Federal Regulations, Part 637 (23 CFR 637), requires each DOT to develop and implement a QA program designed to assure that the materials and workmanship incorporated into Federal-aid highway construction projects on the National Highway System (NHS) conform to the requirements of the approved plans and specifications. Various documents, including FHWA HRT-12-039, further describe a comprehensive QA program as consisting of the following six core elements:

1. Contractor quality control,
2. Agency acceptance,
3. Independent assurance,
4. Laboratory accreditation/qualification,
5. Personnel qualification/certification, and
6. Dispute resolution (if contractor test results are to be used in the acceptance decision).

Apart from sharing these fundamental components, material QA practices vary widely among the DOTs. What constitutes an appropriate acceptance method (or for that matter, an acceptable product) for one DOT may not be acceptable to another.

A DOT's materials QA practices tend to be based on methods that have historically produced satisfactory results. These legacy practices, however, may fail to take advantage of more recent developments in the form of increased understanding of materials behavior, advances in non-destructive testing technology, and increasing use of performance specifications and alternative project delivery methods that shift more responsibility for quality management to industry.

Recognizing that current practices may be outdated or disproportionate to what is needed to ensure a quality product, some DOTs have begun to modify their QA practices to reflect a better balance between efficiency and risk reduction. One approach that has been gaining popularity, along with the rise of statistically-based specifications and alternative delivery methods, entails the use of contractor quality control (QC) test results in the agency's acceptance decision. 23 CFR 637 was redrafted in 1995 to allow contractor test results to be used in acceptance decisions with the requirement that the DOTs conduct verification and independent assurance (IA) testing to validate the QC data. By including validated QC data in the acceptance decision, the frequency of testing by the DOT (or its designated agent) may be reduced. According to a FHWA program evaluation report (FHWA 2013), more than 31 DOTs use contractor test results in acceptance decisions.

Other optimization strategies include adopting a less rigorous materials QA plan, a more advanced protocol at higher cost, or using different acceptance properties that are more indicative of performance. The determination of what is appropriate for a particular material or project is often driven by factors such as material criticality, quantities, and type/size of project.

Research Scope and Objectives

In general, the optimization efforts discussed above are often largely qualitative and informal in practice, with much discretion left to project engineers to modify rates or protocols based on engineering judgment. However, regardless of the level of rigor applied to current QA decision-making, the use of such optimization strategies suggests that a strong foundation and knowledge base exists for developing and implementing a more rational and structured process for optimizing the costs and risks of materials QA.

To this end, NCHRP Project 10-92 was established to develop a practical methodology that could be consistently applied to optimize the materials QA cost or acceptance plan necessary to meet specification requirements within an acceptable level of risk. To achieve this objective, the research approach consisted of two phases, as summarized below.

Phase 1

The Phase I research effort involved a comprehensive literature review to capture the current status of materials QA. The primary objectives of the literature review were to:

- Identify and collect documents that addressed the current state of materials QA, considering practices used both inside and outside the U.S. highway construction industry
- Benchmark current procedures and document variations in QA and levels of acceptance
- Identify mature or advanced risk-based practices that could support the development of an optimization model in Phase 2

Complete details regarding the approach taken to this literature review, as well as a summary and critique of the key documents collected, are provided in Chapter 2 of this report.

To supplement the information collected through the literature review, the research team employed two additional data collection techniques: a national web-based survey of state DOTs and individual interviews with eight DOTs.

The objectives of the survey were to:

- Identify trends related to materials QA
- Identify different ways DOTs identify, assess, and mitigate quality-related risk
- Obtain general data related to QA costs and probability of failure (non-conformance)
- Assess state DOT materials management systems
- Identify possible candidates for subsequent in-depth interviews
- Identify what additional information would have to be collected through the interviews

Survey responses were received from 37 DOTs. More information on the survey respondents and results can be found in Chapter 3, *Survey*.

To capture a deeper level of insight than could be obtained through a simple online questionnaire, the team also conducted a series of interviews with eight DOTs, selected in part due to their responses to the survey. These agencies included: California DOT, Florida DOT, Ohio DOT, Maryland State Highway Administration, New Jersey DOT, Texas DOT, Virginia DOT, and Washington State DOT.

The interview discussions allowed the research team to expand on trends identified in the literature and survey and to probe for specific data regarding QA risks and costs. More information on the interviews can be found in Chapter 3, *Interviews*.

Phase 2

Building upon the QA practices identified through the literature review and data collection efforts, the team developed a risk-based materials QA optimization framework that balances the costs of implementing a QA strategy against the risk of failure. The methodology is introduced in Chapter 4 of this report and described in detail in standalone document entitled *Guidelines for Optimizing the Risk and Cost of Materials QA Programs.*

Report Organization

As summarized in this introductory chapter, the primary focus of this project was to develop a risk-based materials QA optimization model that balances the costs of implementing a QA strategy against the risk of failure. The remainder of this report is organized into the following chapters:

- Chapter 2 summarizes the literature review that was conducted to establish the state-of-the-practice of materials QA.
- Chapter 3 describes the data collection effort that was performed to support the development of the optimization model.
- Chapter 4 describes the development of the optimization model.
- Chapter 5 presents key findings from this research study, as well as recommendations regarding potential future activities that would help implement or advance the Guidelines.

CHAPTER 2 – LITERATURE REVIEW

The first research task involved a comprehensive literature review to capture the state-of-the-practice of materials QA in the highway construction industry. Complete details regarding the approach taken to this literature review are provided below, followed by a summary and critique of the documents collected.

To supplement this literature review effort, additional data collection efforts, including an industry survey and in-depth interviews, were also performed, as discussed in Chapter 3.

Methodology

Understanding current QA practices is an essential starting point for the development of an optimization model that can be adapted to projects of varying types, size, and complexity. The first goal of the literature review was to therefore synthesize the breadth of methods used for materials QA across the US and to benchmark current procedures. To this end, the research team collected and reviewed construction and materials manuals and related QA documents (e.g., quality assurance program, standard specifications, minimum sampling and testing requirements, materials control and acceptance guides and forms, etc.) from a geographically diverse set of DOTs, including Arizona, Colorado, Florida, Illinois, New Hampshire, Texas, Virginia, Washington, Wisconsin, and Wyoming. Trends and variations in QA practices and acceptance criteria as identified through this review are summarized within the Content Analysis section below.

An additional goal of the literature review was to identify any advanced risk-based practices applied in construction, manufacturing, or other industries to optimize QA. Literature searches were conducted using general internet search engines, academic and research search engines including Google Scholar, research institutions including the Transportation Research Board (TRB), and societies with journal and conference publications. Particular emphasis was placed on obtaining any documents that would support the development of an optimal QA plan for a highway construction project. An annotated bibliography of these select documents is included in Appendix A.

Content Analysis

The literature reviewed by the research team provided a deep pool of reference material related to materials QA. In the context of the project background and objectives for this research project, a number of key reports, contract documents, and internal DOT manuals provided valuable insights into trends, best practices, and limitations associated with materials QA.

Key observations arising from the literature assessment include the following:

- **QA Program Variability.** Title 23, Code of Federal Regulations, Part 637 (23 CFR 637), requires each DOT to develop and implement a QA program designed to assure that the materials and workmanship incorporated into Federal-aid highway construction projects on the National Highway System (NHS) conform to the requirements of the approved plans and specifications. Various documents, including FHWA HRT-12-039, further describe a comprehensive QA program as consisting of the following core elements: quality control, acceptance, independent assurance, dispute resolution, personnel qualification, and laboratory accreditation/qualification.

Apart from sharing these six fundamental components, materials QA practices can vary widely among the state DOTs. What constitutes an appropriate acceptance method for one DOT may not be acceptable to another. For example:

- For fabricated or manufactured materials, such as structural steel and precast concrete, some DOTs base acceptance on testing and inspection conducted at the plant, whereas others are beginning to rely more heavily on certification programs.

- For project-produced materials, such as pavements and earthwork, some DOTs allow adjustments to the standard frequency of sampling and testing based on the quantity of materials, project delivery method, or criticality of materials, whereas others do not.

- **Quality Management and Alternative Project Delivery Methods.** The use of alternative project delivery methods such as design-build tends to expand industry's role in quality management beyond conventional process control activities. For example, it is now quite common, even under a design-bid-build contract, for agencies to include contractor QC test results for *critical quality characteristics* in their acceptance decisions. However, use of this approach still requires independent verification testing by the DOT, or an agent acting on behalf of the DOT (see FHWA-HRT-12-039 Tech Brief).

  Similarly, even if the work is subject to a warranty, some level of agency acceptance is still required (23 CFR 635.413). For projects with short-term warranties, where the warranty will not cover the anticipated life of the warranted product, agencies will generally perform some level of initial acceptance testing at the end of construction, to be followed by routine evaluations and monitoring of performance criteria during the warranty period.

- **Terminology.** The nomenclature used by the DOTs to describe their QA programs and activities is often inconsistent and in conflict with the definitions found in the FHWA QA Manual (FHWA-NHI-08-067) and AASHTO Specification R 38. For example, instead of using the term *quality assurance* as an umbrella term to refer to the overall system for assuring project quality, some agencies continue to revert to the historic use of QC/QA, with QC referring to the Contractor's role and QA only to the agency's role. Terminology can also get confused under design-build contracts that place considerable quality management responsibilities on the design-build firm. Several agencies have adopted the initialism "QA" to refer to quality *acceptance* testing performed by the contractor (or an independent testing firm retained by the design-build firm) that is used in the acceptance decision. To reinforce the appropriate terminology, Appendix B defines the important research terms in a manner that aligns with 23 CFR 637, TRB Circular E-C173 (Glossary of Transportation Construction Quality Assurance Terms, Sixth Edition), and other FHWA and AASHTO guidance documents.

- **QA Optimization Strategies.** DOTs currently "optimize" their materials QA to some extent, particularly for acceptance, by creating levels of acceptance (i.e., sampling and testing, certification, and inspection) based on what is required for each material or product to assure the quality of the end product. Material Certification and the use of approved products (subject to certification or inspection) has resulted in the acceptance of increasing numbers of materials and products by certification, and has allowed for reduced levels of sampling and testing and inspection.

  The rationale for selecting a particular acceptance method (ranging from continuous or statistically-based sampling and testing to certification and inspection) may be based on a number of factors, such as:

  - Material variability and level of control required for materials to meet specifications (e.g. prefabricated products or structural elements are less variable and typically require less field control than pavement materials or soils)

  - Criticality of specific materials or products from the perspective of difficulty to repair or replace, safety, maintenance cost, or cost of rework;

  - Project characteristics, such as type, size, and complexity. (Generally foundation materials, pavements, and structures represent the most critical assets and involve a commensurate investment in materials QA.)

  What was not readily apparent from the literature was the level of rigor used to support this QA decision-making. In general, it appears that optimization efforts may be largely qualitative and informal in practice, with much discretion left to project engineers to modify rates or protocols based on engineering judgment.

- **Risk-Based Optimization.** Some agencies are incorporating or have developed risk management tools to optimize materials QA based on a qualitative risk rating of materials and the alignment of these materials ratings with appropriate levels of materials QA effort to assure acceptable quality.

- **Cost of Quality.** Achieving an optimal balance between the *cost of quality* and the *value of quality* has been a longstanding pursuit of managers and engineers, particularly in manufacturing and production industries. The conceptual foundation for analyzing and optimizing the economics of quality is therefore well established in the literature and could theoretically be adapted to the construction industry. Key inputs would include items such as:

  - Cost to implement different levels of QA (testing, inspection, certification)

  - The probability of a non-conforming material for each level of QA

  - The cost of repairing or replacing non-conforming materials should a defect occur

A more in-depth discussion of such findings follows below.

Materials QA – Current State Analysis

Categories of Materials

To understand the current state of materials QA, it is important to first recognize that materials used in transportation construction can be broadly assigned to one of three categories based on their source and methods of production.

As described in AASHTO R 38, these materials categories are as follows:

- **Project-produced** materials include items that are produced directly for a specific project, often at the project site, and that typically require subsequent mixing, compacting, finishing, curing, or other processes for incorporation into the work. Examples of project-produced materials include earthwork, subbase and base courses, hot mix asphalt, and portland cement concrete.

- **Fabricated** structural materials include structural items produced for a specific project by a material fabricator under what are generally controlled conditions. The properties of fabricated materials are stable and, assuming proper transporting, handling, and storage practices, will not be subject to alteration. Examples include structural steel and precast/prestressed concrete structural elements.

- **Standard manufactured** materials include items that are mass-produced for routine use (i.e., not for a specific project) under highly controlled conditions. Properties of standard manufactured items are highly stable, assuming proper transporting, handling, and storage practices. Examples include binders, paints and coatings, geosynthetics, landscaping items, piping, and traffic control devices.

To a large extent, materials falling within the same category will generally share similar characteristics regarding level of production control and stability of properties, and will thus likely require a similar level of QA to assure product acceptability. For example, for field-produced materials, a high level of testing and inspection is often required or anticipated to control variability or assure performance.

FHWA QA Requirements and Use of Contractor Testing

Federal requirements can also heavily influence a DOT's QA practices, particularly those used for acceptance. Such requirements have undergone some modification over the years in recognition of the increasing role played by industry in assuring materials quality. As contractors began to assume more sampling and testing responsibility (often in connection with statistically-based QA specifications and alternative project delivery methods that placed more performance risk on industry), traditional acceptance testing performed by DOTs became somewhat redundant. FHWA's sampling and testing regulation, "QA Practices for Construction" published at Title 23, Code of Federal Regulations, Part 637 (23 CFR 637) was therefore revised in 1995 to expressly allow use of contractor QC test results in a DOT's acceptance decision provided that:

- The sampling and testing is performed by qualified laboratories, using qualified sampling personnel.

- The DOT, or its designated agent (i.e., consultant under direct contract with the DOT), validates the contractor's test results by performing some level of independent verification sampling and testing. Use of a third-party testing and inspection firm hired by the contractor does not relieve the agency of its responsibility for verification. Likewise, splits of contractor-obtained samples cannot be used for verification purposes.

- The QC sampling and testing is evaluated under an independent assurance (IA) program.

- The DOT has a dispute resolution system in place to resolve possible discrepancies between the contractor's QC and the agency's verification data.

FHWA provided guidance and recommendations related to the use and validation of contractor test results in Technical Advisory T6120.3 (*Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks*) issued on August 9, 2004, and in the Tech Brief entitled *Construction Quality Assurance for Design-Build Highway* Projects (FHWA-HRT-12-039) issued in April 2012.

Additional guidance on the CFR requirements was provided through Federal-aid Policy Guide Non-Regulatory Supplement NS 23 CFR, Part 637B, issued on July 19, 2006, which clarified the following key points:

- Sampling and testing frequencies may vary across the States as material quality and uniformity varies. DOTs have some discretion to adjust testing frequencies for materials with a "history of accurate, uniform test results that consistently meet specification requirements. The rate of testing should be higher on newly developed material sources, sources with questionable quality, sources with a wide range of test results, and sources with failing test results."

- If contractor QC test results are to be used in the acceptance decision, but the DOT and contractor results do not compare, the frequency of the DOT's verification testing should be increased.

- A DOT's acceptance program should not focus solely on testing, but should also provide a reasonable level of inspection to "adequately assess the specific attributes which reflect the quality of the finished product." Inspection should cover component materials at the time of placement or installation as well as the workmanship and quality of the finished product.

- The requirements in 23 CFR 637 were intended to address only *project-produced* materials. The regulation was not meant to cover *manufactured* items. To develop an acceptance program for manufactured items, the supplement encourages the DOTs to perform a risk analysis that considers the use and historical quality of the product, as well as safety and cost.

By including validated QC data in the acceptance decision, the frequency of testing by the DOT may be reduced, allowing for some optimization of agency resources (even if, on the whole, the overall testing effort is not reduced). The agency should perform enough verification sampling and testing to be able to identify statistically valid differences between its results and those of the contractor. [The F-test (comparison of variances) and t-test (comparison of means) are commonly used together to validate contractor test data.] While there is no universally accepted standard, a minimum rate of 10% of the contractor's testing rate has been suggested as a rule of thumb.

FHWA-HRT-12-039 acknowledges that rates of verification may differ based on the risks involved, and offers as an example that structural concrete would likely require more verification testing than embankment materials (FHWA 2012). In the case of small quantities, where the number of contractor tests and agency verification tests is too limited to perform a statistical comparison, the acceptance decision is often based only on the DOT's test data.

Such requirements and guidance regarding agency verification are intended to minimize the risks (e.g. potential fraud, inadequate contractor QA systems, etc.) associated with using contractor test results in the acceptance decision. However, FHWA annual stewardship reviews of DOT QA programs have revealed several deficiencies in DOT verification efforts, suggesting that the required validation processes are not being implemented as envisioned by the regulations. Significant shortcomings noted in the reviews include a lack of independent sampling for verification tests, inadequate statistical comparisons of test results, lack of verification of pavement smoothness data, and insufficient DOT control of test samples, sampling locations, and testing data (FHWA 2007; FHWA 2013). Such program deficiencies suggest that the strategy of using contractor test data, while having the potential to effectively optimize the use of state forces, is not without its own challenges and risks.

DOT Acceptance Methods

FHWA regulations provide the DOTs with rather broad latitude to establish QA practices that suit the needs of their particular programs, as long as these practices include the core elements of quality control, acceptance, independent assurance, dispute resolution, personnel qualification, and laboratory accreditation/qualification. It is therefore not surprising that a review of the materials acceptance practices used by a geographically diverse set of DOTs revealed great variation in the specific methods used to sample, test, inspect, and accept materials. Table 2.1 provides a summary of the state practices reviewed.

Table 2.1: Summary of State Processes Reviewed

Arizona addresses materials acceptance practices in the Standard Specifications, Materials Testing Manual, and Construction Manual. Acceptance criteria are addressed for both Department and contractor supplied sources. The Department maintains a Qualified Products List. A range of certifications exists requiring either a Certificate of Compliance or a Certificate of Analysis.
Colorado's QA Procedures document provides a thorough description of the requirements of 23 CFR 637. Sections 105 and 106 of Standard Specifications detail information about statistically-based acceptance and pay factors for specific materials. Information is provided about materials sampling and testing with detailed requirements about tiers based upon material type. Form 250 is used to develop the project specific minimum sampling and testing requirements. The Field Materials Manual gives detailed information about Qualified Manufacturers List and Approved Products List (CP 11-12).
Illinois maintains a Project Procedures Guide, which describes the range of materials acceptance in Section 200. This document addresses QC/QA programs for asphalt binder, emulsified asphalt, Portland cement, Precast Concrete products, and reinforcement bars/fabric. There is no mention of the NTPEP, but the document makes reference to a process to qualify for addition to the approved list for materials. Manufacturer's certifications are also used for acceptance for certain types of materials and products, and visual inspection is required on the project site when possible. Visual inspection is acceptable when sampling is impractical, destructive, or when small quantities are involved.
New Hampshire performs sampling and testing at both the job site and preliminary acceptance at the materials source (such as aggregates) and manufacturing sites (such as concrete pipe and structural steel). Section 700 of the Standard Specifications describes the range of acceptance methods, which in addition to sampling and testing, also includes Certificates of Compliance and a QPL. For small projects, sampling and testing requirements are modified accordingly. Details for the testing frequencies of a wide range of materials are described in section 703.3 of the Standard Specifications.
Texas developed two types of acceptance procedures for Design-Build projects with optional maintenance agreements. The first type uses TxDOT-performed acceptance testing and inspection where only TxDOT testing and inspection results are used in the acceptance decision. The second type of acceptance is contractor-performed acceptance where frontline testing and inspection is performed by the contractor or Developer's Construction QA Firm (CQAF). Under this approach, the contractor is required to submit a Construction Quality Management Plan (CQMP). Under contractor-performed acceptance, statistically based owner verification tests along with periodic TxDOT independent audits of the contractor's CQMP are the basis for acceptance. The TxDOT QAP Implementation Guide defines three levels of verification tests based on material and test method. Level 1 testing is for analysis of parameters that are strong indicators of performance (.e.g., compressive strength for structural concrete, percent soil compaction, and percent asphalt content). Level 2 testing is for parameters that are thought to be secondary measures of performance (e.g., slump test for concrete). Level 3 provides observation verification for materials that require few QA tests for compliance or materials whose risk of failure does not affect long-term performance of the facility.
Virginia's process includes the development of a Materials Notebook, apparently automated, that addresses MSG and testing required. Contractor data is used for certain materials (e.g. HMA). Virginia also provides for certified products, and materials accepted by a manufacturer's certification. The procedure allows the SME (State Materials Engineer) to override the requirements of the Notebook, and provides different responsibilities and requirements based on project type (a) Design-Bid-Build, Rest Areas, Minimum and No Plan Projects, FHWA Safety Improvement Projects and Electrical Installations; (b) Design-Build, Public-Private Partnerships, Local Assistance and Municipally Administered Projects; and (c) State Forces performing work). Details for individual materials requirements are outlined in the Standard Specifications.

Washington's Construction Manual, Chapter 9 - Materials, provides guidance for Project Engineers (PE) on the manner by which materials are evaluated and accepted. The general purpose of job site sampling and testing is to ensure that the materials provided to the project conform to the specifications. The frequency of testing will vary, however, based on the material type, quantity, and variability of quality. The PE has authority to modify the acceptance of materials within the general framework of WSDOT normal materials acceptance procedures. The options available to the PE include reducing the frequency of testing for large volume materials well within specification limits, sampling and testing for small quantities of materials that are not structurally significant, discretionary materials acceptance for non-critical items, and optional approvals for specified materials using visual inspection in the field instead of certification or testing. WSDOT also maintains a listing of low risk materials that may be accepted without documentation unless specified in the Contract. WSDOT acceptance practices include testing (statistical PWL and non-statistical evaluations), inspection and documentation of fabricated items, visual acceptance, manufacturers certificate of compliance, miscellaneous certificates of compliance, shop drawings (fabricator drawings), and catalog cuts. WSDOT has provisions for materials certification for both fabricated and non-fabricated items, and compliance reviews for certified materials.

Wisconsin addresses materials acceptance requirements in the Standard Specifications. Guidance for materials sampling, testing and inspection for the engineering, testing, and inspection staff is found in the Construction and Materials Manual (CMM), Chapter 8 – Materials Testing, Sampling, Acceptance. WisDOT uses an E-Guide system for developing project specific acceptance for standard bid items. The CMM Chapter 8 includes documentation requirements for different acceptance types and differentiates between approved materials (i.e. from an approved source or supplier) and acceptance of materials through inspection or testing when incorporated into the project. Different frequencies and scope of sampling, testing, and inspection are applied as needed or appropriate for adequate control of quality and compliance with specifications. WisDOT maintains a listing of low risk or non-critical materials that may be accepted through visual inspection and not require documentation.

Wyoming generally develops the following three forms for each construction project to provide guidelines for materials acceptance testing and documentation requirements:

- WYDOT Form T-128, Construction Test Requirements,
- WYDOT Form T-131, Manufactured Products Received, and
- WYDOT Form T-132, Engineer's Verification of Specification Compliance [WYDOT 107.0].

Sampling and testing frequencies are identified in Form T-128. Manufactured products are accepted by certification using Forms T-168 and T-131. Verification acceptance of certain materials and manufactured items may also utilize Form T-132 in some instances. Qualified suppliers are also identified for certain materials and are identified on the agency website.

Despite differences in the specific details according to which DOTs manage the acceptance of materials and manufactured products, current materials acceptance programs, as summarized in Table 2.2, all generally include some combination of sampling, testing, certification, inspection, and evaluation processes intended to assure that the materials, products, and workmanship incorporated into a project are in reasonably close conformity to the approved plans and specifications. The check marks in Table 2.2 represent that the agency identified in each column uses the specific materials QA acceptance methods listed.

Table 2.2: Materials QA Acceptance Methods

Levels	Arizona	Virginia	Illinois	New Hampshire	Colorado	Texas QAP DB	Washington	Wisconsin	Wyoming

Levels	Arizona	Virginia	Illinois	New Hampshire	Colorado	Texas QAP DB	Washington	Wisconsin	Wyoming
Sampling and Testing									
Field Statistical (PWL or other)	✓				✓	✓	✓	✓	
Field Statistical (use of Contractor QC in acceptance)		✓			✓		✓	✓	
Field – non- statistical	✓	✓	✓	✓	✓	✓	✓	✓	✓
Plant	✓	✓	✓	✓	✓	✓	✓	✓	✓
Central Lab Verification	✓	✓	✓	✓	✓	✓	✓	✓	✓
Source of supply	✓	✓	✓	✓	✓		✓	✓	✓
Small Quantities	✓		✓	✓			✓	✓	
High Volume (Reduced Frequency)								✓	
Other	✓	✓			✓		✓	✓	
Materials Certification									
Manufactured Products from Certified Suppliers	✓	✓	✓	✓	✓		✓	✓	✓
Certified sources of supply	✓	✓	✓	✓	✓		✓	✓	✓
Qualified/Certified Products									
NTPEP	✓	✓	✓	✓	✓			✓	✓
DOT									
Tiered Certification (criticality of products)	✓	✓			✓				
Statements of Compliance	✓				✓		✓	✓	✓
Inspection									
Shop or source inspection		✓	✓	✓	✓		✓	✓	✓
Desktop								✓	✓
Diary Documentation								✓	
Visual field inspection		✓	✓	✓	✓		✓	✓	✓

A closer look into DOT acceptance practices suggests the existence of an informal hierarchy based loosely on materials type (i.e., project-produced, fabricated, standard manufactured item), how the material is to be used on the project, the quantities involved, and other factors. This hierarchy includes the following levels:

- The highest level of materials QA, **materials sampling and testing**, involves a range of testing options, including statistical and non-statistical methods and possibly the use of contractor QC results in the acceptance decision. The type and frequency of tests may vary depending on the location where the samples are taken, the test method, the quantity or variability of materials, and project type. QA of project-produced materials generally entails some level of sampling and testing.

- The second level or general category of materials QA is acceptance through **material certification**. This procedure is commonly used on manufactured materials or products. Certifications vary from very specific sources, such as a mill test report for a specific lot of material (issued by the fabricator or producer of the raw materials), to very general (such as a contractor's certification that the materials were obtained from a reputable source of supply). The certification might apply to pre-approved materials through the NTPEP or materials on a Qualified Products List (QPL), or from pre-approved sources. Certifications can be issued by DOTs or by the contractor or supplier using a Certificate of Compliance to assure that the materials meet certain criteria. A Statement of Compliance found on a material certification is defined more narrowly as a statement certifying that the supplied material meets the required specifications.

- The last category consists of **inspection**, ranging from plant or source to desktop and visual.

The various methods by which materials and products may be accepted are discussed in greater detail below.

Sampling and Testing

A DOT's sampling and testing program is typically guided by some type of minimum sampling and testing guide (MSTG) and can be included in a written manual, an electronic data management system, or on a fixed web-based system. Many states develop a project-specific MSTG (called a Materials Notebook by at least one state) that populates the bid quantities and produces the minimum number of samples and tests required for final acceptance of the project. The MSTG typically allows for some type of overrides and explanations for the resolution of failures; some states also allow the engineer some discretion to waive or reduce the requirements if warranted. Some states have a tiered system that produces different MSTG depending on project type, funding source (such as local municipality or state-funded), or project delivery system.

The range of sampling and testing criteria varies from the use of statistical methods such as percent within limits (PWL) to taking no samples at all for small quantities of materials used. Typically, PWL or other statistically-based methods are used for higher value or more critical project-produced materials such as hot mix asphalt (HMA) pavements, portland cement concrete pavements (PCCP), structural concrete, and soils for embankment construction.

Sampling and testing may be performed at the source of the material, production site or plant, or on the project site to determine compliance with a predetermined specification range for acceptance. As noted above, contractor data may be used in the acceptance decision provided that the 23 CFR 637 requirements for owner verification are satisfied. Examples of this type of system include quality management systems for aggregate base courses, HMA, and concrete. Other materials may only be sampled at the project site and either tested on site (e.g., density, fresh concrete properties) or taken to a qualified laboratory. Most states provide for the waiver of sampling and testing for small quantities of materials used, and some states will reduce the frequency of sampling for high volume materials once initial testing has verified that the materials supply is relatively uniform or statistically under control and within specification limits. However, states generally do reserve the right to focus and increase QA testing if conditions suggest that the process is somehow changing and is not consistently under control.

As an example of possible adjustments that can be made to standard sampling and testing criteria, Washington State DOT (WSDOT) in Chapter 9 of its Construction Manual provides Project Engineers with substantial latitude to judiciously adjust testing frequencies based on established guidelines. In accordance with the Construction Manual, the following options are available to Project Engineers:

- **Sampling and Testing for Small Quantities of Materials.** Project Engineers may choose to accept small quantities of materials without meeting the minimum sampling and testing frequencies (e.g., by visual acceptance, certification, or other methods) if the proposed quantity for that material is less than the minimum required testing frequency.

Other considerations that the Project Engineer may factor into its decision to use small quantity acceptance include whether or not:

- The material has been previously approved
- The material is certified
- A mix design or reference mix design is available
- The material has been recently tested with satisfactory results
- The material is structurally significant

Small quantity acceptance may also be used for any quantity of the following:

- Curbs and sidewalks
- Driveways and road approaches
- Paved ditches and slopes
- Packaged concrete meeting ASTM C387 used for jobsite mixing

- **Reducing Frequency of Testing.** For projects with high volumes of materials, WSDOT may choose to reduce sampling frequency and/or eliminate selected test properties after ten consecutive samples taken at the standard testing frequency are shown to be well within the specification limits. If there are any failing tests, the sampling and testing frequency will revert back to the normal schedule. The authority to approve deviations to testing frequencies is as follows:

Role	Authority Level
Project Engineer	May initiate and approve up to 10% deviations from the testing frequency schedule, with the exception of the following materials: hot mix asphalt, warm mix asphalt, structural concrete, and cement concrete pavement
Region Materials Engineers	May approve requests from Project Engineers for: • An additional 10% deviation, with the exception of the following materials: hot mix asphalt, warm mix asphalt, structural concrete, and cement concrete pavement • Elimination of fracture and/or SE from a Quarry Site
State Materials Engineer or Assistant State Materials Engineer	May approve requests: • To eliminate any other testing not expressly delegated to Project Engineers or Region Materials Engineers • For sampling frequency deviations exceeding the authority of Project Engineers and Region Materials Engineers • For sampling frequency deviations for hot mix asphalt, warm mix asphalt, structural concrete, and cement concrete pavement

- **Project Engineer Discretionary Materials Acceptance.** The Project Engineer may choose to modify the normal acceptance procedures for minor, noncritical work items occurring outside the traveled way. Acceptance in such cases typically entails verifying dimensional conformance to the plans and making a visual determination that the materials are suitable.

- **Optional Approval/Acceptance for Materials.** WSDOT's Construction Manual includes a list of materials that the Project Engineer may accept by visual inspection. If the quality or ability of the material to perform as intended is in question, the Project Engineer must determine if visual acceptance is appropriate or if additional acceptance testing or certification is necessary. The materials included on the list include items such as erosion control materials and miscellaneous fittings and hardware.

The decision to implement one of the above options is to be documented on WSDOT's Reduced Acceptance Criteria Checklist *prior* to the work being performed (i.e., not retroactively to justify deficiencies identified after completion). The State Materials Laboratory and Construction Office have final authority to approve or reject any request for modification.

Certification

DOTs also accept certain materials by certification. Certifications may or may not require additional field sampling and/or testing at the project site. The requirements for such sampling or testing are usually identified in the standard specifications, supplementary materials or construction manuals, or the MSTG. The source of supply, such as an aggregate producer, concrete producer, cement producer, or other manufacturer, may be certified through a process described by the DOT. Manufactured products, such as bridge girders, precast concrete products, and pipe materials, may be certified by the DOT. DOTs using certifications typically have a range of certifications with varying degrees of detail, from a Statement of Compliance to a Certificate of Analysis for the specific lot of material being incorporated into the work.

Inspection

Inspections are also used in the acceptance process. Inspections may be conducted at manufacturing locations, sources of supply, or on the project site. Inspections may or may not involve sampling and testing by the producer, contractor or DOT, and the materials or products involved may or may not have been part of a certification or quality management program. Inspections can also include evaluating the documentation or may only involve a visual inspection of the material or manufactured product in an interim or final point of incorporation into the project.

Alternative Project Delivery Methods

Alternative project delivery methods such as design-build provide the opportunity to expand the contractor's role in construction quality management beyond conventional quality control activities to include several of the QA tasks traditionally performed by DOT personnel.

As noted above, in accordance with 23 CFR 637 and FHWA Tech Brief HRT-12-039, a comprehensive construction quality assurance program should consist of: quality control, acceptance, independent assurance, dispute resolution, personnel qualification, and laboratory accreditation/qualification. Use of an alternative delivery method does not diminish the need to perform any of these functions; however, the party performing them may differ from a DOT's standard practices. Possible options include the DOT, an independent evaluator, the contractor (with DOT verification sampling and testing), or some combination thereof. However, it is important to stress that DOTs cannot relinquish responsibility of the acceptance function to the contractor or design-builder per 23 CFR 637.207(b). Given the importance of quality management to the outcome of a project and the likelihood that some of the traditional quality roles will change, the contract documents should explicitly define the quality-related responsibilities of all parties.

On projects delivered using alternative methods, several different approaches or organizational structures for assuring quality have been implemented. One approach seen on large design-build projects in particular entails the contractor's engagement of an independent testing firm to conduct sampling and testing of those critical quality characteristics that will be verified by the DOT as part of the acceptance decision while a separate QC team works in close coordination with the construction forces to conduct the sampling and testing necessary to monitor, assess, and adjust production and placement processes to ensure the final product will meet the specified level of quality. Figure 2.1, adapted from TxDOT's Quality Assurance Program (QAP) for Design Build Projects (TxDOT 2011) illustrates this approach, which includes the Contractor's Construction Quality Assurance Firm (CQAF) in a key acceptance role.

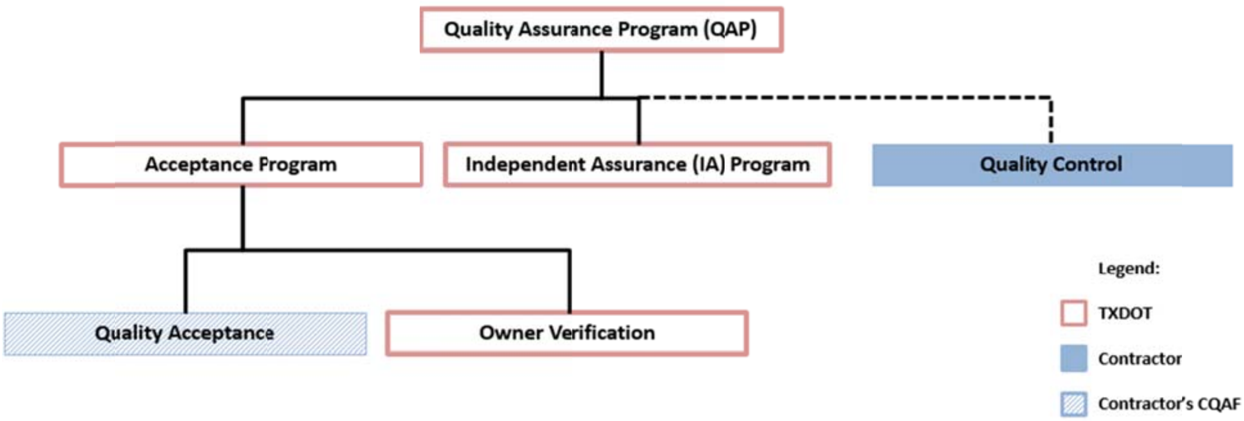

Figure 2.1: Example Organizational Structure for QA Management on a Design-Build Project
[Adapted from TxDOT 2011]

Virginia DOT's (VDOT) manual on the Minimum Requirements for Quality Assurance and Quality Control on Design Build and Public-Private Transportation Act Projects (VDOT 2012) describes a similar system, which requires the construction QA organization to be distinct and separate from the construction production forces staff. Table 2.3 describes VDOT's typical organizational structure for construction quality management for design-build and PPP projects.

Table 2.3: VDOT's Organizational Structure for Construction QA on DB and PPP Projects

Position	Responsibility	Reports To
VDOT	Owner's Independent Assurance (OIA) Owner's verification sampling and testing (OVST)	--
Concessionaire/ Design Builder Project Manager	Responsible for the overall Project design, construction quality management, and contract administration for the Project	Concessionaire/ Design- Builder at the executive level
Quality Assurance Manager (QAM)	Overall responsibility for the development of an adherence to the Design-Build QA/QC Plan	Concessionaire/ Design-Builder Project Manager or other appropriate person at the executive level (Note: The QAM does not report to production forces and cannot have any involvement on construction operations for the Project)
QA Testing Technicians QA Inspection Technicians	Responsible for QA testing and/or inspection of items of work for conformance with plans and specifications	QAM

Position	Responsibility	Reports To
Concessionaire/ Design-Builder Construction Manager	Responsible for the construction portion of the Design-Build QA/QC Plan and for ensuring construction of the work in accordance with the QA/QC Plan	Concessionaire/Design- Builder Project Manager
QC Testing Technicians QC Inspection Technicians	Responsible for QC testing and/or inspection of items of work for conformance with QC plans and specifications	Contractor's production forces

[Adapted from VDOT 2012]

Optimization Strategies

The literature contains some examples of formal attempts by DOTs to explicitly create tiered or risk-based materials QA systems. Although these efforts are largely qualitative in nature, they suggest that a solid foundation exists for developing and implementing a more in-depth process for optimizing the costs and risks of materials QA, as contemplated under this research project.

Tiered or Hierarchal QA Systems

A few DOTs have assigned construction materials to different tiers or levels of QA based on their perceived criticality (consequence of failure).

California DOT's Construction Quality Assurance Program Manual (Caltrans 2015) includes a process for developing tiered materials specifications based on material criticality. As summarized in Table 2.4, Tier 1 items are considered to have the greatest consequence of failure, while Tier 4 items have the least consequence. The QA strategy for each tier varies accordingly.

Table 2.4: Tier Levels Based on Consequence of Failure

Tier	Failure Category	Consequence of Failure	Example Items	QA Requirements
1	Catastrophic	Greatest consequence of failure. Failure is likely to cause loss of life or serious injury.	Structural steel, precast girders, pre-stressing	QA methods designed to provide the maximum level of confidence in the QC efforts of both the contractor and the producer.
2	Safety	Failure creates a safety hazard for employees or the public.	Delineation, safety barriers, lighting, signal controllers	QA methods designed to provide a high level of confidence in the QC efforts of both the contractor and the producer through extensive use of pre-qualified materials from the authorized material list.
3	Interrupt Service	Failure or repair may cause an interruption in service, or environmental impact.	Pavements, bases, embankment, storm water pollution prevention plan-best management practice devices	QA methods based on 23 CFR 637 requirements for jobsite-produced items, applicable rules and regulations included in the contract for the environmental items; and certificates of compliance from the contractor or producer combined with intermittent inspection, sampling, and testing of in-progress work for drainage items.

Tier	Failure Category	Consequence of Failure	Example Items	QA Requirements
4	Monetary	Monetary loss only – consequence of failure is considered minimal in terms of project performance.	Grass seed, drainage and irrigation products, fencing	QA methods typically based on use of commercial quality products or extensive use of certificates of compliance from the contractor or producer combined with periodic random inspection of in-progress work.

[Source: Caltrans 2015]

Caltrans used this tiered approach to classify the materials in its specifications as shown in Table 2.5:

Table 2.5: Caltrans Specification Sections with Associated Tier Levels

Specification Section	Specification Section Description	Tier 1	Tier 2	Tier 3	Tier 4
12	Temporary Traffic Control		X		
15	Existing Facilities		X		
16	Clearing And Grubbing			X	
17	Watering				X
18	Dust Palliative				X
19	Earthwork			X	
20	Landscape				X
21	Erosion Control				X
22	Finishing Roadway				X
24	Stabilized Soils				X
25	Aggregate Subbases			X	
26	Aggregate Bases			X	
27	Cement Treated Bases			X	
28	Concrete Bases			X	
29	Treated Permeable Bases			X	X
37	Bituminous Seals			X	
39	Hot Mix Asphalt			X	
40	Concrete Pavement			X	
41	Concrete Pavement Repair			X	
42	Groove and Grind Concrete		X	X	
46	Ground Anchors and Soil Nails	X			
47	Earth Retaining Structures	X			
48	Temporary Structures	X			

Specification Section	Specification Section Description	Tier 1	Tier 2	Tier 3	Tier 4
49	Piling	X		X	
50	Prestressing Concrete	X		X	
51	Concrete Structures	X	X	X	X
52	Reinforcement	X	X	X	
53	Shotcrete			X	X
53-2	Structural Shotcrete	X			
54	Waterproofing				X
55	Steel Structures	X	X		X
56	Signs		X		
56	Overhead Sign Structures	X			
57	Wood and Plastic Lumber Structures	X	X		X
58	Sound Walls	X			
59	Painting			X	X
61	Culvert and Drainage Pipe Joints			X	
62	Alternative Culverts			X	
64	Plastic Pipe			X	
65	Concrete Pipe			X	
66	Corrugated Metal Pipe			X	
67	Structural Plate Culverts		X	X	
68	Subsurface Drains			X	X
69	Overside Drains			X	
70	Miscellaneous Drainage Facilities			X	
72	Slope Protection				X
73	Concrete Curbs and Sidewalks				X
74	Pumping Equipment and Controls				X
75	Miscellaneous Metal		X		
80	Fences				X
81	Monuments				X
82	Markers and Delineators		X		
83	Railings and Barriers		X		
84	Traffic Stripes and Pavement Markings		X		
85	Pavement Markers		X	X	X
86	Electrical Systems		X	X	X

As can be observed from Table 2.5, although Caltrans' tiered system does highlight safety-critical items, the tiers do not necessarily reflect or align with the amount of resources currently applied to assuring the quality of the materials within those tiers. For example, HMA, which is classified as a Tier 3 material (i.e., failure or repair may cause an interruption in service), currently demands a considerable sampling and testing effort, which is likely attributable in part to the large quantities and high dollar values often associated with pavement construction.

Indiana DOT (INDOT) sponsored research performed by Purdue University to develop a tiered prioritization system for inspection resources. As described in a report prepared by Mostafavi and Abraham (2012), the objectives of this project were to evaluate the current inspection practices of INDOT and develop a risk-based inspection protocol to facilitate the efficient allocation of limited inspection resources to activities with higher risk consequences.

To capture the current state of inspection practice for highway transportation projects, the Purdue research team surveyed the DOTs in 2010. Based on responses received from 23 agencies, the study found that inspection practices vary widely across the states (similar to what other literature has suggested with regard to QA practices in general). Other reported findings included the following:

- 74% of the responding DOTs indicated that they do not have a protocol for prioritizing the inspection of construction activities.
- 44% of the respondents did not consider their current inspection practices to be ''efficient,'' implying that inspection resources are not necessarily allocated efficiently to the most critical activities.
- 65% of state DOTs seek full observation of certain construction activities (deemed to be higher risk) and inspect other activities when resources are available.
- 35% require contractor certification with a quality control (QC) program and provide random inspection for quality assurance (QA).

The Purdue researchers then conducted a risk analysis, using information obtained from 101 experts, representing INDOT, other DOTs, and consultants, to prioritize construction activities based on the perceived risk impacts due to reduced inspection. The results of this analysis are summarized in Table 2.6.

Table 2.6: List of Prioritized Construction Activities for Inspection

High Priority	Medium- High Priority	Medium Priority	Medium- Low Priority	Low Priority
Aggregate base courses Asphalt paving Bolting structural connections Concrete paving Driven piles Embankment Placement of concrete in structures	Beam erection Pipe placement Sub- grade treatment Drilled shafts Guardrail Overhead sign structure Painting steel Traffic marking	Barrier curb Blasting Concrete forms (structures) Drainage Excavation Handling/removal of regulated waste Highway Lighting (foundations and	Cofferdam Electrical conduit and wiring Fence ITS- fiber optic conduit and cable Landscape plantings Milling Placement of lighting features	Clearing site Clearing site- bridge Stripping

High Priority	Medium- High Priority	Medium Priority	Medium- Low Priority	Low Priority
Post- tensioning (pre-stressed structures) Reinforcement steel in structures Retaining walls Structure rehabilitation (repair concrete deck)		poles) Installing soil erosion/sediment control items Sound wall panel placement Sound wall post placement\ Traffic control- set up Traffic signals (foundations and poles)	Seal coating Sheet piles Sidewalk	

[Source: Mostafavi and Abraham 2012]

Based on this prioritization, a protocol for various inspection activities was developed that could be used to assist with the allocation of inspection resources when multiple activities are proceeding concurrently and available resources are not sufficient to fully inspect all ongoing activities.

Table 2.7 illustrates a portion of this protocol. For example, site clearing, which was rated as a low priority activity, would require only random inspection. In contrast, the higher priority activities of base course and embankment construction would require frequent to constant inspection based on the specific inspection item in question. For example, embankment lift height would require frequent inspection whereas density would demand constant attention.

Table 2.7: Protocol for Inspection of Construction Activity

Construction Activity	Priority	Macro- Consequences Due to Missed/Reduced Inspection	Critical Items to Be Watched	Frequency of Inspection
Clearing site	Low	----	Areas to and not be cleared	Randomly
			Clearing obstructions	Randomly
			Removal to adequate depth	Randomly
			Identify wet spots	Randomly
Aggregate base course	High	Functional failures, increased maintenance costs, decreased design life	Moisture and density control	Frequently
			Compactor passes	Constantly
			Depth of each lift	Constantly
			Documentation	Constantly
			Obtain tickets for materials (depending on payment method)	Frequently
Embankment	High	Functional failures, increased maintenance costs, decreased design life	Quality of the soil being placed	Constantly
			Moisture content	Constantly
			Density	Constantly
			Measure embankment area	Constantly
			Lifts height and width	Frequently

[Source: Mostafavi and Abraham 2012]

South Dakota DOT (SDDOT), as described in its manual of Required Samples, Test, and Certificates, implemented a 3-tiered process for certification of materials ranging from critical to non-critical (SDDOT 2013). For example, Tier 1 is defined as material that is considered critical to safety or costly to replace. The certification requirements vary from certificates of compliance supported with test results to certified suppliers to umbrella certificates for component products of a system or assembly. Verification methods for certification ranges from sampling and testing to documented inspection, random audits or annual inspections of suppliers.

Risk-Based Systems

Other DOTs have implemented a more explicit risk-based approach to optimizing materials QA that considers both the probability and consequence of failure. These efforts entail aligning a qualitative risk rating of materials to a level of materials QA that is commensurate with this risk.

Washington State DOT (WSDOT) performed an internal programmatic materials risk analysis between 2002 and 2005 to develop a system to more formally evaluate the risk of materials and to determine the level of QA needed to accept each construction material based on that perceived risk.

As documented in the WSDOT Research Report entitled *Materials Risk Analysis* (Baker et al. 2010), WSDOT employed a novel and step-wise approach to its analysis. First, WSDOT developed a conceptual internal ranking of QA acceptance practices, ranging from the most intensive level of scrutiny to the least intensive as follows:

- **Level 1:** Highest level - WSDOT acceptance testing, or a combination of fabrication inspection coupled with a requirement for a manufacturer's quality system plan (an example would be structural steel)
- **Level 2:** Second highest level - Requires a manufacturer's certification of compliance coupled with a quality systems plan (examples include soil nails, structural earth walls, ground anchors, and guardrail)
- **Level 3:** Intermediate level - Either a certification from the contractor that the supplied material meets contract requirements or a catalog cut stating the qualities of the material being used (examples include fencing, compost, soil amendments, and other non-structural items that do not require testing or certification)
- **Level 4:** Lowest level - Visual inspection in the field to verify the correct product is used

WSDOT then plotted these QA levels of acceptance on a five-by-five risk rating matrix, as shown in Figure 2.2, aligning the QA levels with risk ratings.

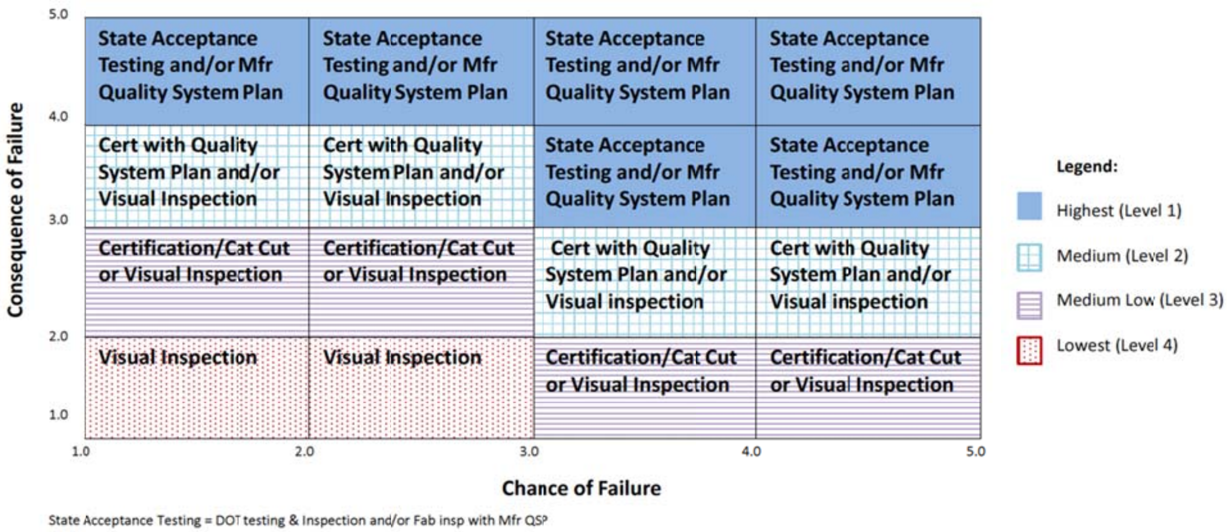

Figure 2.2: WSDOT Materials Acceptance Rating Matrix
[Adapted From: Baker et al. 2010]

Once this framework was established, WSDOT's next step involved assigning risk ratings for all the materials in the WSDOT program, considering both the risk of non-conforming materials and the consequences of non-conformance. As WSDOT noted in its report, information obtained from asset management systems that track both the actual performance and life cycle costs of materials would ideally be used as the basis for the risk analysis. Lacking such data, WSDOT instead used a Delphi process with internal DOT experts to assign risk ratings for various highway construction materials.

As a result of this analysis, WSDOT was able to adjust or optimize the level of QA for certain materials that previously were subject to more rigorous QA. As shown in Figure 2.3, the materials requiring the highest level of examination (i.e., acceptance testing and/or manufacturer's quality system plan) decreased from 98 to 88. Similarly, materials in the second level of acceptance also decreased, while the number of material items that could be accepted based on visual inspection or certification increased accordingly.

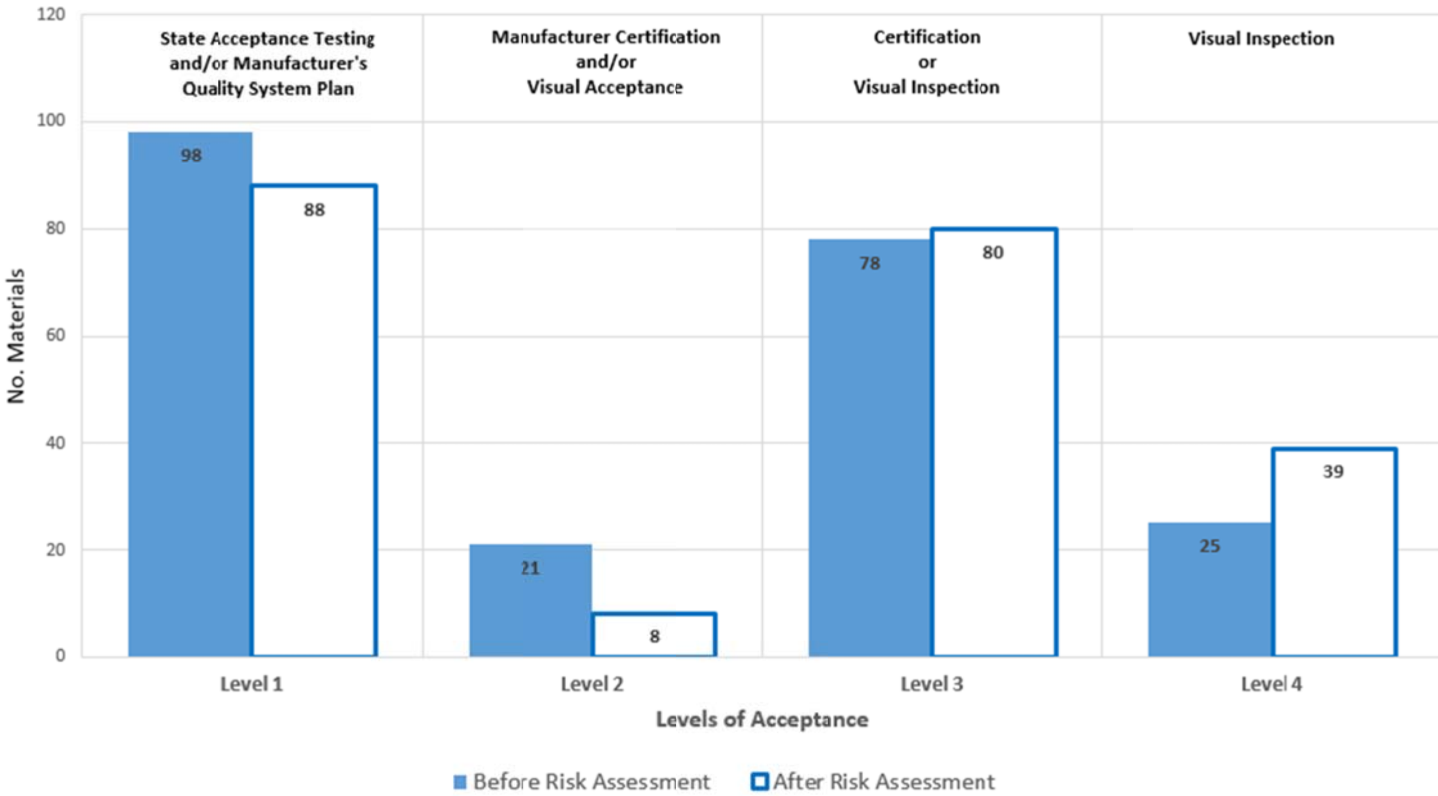

Figure 2.3: Materials Risk Assessment Results
[Source: Baker et al. 2010]

For materials that are primarily accepted on the basis of sampling and testing, **Texas DOT** (TxDOT), in its *Design Build Quality Assurance Program (QAP) Implementation Guide,* focused on the ability of individual material *properties* to act as indicators of performance. This analysis of material properties was then used as a basis for determining how much owner verification testing should be performed to validate contractor test results used in the acceptance decision (TxDOT 2011).

For design-build projects with 15-year capital maintenance agreements, the guide applies three-tiers of owner verification testing to specific materials and properties, which are based on the TxDOT's perceived residual risk after the contractor has completed construction and fulfilled its maintenance obligations. As explained in the guide, these levels are as follows (TxDOT 2011):

- ***Level 1*** *provides continuous analysis for those analysis categories that are strong indicators of performance. Examples include compressive strength for hydraulic cement concrete, percent soil compaction for embankment, and percent asphalt content for hot-mix asphalt concrete. The QA testing frequency is in compliance with the Guide Schedule, and the owner verification (OV) testing frequency should be a minimum of 10 percent of the QA testing frequency. F- and t- tests are performed on these material categories on a continuous basis with the addition of each OV test result.*

- ***Level 2*** *provides independent verification for those materials that are secondary indicators of performance. An example is the slump test for hydraulic cement concrete. The QA testing frequency is required to be in compliance with the Guide Schedule and the OV testing frequency should be a minimum of once per quarter.*

- ***Level 3** provides observation verification for those materials that only require very few QA tests for compliance with the Guide Schedule or tests on materials whose risk of failure does not affect the long-term performance of the facility past the contractual maintenance obligations. An example is the entrained air test (Tex-416-A) for non-structural (miscellaneous) concrete riprap where risk of failure does not affect the long-term performance of the facility past the contractual maintenance obligations. Under the Level 3 approach, OV does not perform tests but observes the QA test performance for equipment and procedural compliance with the test procedure.*

An example, from TxDOT's guide, of the application of these analysis categories to specific materials and properties is shown in Table 2.8.

Table 2.8: Example TxDOT Analysis Categories for Owner Verification

Levels for Analysis	Level 1	Level 2	Level 3

EMBANKMENTS, SUBGRADES, BACKFILL, AND BASE COURSES			
MATERIAL OR PRODUCT	**TEST FOR**	**TEST NO.**	**TxDOT RECOMMENDED**
EMBANKMENT (CUTS & FILLS)	Liquid Limit	Tex-104-E	2
	Plasticity Index	Tex-106-E	1
	Linear Shrinkage	Tex-107-E	2
	Gradation	Tex-110-E	2
	Moisture/Density	Tex-114-E	3
	In-Place Density	Tex-115-E	1
RETAINING WALL (NON-SELECT BACKFILL)	Liquid Limit	Tex-104-E	2
	Plasticity Index	Tex-106-E	1
	Linear Shrinkage	Tex-107-E	2
	Gradation	Tex-110-E	2
	Moisture/Density	Tex-114-E	3
	In-Place Density	Tex-115-E	1
RETAINING WALL (SELECT BACKFILL)	Gradation	Tex-110-E	2
	Resistivity	Tex-129-E	2
	pH	Tex-128-E	2
	Soundness	Tex-411-A	3
	In-Place Density	Tex-115-E	1
UNTREATED BASE COURSES	Liquid Limit	Tex-104-E	2
	Plasticity Index	Tex-106-E	1
	Linear Shrinkage	Tex-107-E	2
	Gradation	Tex-110-E	2
	Moisture/Density	Tex-113-E	3
	Wet Ball Mill	Tex-116-E	2
	Triaxial	Tex-117-E	2
	In-Place Density	Tex-115-E	1
	Moisture Content	Tex-103-E	2
	Thickness	Tex-140-E	1

[Source: TxDOT 2011]

New York State DOT (NYSDOT), in the Quality Assurance Plan Program Guide established for the Kosciuszko Bridge Design-Build Project, applies a three-tiered, risk-based approach to verification testing that is similar to that implemented by TxDOT (NYSDOT 2013). NYSDOT defines these levels (or Risk Factors) as follows:

- ***Risk Factor 1 (RF-1)*** *provides continuous analysis using statistically based (F & t-) testing for those categories of materials and associated test methods that are strong indicators of long-term performance. These are typically considered high-risk, high-volume type materials incorporated into a Design Build project. Examples include compressive strength for hydraulic or PCC concrete, percent soil compaction for embankment, and percent asphalt content for Hot Mix Asphalt Concrete. The Design Builders' QC testing frequency is in compliance with various Department documents and the Departments Verification sampling and testing frequencies should be a minimum of 25% of the QC testing frequency. Acceptance is based upon both validation of statistical analysis of complimentary QC test data population and QA verification test data populations and both test results meeting acceptable material acceptance limits as defined in the contract documents.*

- *In addition to checking that all QC test results are within specification limits, the* ***Risk Factor 2 (RF-2)*** *verification provides independent verification of those materials and associated test methods that are secondary indicators of material performance. Verification testing, in the form of independent verification sampling or split sampling with the QC test, that the test results fall within specification limits is typically appropriate. These materials/material tests are considered a reduced risk from RF-1. An example is the slump test for concrete. Approved list products that require more than manufacturer's certification of compliance to assure quality are covered under this level of verification. The QA verification sampling and testing frequency should be a minimum of 10% of QC testing frequency. Acceptance is based upon verification test method results meeting the specification limits. No statistical validation is required.*

- ***Risk Factor 3 (RF-3)*** *provides observation verification for those materials that only require very few QA tests for compliance with various Department documents or where materials are accepted based on the inclusion in the Departments Approved List of materials. For these materials, risk of failure does not affect the long-term performance of the facility. The Design Builder should still perform QC testing as required. Under RF-3 approach, the Department oversight does not perform tests but observes any QC test performance for equipment and procedural compliance for a product, and/or perform an audit of project procurement records to verify compliance with Departments Approved List, Certification of Compliance on record, Buy America, etc. The frequency of this testing is a minimum of once per calendar year per test method and/or product, or random frequency as determined by the Departments Project Manager.*

NYSDOT reviewed its standard specifications and determined the overall risk and associated QA level of effort for particular materials. An example of this analysis is shown Table 2.9.

Table 2.9: Example NYSDOT Analysis Categories for Verification Testing

Specification Section	Risk Factor, applications, and hold points (as appropriate)	Quality Assurance Actions and Testing
201- Clearing and Grubbing	RF-3- all work	Materials QA: N/A CI QA: random verification of QC records for work documented as progressed, verify adherence to work limits, and compliance with planned/ required protection/ restoration.
202- Removal of Structures and Obstructions	RF-3- all work	Materials QA: N/A CI QA: random verification of QC records for work progressed, adherence to safety requirements, and adherence to safety requirements, and adherence to WZTC per 619 requirements as appropriate.

Specification Section	Risk Factor, applications, and hold points (as appropriate)	Quality Assurance Actions and Testing
203- Excavation and Embankment	Compaction and density: RF-1, high volume embankment construction of 10,000 cubic yards or more placed per day or where structural elements will be constructed atop embankment RF-1, pipe or structural backfill of any quantity RF-2, embankment construction quantities less than 10,000 cubic yards placed per day and where no structural elements will be constructed atop embankment RF-3, embankment construction quantities less than 1,000 cubic yards placed per day and where no structural elements will be constructed atop embankment	Materials QA: Random verification of test result sheets from QC testing, at a rate of 1 check per 10 completed. CI QA: Observe DB embankment sampling and testing to include density, gradation, pH, sulfate soundness, etc. as required per spec. Daily inspection of lift thickness, material placement, compaction operations for all embankment construction.

[Source: NYSDOT 2013]

Cost of Quality

Conventionally, quality costs have been organized into the following categories (Hylton Meier 1991):

- *Prevention costs*: costs of activities to prevent defects in the design and development of a product;
- *Appraisal costs*: costs incurred to inspect, test, and evaluate conformance to specifications;
- *Internal failure costs*: costs incurred when a defect is detected prior to the sale of a product; and
- *External failure costs*: costs incurred after a product is in the hands of the consumer.

Internal and external failure costs are often combined into a single "cost of failure" category (Morse 1993).

The Federal Transit Administration, in its *Quality Management System Guidelines* (FTA 2012), largely adheres to this traditional view of quality costs. FTA groups quality costs into two broad categories - the price of conformance (i.e., detection costs) and the price of non-conformance (i.e., cost of failures). Examples of what these costs may entail are summarized in Table 2.10 below.

Table 2.10: Cost of Quality

Category	Description	Example Components
Cost of Conformance (Prevention + Detection)		
Prevention Costs	Costs related to assuring the product or project meets requirements	Design analysis and reviews Constructability reviews Quality management systems
Appraisal Costs	Costs related to determining the degree of product or project conformance	Inspection Sampling and testing
Cost of Non-Conformance (Defects or Failure)		
Cost of Defects or Failures	Costs associated with non-conforming materials	Repair/rework Schedule delays Road user impacts Reduced life

[Adapted from FTA 2012]

Over the years researchers have proposed and refined a theoretical model for optimizing QA based on these definitions of quality costs and the principle of diminishing marginal returns (e.g., Juran 1951; Kilpatrick 1970; Plunkett and Dale 1988; Hylton Meier 1991; Morse 1993; Schiffauerova and Thomson 2006). As depicted in Figure 2.4, the *Total Cost of Quality* can be represented as a function of QA assessment/prevention costs (i.e., QA Cost) plus the cost of defective or nonconforming materials (i.e., Conformance and Correction Cost).

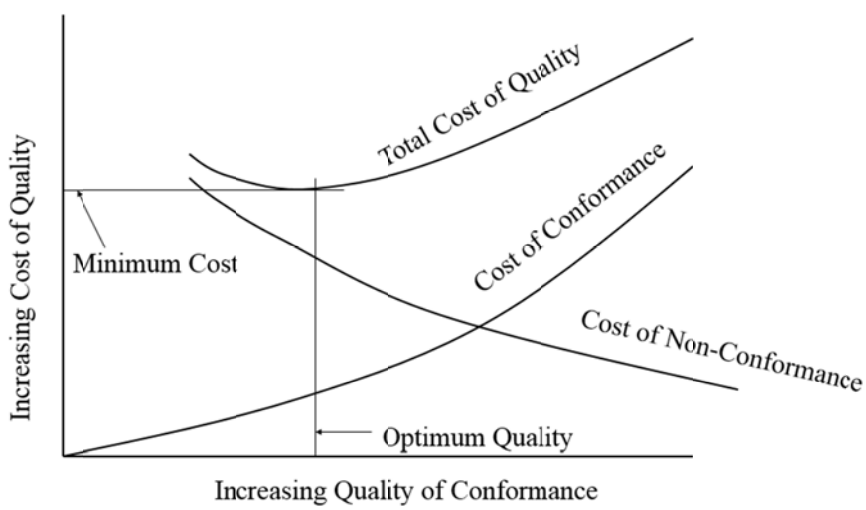

Figure 2.4: Economics of Quality of Conformance
[Adapted from Kirkpatrick 1970]

Theoretically, the cost of improving QA will continue to rise while the cost of failure continues to fall, suggesting the existence of an optimum QA investment point at which the sum of the cost of materials QA and the cost of failure are at a minimum. This would yield the lowest total cost to achieve the desired level of quality. Additional investment in QA beyond this point would yield a suboptimal return.

Although the literature is rich with examples of similar QA optimization models, industry surveys and related research studies suggest that real world application of quality cost calculations is not common, largely due to difficulties in identifying and tracking all of the quality costs (Plunkett and Dale 1988; Schiffauerova and Thomson 2006).

Summary

The literature review did not identify many resources that specifically addressed the application of risk management principles to QA activities. The lack of specific risk management guidance reinforces the opportunity that exists to develop a methodology under this research project that will serve to promote a common and rational approach for optimizing QA risks and costs for highway construction projects.

Given the variability in QA practices across the DOTs, the optimization methodology should be designed to work in conjunction with the existing materials QA management tools used by DOTs, which often apply a hierarchical approach to QA based on project classifications and types of materials incorporated into the work.

To develop this model further required more detailed information related to QA costs and risks, which the research team attempted to obtain through the data collection effort described in Chapter 3.

CHAPTER 3 – DATA COLLECTION

To expand on the trends identified in the literature and ensure adequate input from a diverse cross-section of DOTs, two data collection approaches were used: a survey and individual interviews.

The surveys were used as an initial screening and interest gathering tool designed to reach the broadest group of materials and construction engineers in the shortest time. Follow-up interviews with a targeted group of DOTs were then conducted to capture a deeper level of insight into QA optimization strategies and to probe for specific data regarding QA risks and costs.

Each data collection technique is described in detail below, followed by a summary of relevant findings and implications for subsequent research tasks.

Survey

Survey Methodology

The survey was developed as an online questionnaire using Qualtrics software, an easy-to-use, full-featured, web-based tool for creating and conducting online surveys.

Email invitations, which included a link to the survey tool, were sent to a list of almost 200 individuals, drawn primarily from the AASHTO Subcommittees on Materials and Construction and other contacts of research team members. To ensure the survey reached the intended audience, recipients were asked to identify additional individuals from either within or outside their organizations who had an interest in the research and information to share.

The survey questions were designed to identify and/or assess a wide range of topics, including:

- The extent to which different project factors (e.g., project type, facility type, material quantities, project delivery method, funding source, material criticality, etc.) affect materials acceptance procedures and protocols;
- Any trends related to materials QA and the use of statistically-based specifications, contractor QC data in the acceptance decision, and alternative project delivery methods, such as design-build, maintenance contracts, and warranties;
- Use of tiered or risk-based materials acceptance programs;
- Variability in the materials management systems (e.g., AASHTOWare, internally developed Laboratory Information Management Systems, etc.) used to define QA requirements and track, report, and store QA data; and
- General data related to QA program costs and probability of failure (non-conformance).

To minimize the time and effort of respondents and help ensure an adequate response rate, the following best practices were incorporated into the design and deployment of the survey:

- Use of clear, relatively short, non-leading survey questions that asked respondents to rate, rank, and/or select the best response(s) from a list of provided choices as well as the option to provide additional comments in open-ended dialog boxes;

- Invitations for the respondents to self-select for further participation in the research and to share examples of their QA documents;

- Inclusion of an endorsement letter from the chairman of the AASHTO Subcommittee on Materials stressing the importance of the study and the need for survey participation;

- Periodic reminders sent to non-respondents; and

- Automated data collection and aggregation to reduce the possibility of manual tabulation or interpretation errors.

Survey Results

The team received responses from 37 DOTs, as summarized in Figure 3.1, as well as from the Port Authority of New York and New Jersey, Illinois Tollway, Ontario Ministry of Transport, the Departamento Nacional de Infraestrutura de Transportes and Departamento de Estradas de Rodagem in Brazil, and the Roads Maritime Services NSW Government, Australia. In some cases, multiple responses were received from different individuals within the same agency.

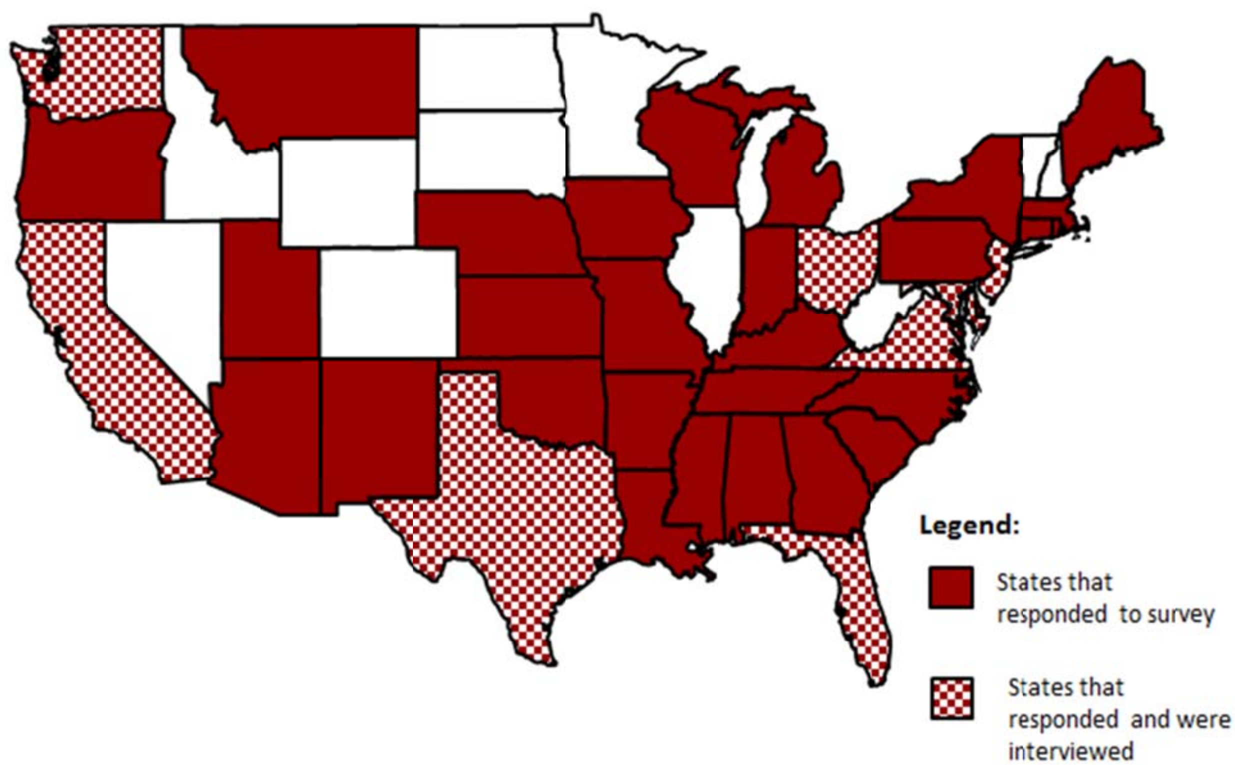

Figure 3.1: State DOTs that Participated in the Data Collection Efforts

For benchmarking and trend identification purposes, the survey results were analyzed from multiple perspectives. Responses from different DOTs were compared to one another to identify any commonalities and differences attributable to capital program size, available resources, geographic location, use of materials management systems, and similar programmatic factors. Project-level factors, such as project size, type, complexity, and delivery method, were also explored to assess their impact on materials acceptance practices.

Key findings from this evaluation are summarized below. A compilation of all questions and responses is provided in Appendix C.

Optimization Strategies (Tiered and Risk-Based)

The survey results confirmed a key finding from the literature assessment that several agencies "optimize" their materials acceptance practices to some degree (whether formally or informally) by creating tiers or levels of acceptance (i.e. sampling and testing, certification, and inspection) based on what is required for each material to assure the quality of the end product. For example, most DOTs responded that they perform sampling and testing (often in combination with inspection) for project-produced materials such as earthwork, base courses, pavements, and cast-in-place structures, but rely on certification and inspection for fabricated or standard manufactured products, such as paints and coatings, which are produced in more controlled environments. This finding held for both "high-profile" projects (defined as large, urban, and/or high volume roadways) and "low-profile" projects.

In addition to material classification (i.e., project produced vs. plant produced vs. standard manufactured items), respondents also indicated that certain key project characteristics, including the quantity of materials involved, the criticality of materials (related to safety or end product performance), and project type (e.g., paving, bridges, grading), can also affect acceptance practices. In contrast, project delivery type, facility type (interstate, primary, secondary, etc.), and funding source were reported as having less influence on acceptance procedures. At the extreme, some DOTs commented that they applied the same QA process regardless of project characteristics.

Several agencies also reported that risk is a factor in their optimization process. For those respondents (45%) answering that they have implemented a risk-based approach to their QA programs, follow-up questions were then used to further explore which QA practices (e.g., sampling and testing, inspection, certification, etc.) were most often targeted for risk-based adjustments. The majority (90%) answered that they modified sampling and testing rates based on risk; 75% indicated that inspection also received some risk-based adjustments.

Eighteen respondents provided additional commentary to clarify their answers regarding the implementation of risk-based practices. For example, several noted that frequency of sampling is decreased for materials perceived to have lower risk (e.g., off roadway application) or a short design life. For the most part, however, the comments implied that the reported "risk-based" processes were largely qualitative and informal, with much discretion left to project engineers to modify rates or protocols based on engineering judgment.

Given the importance of this topic area to the research, the themes of risk-based materials QA protocols and costs were further explored through the structured interview process described later in this Chapter.

Use of Contractor Quality Control (QC) Data

Use of validated contractor QC data in the acceptance decision can also be viewed as an optimization strategy as it may allow for a reduction in agency testing. Consistent with the literature review findings, the survey results indicated that several agencies (21%) "always" incorporate QC data into their acceptance decisions, with another 60% indicating that they "sometimes" incorporate this data. A smaller percentage of agencies (19%) reported that they never use contractor QC data for acceptance purposes.

The use of QC data often stems from the use of statistically-based or so called "quality assurance" specifications that include pay factor adjustments. Statistically-based QA specifications were most commonly reported as being applied to asphalt pavement (96%). A smaller percentage of respondents (67%) indicated that they use statistically-based specifications for concrete pavement, followed by structural concrete (42%), base course (35%), and earthwork (25%).

Some of the respondents also commented that use of QC data for acceptance is more typical of design-build or alternative project delivery projects.

Alternative Project Delivery Methods

The contract documents reviewed as part of the literature review suggested that use of design-build and other alternative project delivery methods may change the "traditional" approach to materials QA by shifting greater responsibility for quality to industry. Survey results were largely consistent with this finding.

The majority of respondents (82%) reported that they did use alternatives to design-bid-build project delivery, with design-build being the predominant alternative. Results also showed that warranties or maintenance contracts are used on a variety of materials, but most often on pavements or pavement elements.

Of those respondents who reported using alternative delivery methods, a slight majority (51%) indicated that they modify their standard materials QA processes based on project delivery method. Some respondents provided additional comments, which are provided in full in Appendix C, to clarify that the primary change entailed use of non-traditional organizational structures (e.g., QC performed by contractor forces, acceptance testing for key quality characteristics by a third-party firm retained by the design-builder, and verification testing and independent assurance by the DOT or the DOT's agent) to manage quality, particularly for design-build projects.

A slightly lower percentage (44%) of respondents indicated that use of alternative delivery methods does not affect materials QA; a few other respondents were unsure of how project delivery method affects materials QA, if at all. This broad range of responses reveals that alternative project delivery does not consistently affect materials QA practices across the different DOTs. Agency preferences, variations in interpretation of federal QA requirements, and maturity of local industry can all influence QA decision-making. However, trends suggest that as agencies gain more experience with alternative delivery, they gradually implement policies (through pilot or demonstration programs) that shift greater responsibility for materials management to industry.

Materials Management Systems

The survey responses indicated use of a wide range of different systems, software, and tools to manage materials QA, including AASHTOWare Project SiteManager, internally designed and developed Laboratory Information Management Systems (LIMS), and simple spreadsheets or Access databases. The additional commentary provided by several survey respondents further suggested that many agencies, even those that now use Site Manager, are moving towards more custom-built systems or modified off-the-shelf tools.

The optimization model to be developed under this research must therefore be sufficiently flexible to ensure compatibility with the wide range of different materials management systems in use today.

Cost of Quality

As noted in Chapter 2, the total cost of quality can be viewed as a function of the cost of conformance (i.e., QA prevention and appraisal costs) coupled with the cost of non-conformance (i.e., cost of defective or failed materials or products). To develop an optimization model, it is necessary to obtain a firm idea of what these costs are.

The research team began to explore the topic of QA costs by asking respondents to estimate the percentage of their program budget allocated to materials QA (i.e., testing, certification, and inspection). Answers ranged from 0 to 73%, with an average value of 11.95%. Such variability in responses may be the result of differences in how respondents interpreted the question or in how DOTs account for QA costs. A key issue to be addressed as part of the interview process therefore entailed determining how QA costs are allocated within agency construction programs and which materials represent the most critical assets requiring a commensurate investment in QA.

Similarly, the team attempted to extract information related to the percentage of defective (or nonconforming) materials or products. When asked if either their agency or qualified producers/suppliers maintained a database of defects, the majority of respondents (43%) replied that they were unaware of such information. Another 28% revealed that such data was not maintained.

Interviews

Consistent with the literature review findings, the survey responses indicated that several DOTs have already introduced varying levels of materials evaluation to their QA programs on the basis of factors such as materials risk, quantities, and project type, size, and/or complexity. The level of rigor used to support such QA decision-making, however, was not readily apparent from either the surveys or literature. The research team therefore conducted a series of one-on-one interviews with various DOT representatives to further explore the extent of DOT awareness of materials risk, the methods used to assess this risk, and the manner in which this knowledge is then used to prioritize QA needs to ensure optimum use of available resources.

The in-depth interviews also provided the opportunity for the research team to probe for specific data regarding QA costs. As discussed earlier with reference to Figure 2.5, to develop an optimization model, the following key inputs are needed:

- Cost to implement different levels of QA (testing, inspection, certification)
- Probability of a defect (non-conformance) when a given level of QA is implemented
- The probability and cost of potential defects

Such data proved too elusive to obtain through just the literature and survey alone. Therefore, a key objective for the interviews was to identify:

- How QA costs are accounted for and allocated within representative agency construction programs;

- What these costs are (either as a hard dollar value or percentage of the program or project budget); and

- Which materials represent the most critical assets requiring a commensurate investment in QA.

The methodology used to elicit such information is described below, followed by a summary of the responses received.

Interview Methodology

One-on-one interviews were conducted by the research team to capture additional insight into materials QA practices. As noted above, the intent of the interviews was to validate the findings from the survey and literature review and to gather data to support the development of an optimization model.

Interview Participation

In accordance with the team's original research plan, the goal was to interview five to eight DOTs representing a variety of different materials management and evaluation systems. Such diversity was considered necessary to ensure the optimization model would have sufficient flexibility to meet the varying needs of different DOTs. Specific criteria for selecting interview participants included the following:

- DOT location (geographical spread)
- Range of materials management systems
- Materials qualification and certification practices
- Experience with alternative delivery and warranty/guarantee provisions
- Structured approach to material QA/acceptance based on material type (project-produced, plant-produced, and standard manufactured products), project types, and other risk factors
- Availability of previous FHWA or internal QA process reviews or audits

Based on the literature review and survey responses (through which several individuals indicated interest and willingness to assist the team with additional information collection), the following agencies were targeted for detailed interviews:

- California DOT (Caltrans)
- Florida DOT (FDOT)
- Ohio DOT (ODOT)
- Maryland State Highway Agency (MDSHA)
- New Jersey DOT (NJDOT)
- Texas DOT (TxDOT)
- Virginia DOT (VDOT)
- Washington State DOT (WSDOT)

Contact information for the primary agency representatives is provided in Table 3.1 below.

Table 3.1: Interview Participation Summary

State	Primary Contact	Number of DOT Participants	Telephone Interview	Onsite Interview
California	METS-OSM Office Chief CT-DOC-OCE	11	N/A	5/21 to 5/22/2014
Florida	Director, Office of Materials	1	5/27/2014	N/A
Maryland	Division Chief, Materials Management Office of Materials	1	6/12/2014	9/25/2014
New Jersey	Manager, Bureau of Materials	1	5/13/2014	N/A
Ohio	Structural Welding Engineer, Office of Materials Management	1	5/13/2014	N/A
Texas	Deputy Director, Construction Division Technical Operations	3	5/12/2014	11/14/2014
Virginia	Assistant State Materials Engineer	1	5/28/2014	N/A
Washington	State Materials Engineer State Construction Engineer	2	5/21/2014, 6/13/2014	N/A

Interview Questionnaire

To guide the interview discussions, the team developed a comprehensive questionnaire that addressed the following key topic areas:

- Characterization of major materials (categories) for consideration in the model (i.e. project-produced, specialty fabricated materials/products, and standard manufactured products);
- Materials QA protocols (i.e. sampling and testing, certification, inspection) for major materials and how they vary based on project type, size, quantity, project delivery method, or other criteria;
- Internal and external QA costs related to sampling and testing, certification, or inspection for verification and acceptance, including how these costs are tracked or accounted for;
- Use of contractor QC test data for acceptance, including how use of such data affects agency resources;
- Use of pre-approved products and materials or QPLs and relationship to materials QA;
- Identification of significant materials/product risks and likelihood and consequences (cost or other) of non-compliance with specification requirements; and
- Use of any emerging or advanced testing or certification methods.

A copy of the questionnaire is provided in Appendix D. This form was distributed in advance of the interviews to provide participants with the opportunity to assemble any necessary information, data, or subject matter experts prior to the interviews. Interview responsibility was divided among the research team, with two team members participating in each interview to help ensure adequate documentation of responses.

Interview Results

Through the interviews, some general trends related to the following key topic areas were identified:

- Optimization strategies (how the DOTs currently optimize materials QA by adjusting the frequency of testing based on material quantities, material criticality, contractor/supplier experience and qualifications, project delivery method, etc.)
- Risk-based approaches used to optimize QA
- QA Costs and budgeting of materials QA

Similar themes were identified in the literature and survey results; however, the interviews provided the opportunity to obtain more detail related to these practices and trends. The raw data obtained from the interviews is provided in Appendix E. It should be noted that this data represents a limited, though targeted, cross-section of DOT experience with materials QA practices and contains both factual information and the opinions of the interview subjects. In interpreting the raw information to create the summaries that follow below, the research team strove to provide an objective assessment of best practices and lessons learned and how these findings could be incorporated into a flexible optimization model designed to appeal to a national DOT audience.

Optimization Strategies

Table 3.2 identifies the various QA optimization strategies that were identified during the interviews, followed by a more detailed summary of each of these practices.

Table 3.2: Optimization Strategies Identified by Interview Subjects

Optimization Strategy	California	Florida	Maryland	NJ	Ohio	Texas	Virginia	Washington
1. Reduced frequency of testing for small quantities and large volumes of project-produced materials under control	✓	✓		✓				✓
2. Streamlined QA requirements for Local Agency projects	✓	✓					✓	
3. Consideration of material criticality	✓	✓		✓				
4. Qualifications of producers or suppliers	✓		✓	✓	✓	✓	✓	✓
5. Alternative project delivery methods		✓	✓			✓	✓	
6. Explicit use of risk management principles	✓					✓		✓

1. *Reduced frequency of testing for small quantities or large volumes of project-produced materials under control*

For field-produced materials, several of the agencies interviewed explained that they reduce the QA level of effort for small quantities and/or large volumes under control. This reduction in QA effort generally entails decreasing the frequencies of sampling and testing found in a DOT's minimum sampling and testing guide, but may also include accepting constituent materials (e.g., aggregates, concrete) on the basis of certification with an option to run a verification test, or, for very small projects, visual inspection only.

Specific examples of such strategies are provided below.

- **FDOT** reported using visual inspection in lieu of sampling and testing for smaller quantities of specific material types (i.e. less than 2000 tons of HMA for an entire project using Type FC and SP asphalt mixtures). Further FDOT may reduce the frequency of sampling and testing for small or low risk projects (i.e. less than $2M). Also, FDOT may reduce the sampling and testing frequency (or increase the lot size) for certain materials shown to be under control from the same production facility. For example, if 10 consecutive concrete strength tests attain an average strength greater than two standard deviations above the specified minimum, the lot size can be doubled.

  FDOT provided examples where the testing effort may be reduced for the specific materials and/or properties as shown in Table 3.3

Table 3.3: Examples of Reduced QA Testing Effort (FDOT)

Material	Possible Optimization Strategies
Section 346 Concrete	50% reduction in sampling frequencies (i.e., doubled lot size) when produced for the same mix design and production facility and where average strength results for 10 consecutive tests meet the strength criteria
Section 347 Non-structural concrete (i.e. sidewalk, curb, gutters)	Acceptance by certification on the delivery ticket, with discretionary sampling and testing to verify quality
Section 120, Excavation and Embankment density Section 125, Excavation for Structures and Pipe density Section 200, Rock Base density Sections 327/330, Pavement cross slope measurements Section 410, Precast Box Culvert absorption tests Section 462 Tendon post-tensioning, and Section 560 Structural steel soluble salt/conductivity tests	50% reduction in the required sampling and testing frequency when materials are shown to be under control
Section 334 hot mix asphalt (Type FC and SP mixtures) that are less than 2000 tons for an entire project	FDOT Engineer can accept the asphalt mix on the basis of visual inspection, and may require the Contractor to run QC tests and run independent verification tests at its discretion

- **NJDOT** indicated that they adjust the frequency of QA testing based on the quantity of field produced materials. For example, for concrete pours of less than 20 yards, and for large volumes under control, the rate of testing is significantly reduced.

- **Caltrans**, as discussed in the Chapter 2 literature review results, developed a Construction Quality Assurance Manual (which was shared with the team prior to the interview) that attempts to strike a balance between practicality and ensuring enough testing to control the process.

During the interview itself, Caltrans explained that the key to achieving this balance is to relate testing frequency to the rate and consistency of production. If the production tends to be continuous and consistent, the testing frequency may be lower than that used if there are multiple interruptions. The testing frequency may also be reduced for materials with a history of accurate, uniform test results that consistently meet specification requirements. Conversely, the rate of testing should be higher on sources that:

- Are newly developed,
- Furnish materials only on an intermittent basis,
- Have a history of questionable quality, or
- Have failing test results.

- **WSDOT** explained that for small quantities of field-produced materials, it uses a reduced testing frequency, which may be on the order of 1 test per 2,000 tons. The interviewees, with reference to Chapter 9 of the WSDOT Construction Manual (which was previously discussed in Chapter 2 of this report), noted that the Project Engineer has significant discretion to adjust testing frequencies. For example, very small quantities of certain materials may be accepted based on visual acceptance alone. For large quantities, the QA frequency may be adjusted downward based on the uniformity of the test results (first 10 tests).

2. *Local Agency Project Specification QA Streamlining*

Some agencies identified the use of simplified specification requirements for non-critical local agency projects as an example of QA optimization:

- **FDOT** has developed a set of streamlined specifications (called the "Big 4") that include a modest reduction in the sampling frequency and amount of samples, along with a relaxation of the conditions (e.g. temperature or haul times) in which the samples or measurements are taken.

- **Caltrans** tailors its Quality Assurance Plans (QAP) for local programs to fit the project profile. Caltrans recently worked with a small local agency (Morro Bay), who hired a materials/testing consultant to develop a project-specific QAP for asphalt concrete. The QAP met federal-aid requirements, but included frequency tables for materials testing that were much simpler and easier to follow than the standard Caltrans frequency tables, and reflected a lower frequency of testing. Based on a follow-up teleconference with the Caltrans local program coordinator, Caltrans is now considering developing a modified QAP with simplified frequency tables for other major materials categories including earthwork (aggregates), asphalt, and structural concrete.

- **VDOT** has established a tiered or risk-based approach to QA oversight for locally let, federally funded projects on which primary QA responsibility has been delegated to local staff but for which VDOT must still perform some level of oversight to satisfy its stewardship role. As shown in Table 3.4, VDOT defines three levels of oversight based on the criticality of project elements. For less critical projects, VDOT conducts random site visits or QA audits. For more critical projects or purposes, VDOT performs more frequent site inspections and/or verification testing.

Table 3.4: VDOT LAP Oversight Levels Based on Risk of Non-Compliance

Oversight Level	Probability	Impact/Probability
High (H)	High probability of non-compliance	Significant impact on infrastructure due to non-compliance Significant effects to quality of construction, cost, and schedule
Moderate (M)	Moderate probability of non-compliance	Moderate impact on infrastructure due to non-compliance Moderate effects to quality of construction, cost, and schedule
Low (L)	Low probability of non-compliance	Moderate impact on infrastructure due to non-compliance Moderate effects to quality of construction, cost, and schedule

3. Criticality of Materials

Three of the agencies interviewed explained that they consider material criticality and consequences of failure when determining the required QA level of effort:

- **FDOT** distinguishes between more and less critical materials, primarily based on safety-critical criteria. For example, FDOT conducts more rigorous inspections for pre-stressed beams, piles, steel beams, and similar safety-critical structural elements. Sampling and testing frequencies are also increased or reduced based on the criticality of the materials.

- **NJDOT** similarly considers the criticality of the element (e.g., fracture critical structural steel, pre- stressed elements, precast) when determining the required level of QA.

- **Caltrans** explained how its Construction Quality Assurance Program Manual includes a roadmap for developing tiered materials specifications based on material criticality. The comprehensive tier level listing is based on the consequence of failure of each item. Tier Level 1 items are considered to have the greatest consequence of failure, while Tier Level 4 items have the least consequence. The four-tiered approach is intended to ensure that the appropriate level of inspection, sampling, and testing resources is applied to each contract item commensurate with the item's consequence of failure.

4. Supplier Qualifications for Fabricated and Manufactured Materials (Approved Producers/Suppliers)

As summarized below, several of the DOTs interviewed noted that they adjust the level of QA effort based on the qualifications and standing of producers and materials suppliers. In some cases, qualifications criteria are based in whole or in part on national certification standards. For example, the American Institute of Steel Construction (AISC) maintains certification standards for structural steel. AISC certified companies must go through a rigorous initial evaluation and are subject to annual audits. The evaluations entail a comprehensive administrative review, a documentation audit, and an on-site audit of the firm's quality management system. For other materials, DOTs reported use of a more subjective or internal system of rating suppliers based primarily on past performance.

- **ODOT's** Materials Management Office defines eight levels of fabricator qualifications for steel structures. As shown in Table 3.5, levels include SF (Standard Fabricated members) and UF (Unique Fabricated members), as well as levels designated as 1 through 6. ODOT classifies each fabricator at the highest level of fabrication it is qualified to perform. The QA requirements then vary with these levels of qualification. At the lowest level – Standard Fabricated (SF) members – the Department will base acceptance on certification backed up by random Department audits of the work and documentation. At the highest level – Level 6, which includes fracture critical members and components – the Department will perform QA reviews of shop drawings and material test reports, and will conduct the most rigorous of inspections.

Table 3.5: ODOT Levels of Fabricator Qualifications

Level	Description of Capabilities
SF	Standard Fabricated (SF) members described and paid for as Item 516, 517, and 518 and detailed by standard bridge drawings. Material and fabrication acceptance by certification with random Department audits of the work and documentation.
UF	Unique Fabricated (UF) members not covered by standard bridge drawings and not designed to carry tension live load. Examples include curb plates, bearings, expansion joints, railings, catwalk, inspection access, special drainage, or other products. Examples also include retrofit cross frames, retrofit gusset plates, retrofit lateral bracing, or other miscellaneous structural members not included in Levels 1 through 6. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, UF Level.
1	Single span, straight, rolled beam bridges without stiffeners, Secondary and Detail materials designed to carry tension live loads such as retrofit moment plates. Case II Loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
2	Multiple span, straight, rolled beam bridges without stiffeners. Case II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
3	Single or multiple span, straight, dog legged, or curved, rolled beam bridges including stiffeners. Case I or II Loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
4	Straight or bent welded plate girder bridges. Case I or II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
5	Straight, curved, haunched, or tapered welded plate girder bridges. Case I or II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
6	Truss bridges, fracture critical bridges, fracture critical members, or fracture critical components new or retrofitted. Case I or II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Level 6.

- **Caltrans** has developed three levels of inspection based on risk and probability and consequence of failure. Past performance of the material supplier is a key factor in the material and workmanship probability assessment. The levels of inspection are:

  - Continuous (F/T inspector at plant)
  - Intermittent (moderate risk items like signals and lighting pole installation)
  - Programmatic (lower risk items such as timber, cyclone fencing

  Fabricators typically have a QC manager. For certified precast suppliers, Caltrans inspection forces will audit the QC process. Aggregate quarries require yearly certification.

Caltrans is adopting a risk-based approach to source inspection that shifts more risk and responsibility to suppliers to self-regulate.

- **NJDOT** indicated that it will adjust or cut back on testing or inspection (or audit), depending on factors such as:
  - Criticality of the element (i.e. facture critical structural steel, pre- stressed elements, precast, etc.)
  - Quality of supplier (past performance)

- **TxDOT** instituted a program of qualified producers. To be on this list, a producer must be re-qualified every two years. If a producer is in the Producer/Supplier QA program (reduced risk), TxDOT will lower the number of required samples and conduct limited verification testing.

- **VDOT** assesses the performance of materials received from its suppliers. Aggregates are usually risk based. Quarries are rated based on quality data. Epoxy, guardrail, cement, fly ash, and other products may use modified acceptance based on certification and an approved supplier source list. For admixtures, at a minimum VDOT checks the paperwork.

- **WSDOT** uses an internal system of ratings or evaluations of fabrication facilities that affects the level of inspection. WSDOT also takes into account nationally certified facilities such as PCI concrete certification.

- **MDSHA** is relying more on national standards to certify plant-produced materials (e.g., PCI, NTPEP) and is moving towards the use of regional plant audits versus project-based audits to optimize limited resources. MDSHA is also exploring a cost-sharing program in which the agencies in the mid-Atlantic region could share in the costs of QA plant inspection (e.g. many agencies use the same supplier, Valmont, for sign structures).

5. Alternative Project Delivery Methods

An important finding in both the literature and the survey was that the use of alternative project delivery methods can change traditional roles and responsibilities for QA. During the interviews, four agencies elaborated on how they modify their standard QA practices for design-build and other alternative contracting methods.

- **FDOT** has a mature alternative project delivery program, with extensive design-build experience, and more recent Public Private Partnership (P3) project experience involving long-term operation and maintenance agreements.

  For FDOT's P3 projects, QC is performed by the contractor, verification shifts to the Concessionaire's Quality Assurance Firm (QAF), and FDOT or its Construction Oversight Services (COS) consultant performs risk-based auditing. The levels of testing may be adjusted if the process is under control.

  For example, as shown in Table 3.6, for FDOT's I-4 Ultimate P3 Project, the initial frequencies for both QC and QA testing of Concrete Paving may be reduced by one-half or greater for 10 consecutive passing lots (performance-based frequency reduction) for the same crew, equipment, and materials. (The reduced frequencies will revert back to the initial frequencies if comparisons of QA and QC results do not meet the specified thresholds.) In contrast, for

Concrete – Structural, the frequencies of testing may not be reduced, suggesting that FDOT considers structural concrete to be a higher risk item. (FDOT 2013)

Table 3.6: Proposed FDOT I-4 P3 Concessionaire and COS Testing Frequencies

No.	Material Type	FDOT Material No.	Test Name	Spec. Section	Test Reference	Concessionaire Contractor QC Frequency	Concessionaire QAF QA Frequency	COT OT Frequency	Sample Size
10	CONCRETE PAVING	145	COMPRESSIVE STRENGTH	350 & 352	ASTM C39	Initial: 1 test per lot, Reduced frequency: 1 test per 4 lots	Initial: 1 test per 4 lots, Reduced frequency: 1 test per 8 lots	Risk-based Audit	4x8 CYLINDERS
			SLUMP		ASTM C143				
			% AIR		ASTM C173 or C231				
			TEMPERATURE		ASTM C1064				
			WATER CEMENT RATIO		FM 5-501				
			PAVEMENT THICKNESS		ASTM C174 or ASTM C1383	Initial: 1 per 2,500 SY, Reduced frequency: 1 per 5,000 SY	N/A		
11	EDGE DRAIN DRAINCRETE	154	DRAINABILITY	446	FM 5-570	Initial: 1 test per lot, Reduced frequency: 1 test per 4 lots	N/A		CYLINDERS
12	CONCRETE-STRUCTURAL	160	COMPRESSIVE STRENGTH	400	ASTM C39	Initial: 1 test per lot, No reduced frequency	Initial: 1 test per 4 lots, Reduced frequency: 1 test per 8 lots	Risk-based Audit	(3) 4x8 CYLINDERS
			SLUMP		ASTM C143				
			% AIR		ASTM C173 or C231				
			TEMPERATURE		ASTM C1064				
			WATER CEMENT RATIO		FM 5-501				

As part of the scope for FDOT's COS on the I-4 P3 project, the COS is responsible for developing a Risk-based Audit Plan (RBAP) to statistically evaluate and validate that the Concessionaire is effectively carrying out its obligations as set forth in the Concessionaire's Agreement. As further explained in the scope:

> *The COS Consultant will be responsible for extracting and organizing requirements from the Contract Documents against a work breakdown structure. The resulting values shall be entered into a Requirements Verification Database that will place a higher value to high risk requirements and a lower value to lower risk requirements. High risk items include but are not limited areas of greatest liability such as:*
>
> - *Foundations;*
> - *Bridge structures;*
> - *MSE walls;*
> - *Design elements;*
> - *Permits;*
> - *Right of way*
> - *Owner commitments, etc.*
>
> *The RBAP plan shall optimize the process for systematically combining both the likelihood of failure and the consequence of failure to establish a prioritized strategy for the monitoring of the Concessionaire's operations as they relate to their QA/QC Plan and Agreement requirements. The RBAP shall utilize best practices and allow the COS to shift resources to provide a higher level of coverage on high-risk activities and an appropriate effort on lower risk activities.*

- **TxDOT** explained the origins and implications of its *Design Build Quality Assurance Plan (QAP) Implementation Guide*. As discussed in the Chapter 2 literature review, the QAP guide is intended to help provide statewide consistency and a programmatic approach to QA for design-build projects on which the contractor's test results are used in the acceptance decision.

  The guide applies only to design-build projects with an optional Capital Maintenance Agreement. (TxDOT noted that it had previously experimented with using contractor QC tests for HMA in acceptance decisions, but the process was deemed not workable and was discontinued in 2003.)

  The guide, and its three-tiered approach to owner verification, evolved from lessons learned on the SH 130 design-build project, which consisted of 40 miles of roadway with long-term warranty options. TxDOT conducted an initial materials risk workshop related to SH 130 after recognizing that the pace of the project was not conducive to standard TxDOT acceptance testing. Based on this workshop, TxDOT developed a project-specific QAP that allowed for the use of contractor-performed acceptance test results if they are validated by owner verification (OV) testing. From this, TxDOT's stratified tiered QAP guide evolved. (Note that in TxDOT's parlance, QA testing refers to quality *acceptance* testing performed by the contractor that is used in the acceptance decision; OV testing refers to TxDOT's owner verification testing used to validate the contractor's QA results.)

TxDOT initially found that its design-build CDA contractors were performing QA testing far in excess of the minimums identified in the TxDOT Guide Schedule, which in turn caused TxDOT (or TxDOT's testing consultant) to perform significantly more OV testing than anticipated (given that the proportional frequency of OV testing in the Guide Schedule is typically 10% of the contractor testing frequency), thereby increasing TxDOT internal QA costs.

After experiencing increased OV testing because of the number of QA tests run by the contractor, TxDOT now allows for the development of a project-specific OV approach with a recommended OV test frequency based on unique project risks, length of warranty (i.e., TxDOT's residual risk after the contractor has completed the project and has fulfilled its maintenance obligations), and other factors. Currently, most design-build CDA contracts have a 5-year mandatory warranty and TxDOT chooses whether or not to include additional 5-year increments. The warranties typically address soils, pavements, drainage, and structures. Usually, Level 1, the highest level of OV testing, is currently reserved for soils, pavements, and structures.

TxDOT's tiered-approach to OV testing was initially based on the perception of what testing is most critical for work with a *15-year* warranty. The Department is now implementing a new project delivery process called Comprehensive Maintenance Agreements (COMA) that includes a *25-year* total maintenance requirement for both planned and preventative maintenance, as well as routine mowing, snow removal, animal removal, patching and other routine maintenance work. Given the extent of industry's responsibilities for such 25-year maintenance agreements, TxDOT is trying to determine the appropriate level of OV to apply during construction to ensure both efficiency and effective compliance with the provisions of 23 CFR 637.

- **VDOT**, as summarized in the Chapter 2 literature review, has developed a manual addressing the *Minimum Requirements for Quality Assurance and Quality Control on Design Build and Public-Private Transportation Act Projects* (January 2012). VDOT explained during the interview that the guide is a reflection of VDOT's philosophy that, particularly for P3 projects, the developer/concessionaire has "equity" in project and thus VDOT need not act as the sole owner of the project. Nevertheless, VDOT retains final authority for determining the acceptability of materials and workmanship, and bases its acceptance decision on the following:

    - Results of the concessionaire/design-builder's QA and QC sampling and testing conducted at specified frequencies and locations (In this case, "QA" refers to acceptance testing and inspection performed by an independent firm retained by the concessionaire/design-builder. This third-party QA effort includes monitoring of the contractor's quality control program, which is a separate and distinct subset of the concessionaire/design-builder's overall QA plan.);

    - Results of VDOT's (or its agent's) verification sampling and testing conducted at specified frequencies and locations;

    - VDOT's inspection of attributes and processes that may affect the quality of the finished product; and

    - Any dispute resolution processes used to resolve discrepancies between the VDOT's verification sampling and testing and the contractor's sampling and testing.

- **MDSHA** explained that it modifies its standard materials QA processes for design-build mega-projects. For a design-build project, the contractor must prepare and submit for approval a Quality Management Plan (QMP). MDSHA then hires a consultant to assure that the design-build contractor follows its approved QMP. The SHA performs verification testing of contractor test results used in the acceptance decision.

6. *Risk-Based Methods for Determining Level of Materials QA*

The literature review and survey responses suggested that several agencies do consider risk, whether formally or informally, when developing their QA programs. A key objective of the interviews was to further explore how DOTs assess risk and use this information to prioritize QA needs to ensure optimum use of available resources.

This topic was primarily discussed with California, Washington State, and Texas DOTs, all of whom, based on the literature review results, have implemented risk management practices to optimize materials QA.

- **Caltrans**, as stressed by the interview participants, is a strong advocate of formal project risk management, and requires that risk management processes be applied to all capital and major maintenance projects to help ensure cost, schedule, and scope objectives are met.

  Given this culture of risk awareness, different Divisions within Caltrans are attempting to incorporate risk-based decision-making into their procedures. For example, as discussed previously in the Chapter 2 literature review, the Caltrans Division of Construction has developed a risk-based approach to assigning tiers to construction materials based on their criticality (consequence of failure).

  Similarly, the Caltrans Office of Structural Materials (OSM) has initiated a qualitative risk-based decision framework for acceptance of fabricated materials. The Material Plant Quality Program (MPQP) certification is used for plant produced materials. The program assures that the QA effort is scaled correctly by deploying inspectors through a risk-based decision process that determines the level of inspection (i.e., from programmatic to intermittent to continuous). High priority/high risk items are inspected or tested at higher inspection levels. Project type is also considered in the evaluation, with higher profile or higher risk projects subjected to more rigorous QA.

  As shown in Figure 3.2 below, which Caltrans shared with the team, the qualitative risk process involves a material and workmanship probability assessment (low-medium-high) and an impact assessment scaled according to material failure and project types. The risk assessment determines the level of plant inspection (QA effort) required, ranging from low (programmatic) to high (continuous inspection). A low or programmatic level might not entail a shop inspection whereas higher levels would entail intermittent shop inspections or a full/time plant inspector. Caltrans distinguishes between projects with a regular production schedule and those with accelerated or higher impact production schedules, which tend to increase the level of QA required.

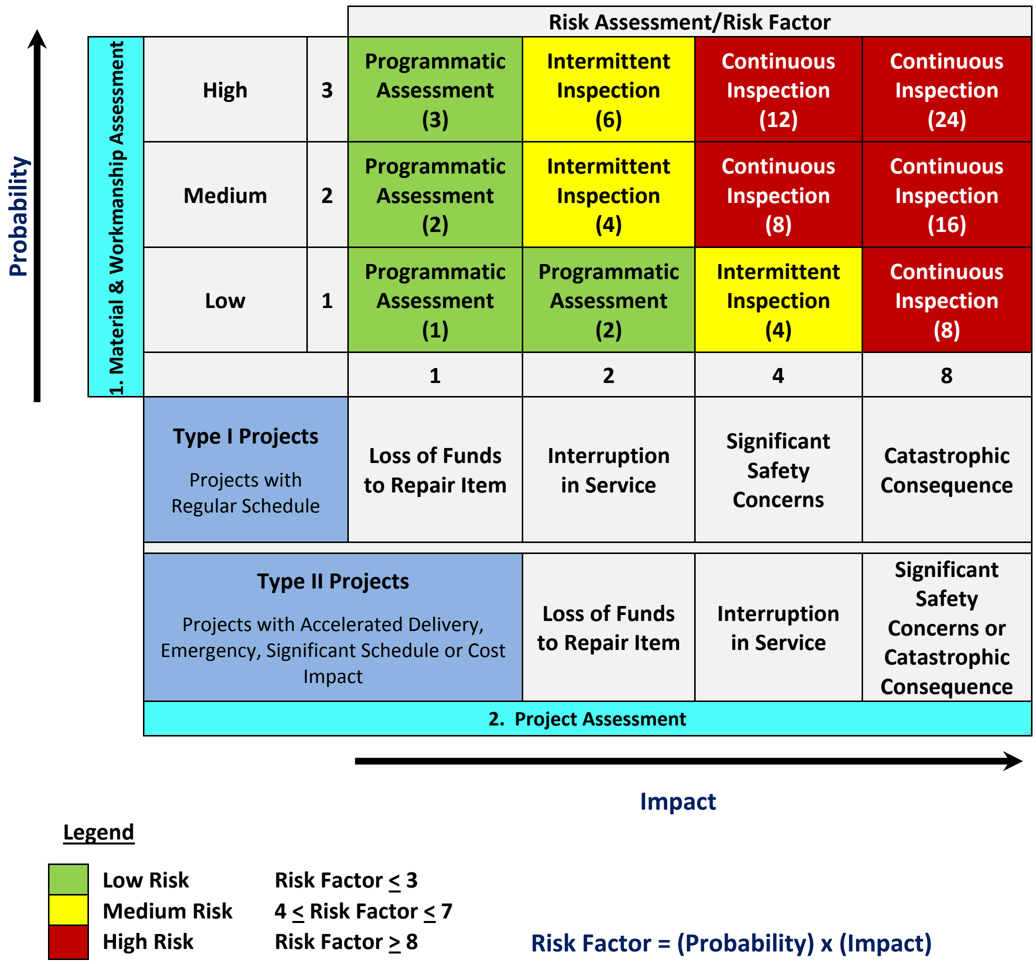

Figure 3.2: Caltrans OSM Risk Management Matrix
(Courtesy of Caltrans)

- **WSDOT**, between 2002 and 2005, conducted an internal programmatic risk analysis to rationally determine the appropriate level of QA needed to accept each construction material. The results of this effort formed the basis of the *Materials Risk Analysis Report* (WSDOT 2010) discussed in detail in Chapter 2. During the interview, WSDOT shared additional insight into its risk process and the results it generated. For example, WSDOT was able to use the results of this analysis to adjust or optimize the level of QA for some materials that previously were subject to more rigorous QA.

  As noted in its report, WSDOT also stressed that in an ideal situation, a DOT would have electronic materials and asset management systems that would provide the data needed to assess actual risks and actual costs, rather than have to rely on estimates provided by subject matter experts. Without such information, however, a Delphi panel of experts can provide a reasonable approach for developing a more rational materials acceptance system.

- **Texas DOT**, as discussed above and in Chapter 2, has implemented a three-tiered approach for owner verification (OV) testing that is based on TxDOT's perceived residual risk for material performance after the Developer's maintenance obligations expire.

Cost of Quality

QA Costs and Budgeting of Materials QA (Cost of Conformance)

In the survey responses, when the agencies were asked what percent of the program budget was allocated to QA, the responses ranged from 0 to 73 percent with an average value of 11.95%. The lack of consistency in the responses received suggests that the question was too broad or that the cost allocation is accounted for differently among the DOTs interviewed. In the interviews, the team attempted to explore this issue further to obtain more clarity and detailed information related to QA costs.

The team first asked the DOTs to explain the elements of their QA costs (e.g., sampling and testing, certification programs, inspection in the field or at the fabrication facilities, etc.) and how they derived and accounted for these costs. In general, the results indicated that materials division staff (Central Office and Districts), laboratory staff, and plant inspection staff are typically accounted for as a percentage of the overall *program* budget (similar to an internal indirect overhead cost). In contrast, project-level QA field costs, consisting of inspection and testing of project-produced materials (also inspection of materials/products delivered to the construction site), are generally estimated as a percentage of the *project* construction budget. The percentages of QA may vary depending upon the project size or type of material.

Follow-up questions asking for the percentages of QA costs also received a wide range of responses from the different DOTs interviewed. For example, estimates of programmatic costs (including laboratory testing and plant inspections) ranged from 0.4 to 4% of the program budget. Estimates of project-level QA costs ranged from 10% to 30% of the project construction budget depending on the DOT, District, and project type. It was suggested that, if needed, the team might want to reach out to a DOT budget and finance office to get more precise data on QA costs. In general, however, the team learned from the interviews that QA cost information is generally not readily available.

TxDOT recounted its own difficulties in using QA cost data to optimize sampling and testing frequencies. TxDOT's Guide Schedule of Sampling and Testing provides the basis of the Department's materials testing requirements. The current version of this document is based in part on the findings of a research effort that was completed in 2001 (project 1781) by the UT Center for Transportation Research. TxDOT shared and discussed the resulting report, entitled *Development of a Methodology to Determine the Appropriate Minimum Testing Frequencies for the Construction and Maintenance of Highway Infrastructure*, with the research team.

As discussed in the referenced report, the goal of the UT research project was to statistically determine the optimal sample size and appropriate testing frequencies based on: the variability of the quality characteristic being measured, the risks that a state DOT or a contractor is willing to take, the tolerable errors each is willing to accept, and the cost of the testing to be performed.

The study found that there was a high level of perceived risk, but the level of testing needed to avoid such risk was not deemed practical. The frequencies included in the Guide Schedule are therefore primarily driven by engineering judgment rather than on cost-based statistics due to the difficulty in capturing and tracking such data. A preamble was inserted into the Guide Schedule noting that the risk to both the Department and the Contractor of either rejecting "good" material or accepting "bad" material ranges from 20% to 40%.

WSDOT provided the most detailed assessment of costs for materials QA at both the program and project levels. At the program level, materials management QA cost (including laboratory testing, plant inspectors, and QA staff) amounts to approximately $22M per year. This amounts to less than 1% of the

WSDOT capital budget for highways in years 2013-2015 (assuming that this cost is allocated across the whole highway program).

Additionally, each project has a QA component. The WSDOT budget office maintains data on such project-level costs. For standard manufactured products (e.g., rebar, reflective materials, pipe), that are certified by AASHTO NTPEP or other national standards, the industry bears the cost of material evaluations and testing to become qualified or maintain its qualification on the QPL.

WSDOT provided the team with a standard schedule of billing rates for services and testing for all of the tests run in the lab. The 2014 rates included both hourly rates and estimated test times for tests and analyses of the material.

The WSDOT State Construction Engineer provided additional input on construction verification and acceptance costs. Typically CE consultant contracts range from 8 to 10% of construction costs for a project. Approximately 30% of that amount (or 2-3% of construction) is for DOT materials inspection and testing for acceptance.

WSDOT further noted that pavements and/or structures typically amount to 40% to 50% of the Department's QA costs for typical projects, depending on the scope. In general, fabricated items result in lower construction QA cost for the Department. Field-produced asphalt pavements typically require more CE attention to both quantities and QA. Structures may also drive the QA effort depending on the project type.

A trend identified through the interview discussions is that is industry is assuming more responsibility for the cost of materials QA through national, regional, or state qualification or certification programs and greater use of contractor QC testing for acceptance. Most of the DOTs interviewed believe that this trend will continue as DOTs continue to downsize their inspection and testing staff while maintaining or increasing the size of their projects or programs. With this transfer of QA costs, there is logically a built-in market-based efficiency. For example, TxDOT indicated that it was able to negotiate the same rates for various laboratory testing services with approximately 12 in-state commercial laboratories given the level of competition. However, capturing such efficiencies on a scale that could be incorporated into the optimization model would be difficult.

Deviations from Specifications or Failure Issues (Cost of Non-Conformance)

QA optimization must also consider the cost of non-conformance. MDSHA was able to provide the most feedback related to material non-conformances or failures that required rework. The SHA indicated that they have experienced more issues related to in-place concrete workmanship, attributable primarily to either bad pours or bad curing of cylinders (in some cases related to test technician workmanship), than with other materials. Other issues included segregation of pavement caused by not loading trucks properly (again a workmanship issue). These observations suggest that greater levels of QA effort (cost) should be allocated for field-produced materials (testing and inspection), particularly for soils, pavements, and cast-in-place structures because of the variability in the production and placement of these materials. This is consistent with the WSDOT response that 40-50% of its QA costs were allocated to field-produced pavements and structures.

MDSHA also noted that it had experienced issues with manufactured or plant-produced materials, and cited as an example the premature corrosion of couplings on pre-fabricated sign poles, which was ultimately determined to be a major manufacturer issue requiring state-wide replacement of couplings. MDSHA also experienced a major issue concerning defective anchor bolts on traffic structures (which became a national safety issue related to heat treated bolts) that resulted in the replacement of the defective bolts. Other issues included a precast supplier shorting steel in beams (the steel did not meet design standards), and installation of bridge seals without proper lubrication. From a risk standpoint, MDSHA commented that it had the most concerns for bridge decks and anchor bolts for overhead sign structures.

Summary

The data collection effort, similar to the literature review findings, suggested that different DOTs approach materials QA in a variety of ways. However, despite such diversity in QA programs, the following general trends can be identified:

- A number of DOTs currently optimize their materials QA practices to some extent, particularly for acceptance, by modifying their standard sampling and testing schedule to reflect different tiers or levels of effort based on material criticality, quantities, type/size of project, project delivery method, and similar factors. There were no noteworthy differences in the types of optimization strategies used that could be correlated to a DOT's size, geographic location, or other factors, suggesting that these strategies could be universally applied. Information received from international transportation agencies suggested less reliance on owner-performed sampling and testing and greater use of contractor and supplier-provided certifications than their US counterparts.

- Material certification and the use of approved products (subject to certification or inspection) has resulted in the acceptance of increasing numbers of materials and products by certification, and has allowed for reduced levels of sampling and testing and inspection.

- Some DOTs have developed processes to incorporate risk considerations in their materials QA practices. This is essentially an extension of DOT efforts to tier materials QA based on the criticality of materials by applying a more formal framework for risk rating materials.

- With regard to materials management systems, several agencies have, or are moving towards, custom-built or modified off-the-shelf tools. As the goal of the model is not to replace the steps and procedures that DOTs normally would follow in developing a materials QA plan for a given project, but to enhance or optimize these processes, the optimization model must have the flexibility needed to ensure compatibility with the variety of different materials management systems in use.

- Actual cost of QA is not well defined in most agencies. Typically, the DOTs capture total QA costs and distribute them across the project or program to develop an operating percentage.

- Greater levels of QA effort (and thus QA costs) tend to be allocated to project-produced materials due to the perceived variability in the production and placement of these materials.

CHAPTER 4 – OPTIMIZATION MODEL

Model Overview

As discussed in Chapter 2, the conceptual foundation for analyzing the economics of quality is well established. Theoretically, if prevention, appraisal, and failure costs are measured and tracked, it is possible to determine an optimum QA investment point at which the total cost of quality (i.e., the sum of the cost of conformance and the cost of failure) is at a minimum.

Applying such an approach, however, can be challenging. As suggested in Chapters 2 and 3, the practical implementation of a quality-cost model may prove difficult absent tangible cost data. For example, to fully develop the cost-of-quality curves shown previously in Figure 2.5 requires the following key inputs:

- Cost to implement different levels of QA (testing, inspection, certification)
- The probability of a non-conforming material for each level of QA
- The cost of repairing or replacing non-conforming materials should a defect occur

For organizations that actively track this information (e.g., through a materials management and/or asset management system), adopting such an optimization model would allow for a direct approximation of costs, thereby reducing the need for (or perception of) subjective decision-making.

The cost of QA can be elusive for agencies. For those that may find the required quality-related costs too difficult to capture and track, it may still be possible to develop reasonable approximations of the required inputs through expert judgment or other experimental data collection techniques (e.g., Delphi Survey).

Alternatively, if reliable cost information is too elusive to collect, taking a more qualitative approach to optimization can also provide actionable information. Engineering judgment combined with classic risk management principles can be used to prioritize materials and QA activities on the basis of the probability and consequence of material failure. What such a qualitative process may lack in academic rigor, it can make up for in accessibility and ease of use. As discussed in Chapter 2, WSDOT has had a positive experience implementing such a qualitative approach.

To ensure broad applicability, the framework presented in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs* (provided under separate cover) combines the explicit cost-based optimization approach with more qualitative processes for risk ranking materials and material properties. The resulting three-level analytical framework, as summarized below, is sufficiently flexible to accommodate the range of materials and acceptance practices in use today as well as any new products that may emerge in the future.

The three levels of the framework can be described as follows:

- **Level 1** entails conducting a qualitative risk rating of materials and then aligning these ratings with QA methods that can provide reasonable assurance of acceptable quality. This level is similar in concept to the processes used by WSDOT and Caltrans to risk rank materials, as described in Chapter 2.

- **Level 2** has a narrower focus, attempting to optimize acceptance testing by emphasizing properties and test methods that are more direct indicators of performance. This level is similar to the approach used by TxDOT and NYSDOT, as described in Chapter 2, to determine the appropriate level of owner verification testing.

- **Level 3** adapts the classic total cost of quality model (as illustrated previously in Figure 2.5) to compare the cost of different QA protocols to the cost of potential defects to arrive at the optimum QA investment point. In contrast to the other levels, this method allows for a direct approximation of costs.

As illustrated in Figure 4.1, progressing through the levels requires an increasing degree of objective information and analysis; users may choose to proceed through each level, or to stop after an answer of sufficient specificity is found or the quality of the input data does not justify the additional analytical effort associated with the subsequent steps.

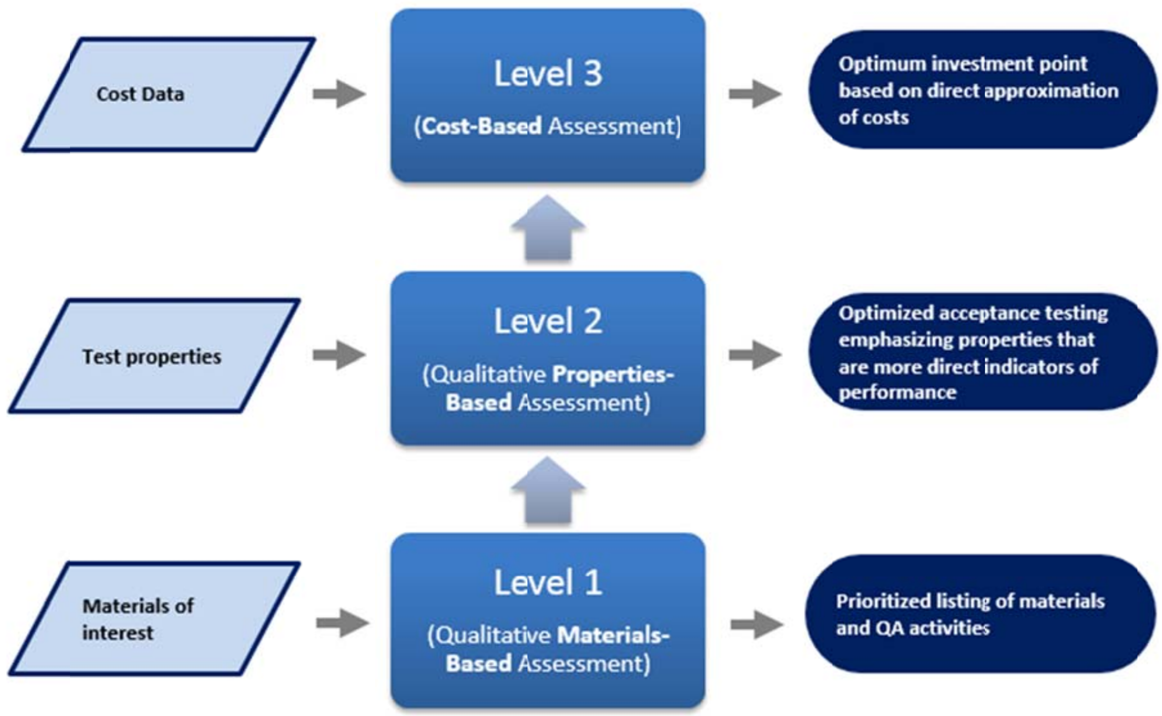

Figure 4.1: Optimization Framework

The decision of which level to use will depend in part on the application (e.g., programmatic vs. project-level assessment), the availability and quality of the input data, and the desired level of analytical rigor. As summarized in Table 4.1, each level has unique objectives, benefits, and challenges, which should be considered when selecting the appropriate approach to use for a particular program, project, or project element.

Table 4.1: Comparison of Optimization Levels

	Level 1	Level 2	Level 3

	Level 1	Level 2	Level 3
Objective	Adjust QA effort (e.g., greater reliance on certification and inspection) based on qualitative assessment of the risk of material failure	Adjust owner QA **testing** effort based on material property importance and risk	Obtain the optimal QA investment point based on an explicit consideration of the cost of QA vs. the cost of nonconformance
Inputs	• Materials of interest • Standard acceptance plans • Expert judgement regarding material risk	• Standard acceptance plans • Primary and secondary properties and test methods • Traditional and advanced properties and test methods • Expert judgement regarding material risk	• Cost to implement different levels of QA (testing, inspection, certification) • The probability and cost of potential defects
Output	Prioritized listing of materials and QA activities	Optimized acceptance testing emphasizing properties that are more direct indicators of performance	Optimum QA investment point
Benefit	Ease of use	Enhanced focus on materials properties	Direct approximation of QA and non-conformance costs
Challenges	Subjectivity of qualitative ratings, which can be difficult to defend	Subjectivity of relative contribution of properties to material performance	Difficulty of obtaining actual cost data (or reasonable approximations thereof)

Each assessment level is discussed in brief in the sections that follow. For complete step-by-step details, refer to the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs* (provided under separate cover).

Level 1 Assessment

The Level 1 assessment framework, as summarized in Figure 4.2, provides a structured, risk-based decision process for prioritizing materials and QA activities on the basis of the probability and consequence of material failure or nonconformance.

This knowledge is then used to effectively allocate QA resources to different project items on the basis of their perceived risk of failure. For example, high risk materials are aligned with acceptance methods designed to provide maximum confidence in the quality of the materials provided, whereas less resource-intensive methods are considered for lower risk materials.

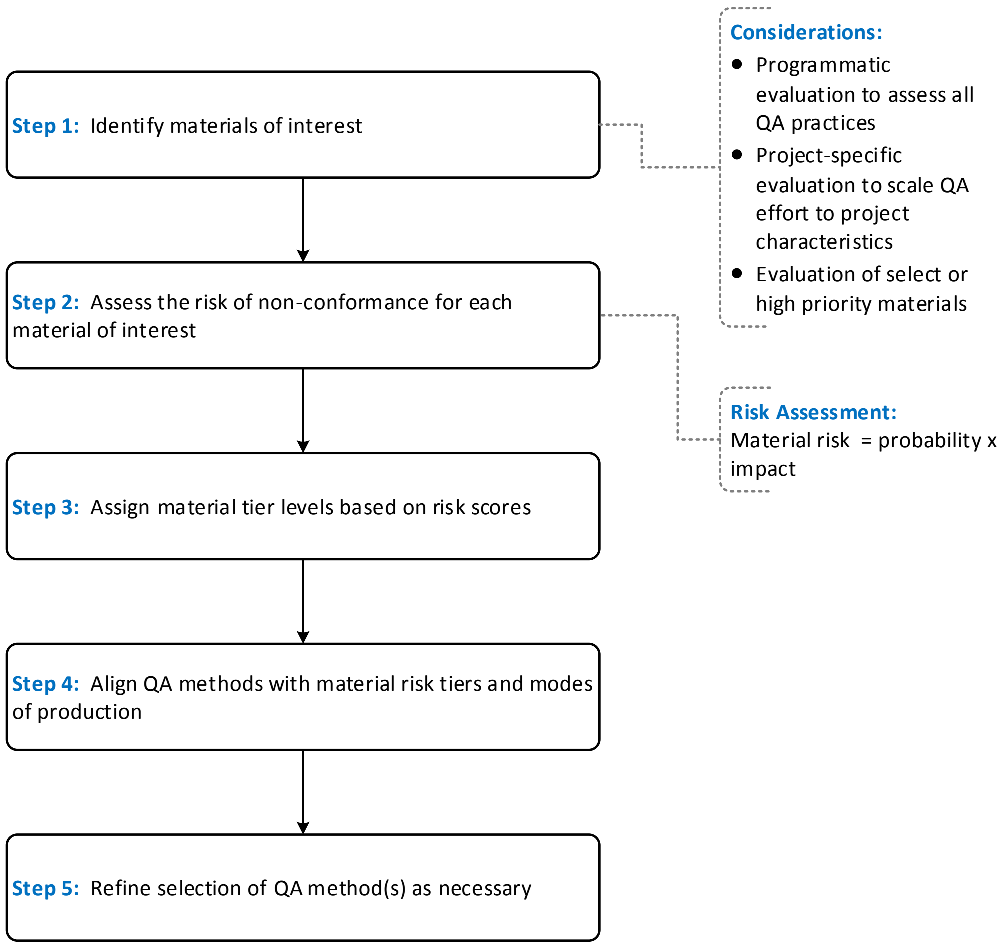

Figure 4.2: Level 1 Assessment

Complete details regarding each step in the process are provided in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs*.

Level 2 Assessment

For materials that are to be accepted by *sampling and testing*, the Level 2 optimization process provides a systematic approach for further evaluating:

- properties and test methods that are more direct indicators of performance
- the appropriate level of owner verification testing (if contractor test data is being used in the acceptance decision)

The Level 2 assessment framework, as summarized in Figure 4.3, provides a structured decision process for prioritizing material sampling and testing activities on the basis of the risk (i.e. likelihood and consequences) of nonconformance of key material properties.

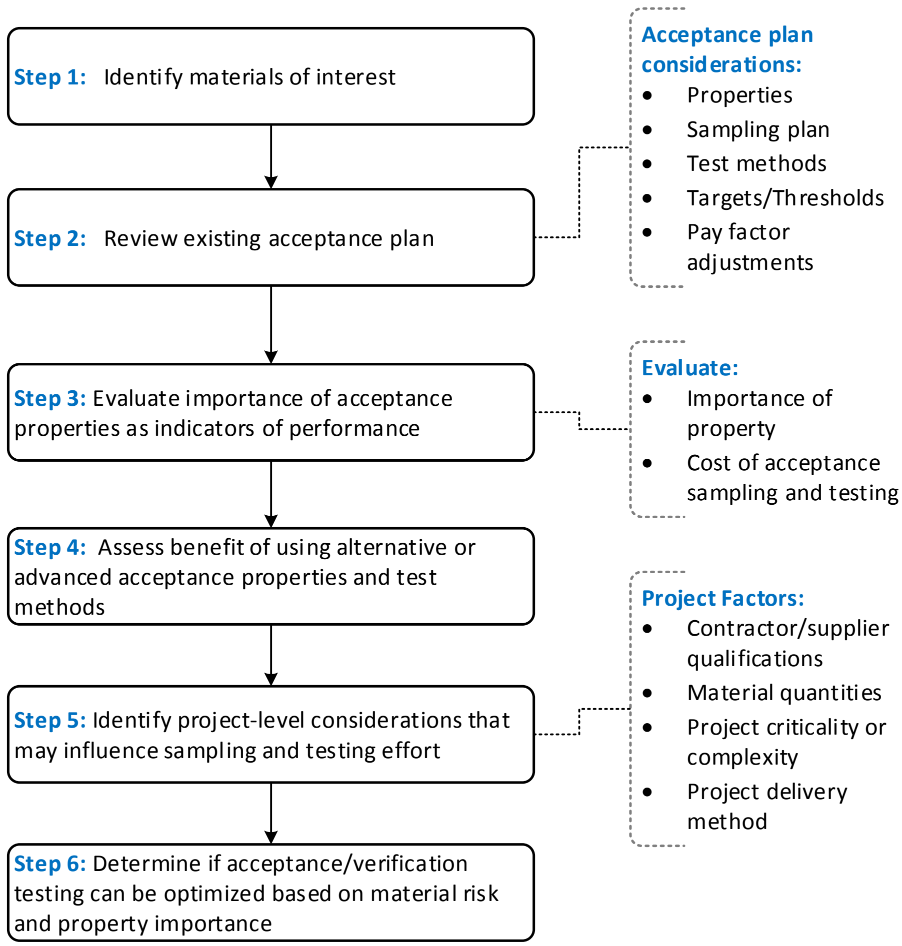

Figure 4.3: Level 2 Assessment

Complete details regarding each step in the process are provided in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs*.

Level 3 Assessment

In contrast to the Level 1 and 2 analyses, the Level 3 optimization process can be used to explicitly compare the direct costs of different QA protocols to the associated cost of material failure to arrive at the optimum QA investment point.

The goal of the Level 3 optimization process is to find the minimum value of the total cost of quality, based on the understanding that, for any given material and QA protocol, a point exists where additional investment in QA would yield a sub-optimal return. The level of QA associated with this investment point would represent the optimum balance between the *cost* of quality and the *value* (or benefit) of quality.

The steps in the Level 3 process are summarized in Figure 4.4 and described in detail in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs*. An Excel-based tool, included with the Guidelines, was also developed to facilitate the analysis.

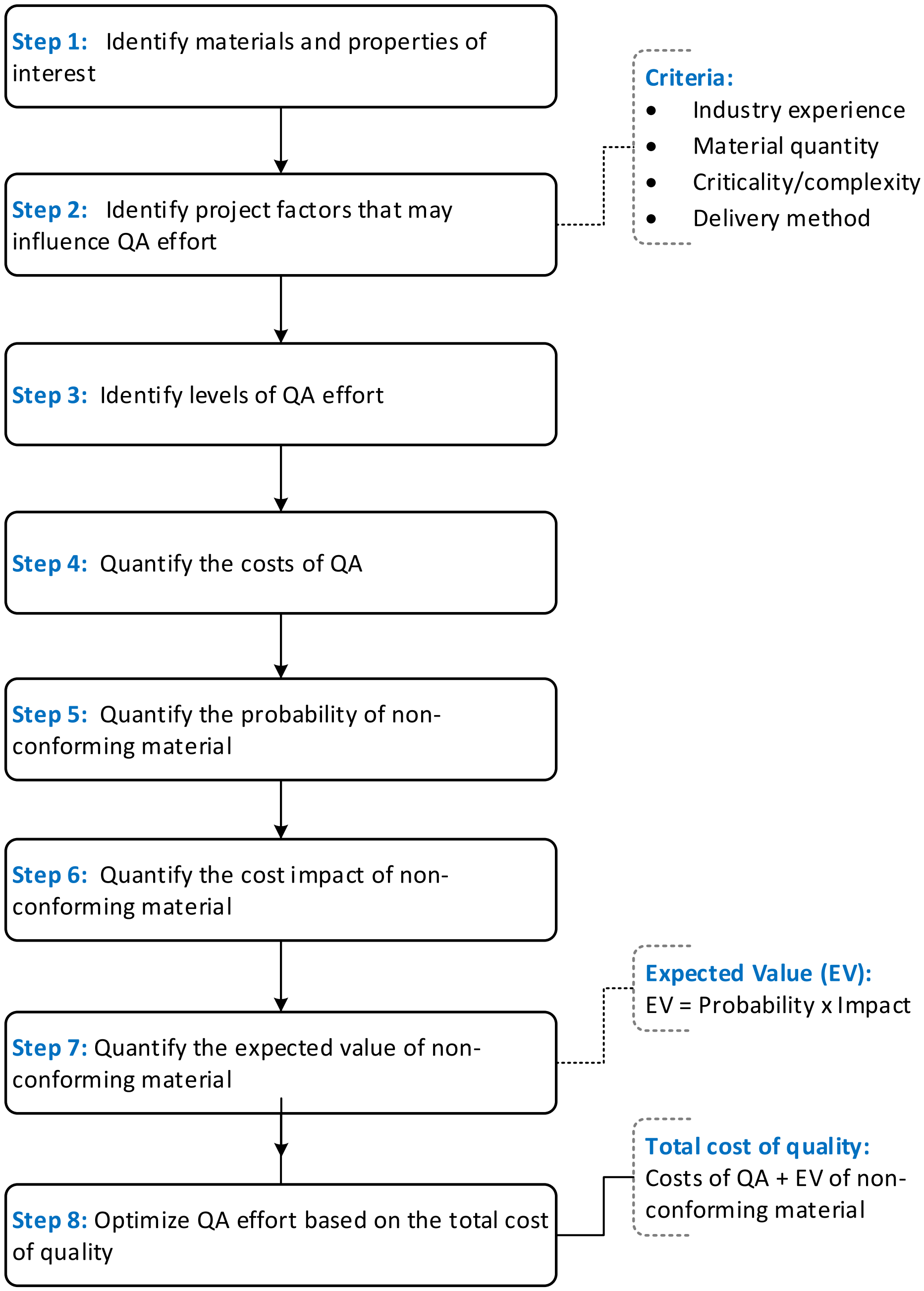

Figure 4.4: Level 3 Optimization

The Level 3 model is designed to use actual or estimated QA costs and potential cost impacts related to material non-conformance to optimize materials QA. If historic data on QA costs and risk-related impacts (e.g., increased cost of maintenance, repair, or replacement of non-conforming materials) are readily available, the user can directly input these cost elements into the model. If historic data is not available, experts can be used to estimate QA costs, the likelihood of non-conformance, and costs of non-conformance. Collection of expert data can take the form of judgements of a single subject matter expert or, more frequently, judgements of a group of experts using a workshop, survey or Delphi data collection technique.

To test the validity of the Level 3 model, a Delphi panel of national experts on various materials of interest was convened to arrive at a consensus estimate of material QA costs and the expected value of nonconformance. Details regarding the Delphi process and results are provided in Appendix F.

Although the results of this Delphi analysis generally supported the theoretical basis of the model, the expert panel had difficulty reaching consensus on some of the required inputs. This finding highlights the difficulty of fully implementing a cost-based optimization approach without hard data – a challenge that suggests that the more qualitative Level 1 and 2 analyses may be more readily implementable in the short-term.

CHAPTER 5 – CONCLUSIONS

Summary of Research Findings

The literature review and data collection efforts provided insight into materials QA principles and processes, and clarified how, and to what extent, these practices can be optimized on the basis of risk and cost within the transportation construction industry. A synthesis of these findings, as summarized below, guided the research team in developing the optimization process introduced in Chapter 4 and presented in detail in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs*.

- **Program Variability and the Need for a Flexible Model.** Based on the literature review and survey and interview responses received, no single approach to materials QA can be considered typical of all DOTs. Cultural and organizational differences, staff resources and expertise, risk tolerance, and the size and competence of the local industry, among other issues, can all drive the strategy ultimately used to assure materials quality. In addition, the nature of the project itself (e.g., level of complexity, project delivery approach, quantities, etc.) can also play a large role in determining the most efficient and effective use of DOT resources. QA practices are also evolving, particularly with regard to greater use of alternative project delivery methods that shift more responsibility to industry for managing quality, and with advances in general understanding of materials/product behavior, use of more performance-based quality measures, and advances in non-destructive testing and related technologies that provide for continuous sampling and data collection. To appeal to a national audience of DOTs, sufficient flexibility was built into the optimization framework to accommodate the range of materials and acceptance practices in use today as well as any new products or practices that may emerge in the future.

- **Existing Optimization Strategies.** Several DOTs currently optimize their materials QA practices to some extent by creating levels of acceptance (i.e., sampling and testing, certification, and inspection) based on what is required for each material or product to assure the quality of the end product. The rationale for selecting a particular acceptance method (ranging from continuous or statistically-based sampling and testing to certification and inspection) is often not well-defined but may be based on factors such as material criticality, quantities, type/size of project, and project delivery method. In general, it appears that existing optimization efforts are largely qualitative and informal in practice, with much discretion left to project engineers to modify rates or protocols based on engineering judgment. Regardless of the level of rigor applied to current QA decision-making, the use of such strategies suggests that a strong foundation and knowledge base exists for developing and implementing a more in-depth process for optimizing materials QA.

- **Cost of Quality.** Striking the optimal balance between the *cost of quality* and the *value of quality* has been a long-standing goal of managers and engineers, particularly in the manufacturing and production industries where an effective mix of quality improvement activities can play a vital role in helping firms achieve and maintain both customer satisfaction and long-term profitability. The conceptual foundation for analyzing the economics of quality is therefore well established in the literature. However, the literature also suggested that real world application of quality cost calculations is quite uncommon, largely due to practical difficulties in identifying and tracking all of the necessary cost inputs. The surveys and interviews conducted as part of this NCHRP research project similarly found that DOTs may struggle to define and collect tangible cost of quality data (i.e., cost of conformance and cost of failure). The challenge of obtaining cost data suggests that a more qualitative approach to optimization may be more readily implementable for most DOTs.

Research Product

Based on the findings summarized above, the research team developed a flexible optimization methodology, as described in the accompanying *Guidelines for Optimizing the Risk and Cost of Materials QA Programs*, for allocating a DOT's QA resources based on an analysis of risks and costs.

As QA practices vary widely among DOTs, the goal of the Guidelines is not to prescribe quality management solutions but to instead provide a flexible analytical framework that can be adapted to the needs of any program or project. The framework is based on the principle that materials QA is an inherently scalable activity, and the approach and resource commitment invested by DOTs to assure quality should be commensurate with:

- Material variability and the level of control required for materials to meet specifications, as well as

- Material criticality from the perspective of:

    - Difficulty to repair or replace
    - Safety
    - Maintenance cost, and/or
    - Cost of rework.

Recognizing the difficulty that some users may encounter in identifying and measuring the costs of quality, a three-level optimization framework was developed that allows for both qualitative and quantitative evaluation options. Advancing through the levels requires an increasing degree of objective information and analysis; users may choose to proceed through each level, or to stop after an answer of sufficient specificity is found or the quality of the input data does not justify the additional analytical effort associated with the subsequent steps.

Until adequate data is more readily available, the use of the Level 3 optimization model may be limited to those agencies and/or materials where such data has been collected. The majority of users may opt for a Level 1 or Level 2 analysis, which will still ultimately help reduce costs while reducing the risk of non-conformance. With increased attention to performance-based acceptance, the Level 2 analysis may prove to be the most effective tool for agencies to use absent the cost data or resources to adequately perform a Level 3 analysis. A commitment to resource allocation is still needed for the Level 1 and Level 2 approach.

Until quantitative data is more readily available, wide variability of QA and non-conformance costs between agencies is expected. The use of a data collection process such as the Delphi method could minimize this effect. The costs of material QA will become better defined and more readily available as agencies automate reporting and data collection of materials QA activities.

Future Activities and Implementation

Potential follow-on activities that would help move the optimization framework into practice or further develop materials QA optimization strategies are discussed below.

Additional Research into the Costs of Quality for Transportation Construction Projects

Practical application of a cost-based optimization model for materials QA requires reliable, accurate, and complete information regarding the total cost of quality over the course of a material's lifecycle. The total cost of quality includes both the cost of conformance (prevention and appraisal) and the cost of non-conformance or failure. Currently, neither cost category is well defined and/or tracked by most DOTs.

Cost of Materials QA

With regard to the cost of conformance, the research found that most DOT materials divisions capture *total* QA costs at a programmatic level and distribute such costs across the program and project budgets as an operating percentage. DOT construction typically estimates QA inspection and testing at the project level as a percentage of the project or construction budget, which may include internal or external consultant resources. This can make it difficult to isolate the discrete costs needed to assess the cost-benefit of different QA strategies (testing, inspection, certification, etc.), particularly those that may entail new or non-traditional QA methods or approaches (e.g., use of advanced performance-based testing, support of national or regional product evaluation programs, etc.).

Future work is needed to better segregate and quantify internal DOT costs for different QA functions (i.e. inspection and testing) and for different material classifications (i.e. project-produced, fabricated, and manufactured). These QA costs may vary significantly among the different DOTs depending on local or regional economic factors and the extent that QA is outsourced or relies on national standards or industry certification. One approach would be for DOT materials and construction to work with the budget and finance office to develop actionable quality cost reports. These reports would account for internal or external quality costs (labor, equipment, materials) for specific QA functions (e.g. inspection and testing) by project or material category.

Costs of Material Non-conformance

State-of-the-art transportation asset management systems compile information on asset inventories, asset condition and performance; help prioritize maintenance and rehabilitation strategies; and determine the best alternative among all maintenance or capital improvement options. As these electronic management systems have evolved, they provide more information regarding the actual performance of materials over their life cycles.

Current research (e.g., with regard to pavements and bridges) is attempting make correlations between design criteria and measured or tested material properties and material performance to develop longer-lasting and better performing assets. Similar research is needed to use this information to better understand the risks and costs of material non-conformance or failure modes over time (e.g., cost of premature repair or replacement), and correlate the likelihood of these conditions with the range of QA activities (e.g., inspection, testing, and certification) being used for material acceptance.

Advancements in QA

As advancements are made in the understanding of material properties and test methods that are potentially better indicators of performance, more coordinated (or pooled) research is needed at the national level to evaluate the cost benefit of using advanced non-destructive testing, performance-based tests, or other QA techniques and compare these methods with existing QA protocols. Many DOTs are moving forward with individual demonstration programs to evaluate specific non-traditional or advanced test methods. These evaluations should also consider the total cost of quality in the cost/benefit analysis (i.e. cost of QA plus cost of non-conformance).

Industry Standards for Certification of Materials

With reduced state DOT staffing and capacity to perform materials QA, state DOTs are increasingly relying on industry to assure material quality. More materials are accepted by certification using national (NTPEP) or international (ISO) standards for pre-approval or acceptance. One international agency reported that virtually all its major material categories are accepted by certification including project-produced materials. More research is needed to assess the risk of accepting materials using current industry certification standards or the feasibility of expanding certification to accept materials by certification that traditionally are accepted through testing and inspection.

Training and Workshops

To assist with the implementation of the *Guidelines for Optimizing the Risk and Cost of Materials QA Programs* developed under this research project, the research team recommends that training or workshops be developed to introduce and demonstrate the application of the optimization framework and ensure that it is implemented correctly. Different optimization levels can be demonstrated for selected projects or programs working with DOT sponsors using a pooled fund or other implementation funding.

Follow-up Survey

In the longer-term, it would be useful to conduct a survey of the state DOTs to measure the level and usage of the optimization framework. One approach could be to conduct a survey in 2 to 3 years to gauge the success of using the optimization framework, particularly for the Level 3 model.

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APPENDIX A: ANNOTATED BIBLIOGRAPHY

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Materials acceptance is addressed in the Standard Specifications, the Materials Testing Manual and in the Construction Manual. When specified and for specific materials, the contractor is responsible for QC when minimum bid quantities exceed the quantity shown in the table in section 106.04 of the Construction Manual. Acceptance criteria is addressed for both Department and contractor supplied sources, and the agency maintains and QPL. A range of certifications exists requiring either a Certificate of Compliance or a Certificate of Analysis.

Baker, T., Molohon, J., White, R. 2010. “Materials Risk Analysis.” Washington Department of Transportation Materials Laboratory Research Office

A research report issued by Washington DOT documented a risk-based optimization process developed by WSDOT including a qualitative risk-based matrix defining four levels of materials acceptance methods ranging from the highest risk (using statistically-based sampling and testing) to the lowest risk (visual inspection). The interim levels included periodic plant or fabrication facility QA inspections and audits, and manufacturer certifications of compliance or materials documentation for commercially manufactured materials. The WSDOT matrix aligned the acceptance methods based on the likelihood of occurrence and consequence of failure. The researchers used a Delphi approach using internal DOT experts to develop risk ratings for various highway construction materials. The approach taken with this optimization represents a practical and novel step-wise approach for multiple materials. It is qualitative in approach, but provides future recommendations for incorporating pavement management costs as a measure of materials quality and performance.

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California Department of Transportation. 2007. "Caltrans Risk Register Excel Document." California Department of Transportation, State of California. <http://www.dot.ca.gov/hq/projmgmt/guidance_prmhb.htm>. (October 25, 2013).

This is the California DOT risk register excel document used to help manage risk for transportation projects in the state of California. The excel document has three levels of risk register that help the user to identify, assess and quantify risks.

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This manual provides us with the sampling methods in Chapter 6 “Sample types and frequencies”. The manual also distinguishes from priority tests and normal tests depending on the material type and the use of that material.

Chapman, R.J. 1998. "The Effectiveness of Working Group Risk Identification and Assessment Techniques." International Journal of Project Management

This paper compares the effectiveness of three risk identification techniques used in the construction industry: (1) brainstorming; (2) nominal group technique and; (3) the Delphi technique. The strengths and weaknesses of all three methods are considered and summaries are provided for the different elements needed to make each technique effective.

Colorado Department of Transportation 2013. "Quality Assurance Procedures for Construction and Material Sampling and Testing – 14", Colorado Department of Transportation Quality Assurance Program

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Colorado Department of Transportation. 2013. "Frequency Guide Schedule for Minimum Materials Sampling, Testing and Inspection." Colorado Department of Transportation Quality Assurance Program

This guide details information about materials sampling and testing with detailed requirements about tiers based upon material type. It also describes the guidelines for Test Frequency Reduction.

Federal Highway Administration, Department of Transportation. April 2012. "Publication FHWA-HRT-12-039", Construction Quality Assurance for Design-Build Highway Projects, Techbrief.

This FHWA Techbrief addresses the requirements of 23 CFR Part 637 in the context of Design-Build, which shifts materials QA roles and responsibilities to the industry. A concern raised in this document was that the roles and responsibilities for QA verification and acceptance for some Design-Build (DB) projects as noted in NCHRP Synthesis 376 [Gransberg, et al., 2008] were not clearly defined in the project requirements. The purpose of the FHWA Techbrief was to clarify these roles and responsibilities for DB projects. Given the trend among DOTs towards using contractor QC data in acceptance decisions for certain types of materials and projects, it defined QA as all the core elements to assure quality including contractor QC, DOT acceptance, independent assurance, personnel qualifications, and laboratory accreditation. For DB, there is no change in core functions. The DB contractor still has the responsibility for QC, and the agency the responsibility for acceptance. For acceptance, 23 CFR Part 637 allows the use of contractor QC test data in the acceptance decision, provided that the QC data is validated by the independently obtained agency verification data and the agency also performs Independent Assurance (IA) to assure the reliability of all the data. The Techbrief points out that the verification testing will typically be performed at a lower frequency than the QC testing, and for some large DB projects 1 verification test in 10 QC tests, as long as there are a sufficient number of verification tests to obtain reliable results. It also points out that the rates of verification testing may also vary based on the risks involved or criticality of the materials (e.g. verification testing may be more frequent for structural concrete than for embankment materials).

Federal Highway Administration, Department of Transportation. June 2007. "Quality Assurance in Materials and Construction, Final Report." Office of Professional and Corporate Development Program Improvement Team

According to a FHWA national program evaluation report [FHWA 2007] and various quality assurance stewardship reviews for 2003-2008, more than 34 DOTs use contractor QC test results in acceptance decisions, but a number of these DOTs lack the proper systems to verify contractor test data. Without these controls, the risks of accepting non-conforming materials are higher. The FHWA report recommended that risk-based evaluation tools should be developed to assess appropriate testing frequencies and risks for a variety of materials. The report also noted that the federal regulations found in 23 CFR 637, Subpart B – Quality Assurance Procedures for Construction, needed to be updated to address alternative delivery methods, to more formally address construction inspection and processes for acceptance of manufactured materials, and to be more applicable to all federal-aid projects regardless of system, class, or type.

Federal Highway Administration, Department of Transportation. April 1, 2011. 23 CFR Ch.I. Subpart B–Quality Assurance Procedures for Construction

This document describes procedures and guidelines to assure quality of materials and construction in all Federal-aid highway projects on the National Highway System. It goes all the way through the Acceptance and Independent Assurance programs, samples, laboratories, QA and verification sampling and testing. The policies, program, and laboratory for QA are explained in a general manner. The federal regulations 23 CFR 637, Subpart B - Quality Assurance Procedures for Construction, further require that a comprehensive construction QA program (including materials) should consist of the following six core elements: quality control, acceptance, independent assurance, dispute resolution, personnel qualification, and laboratory accreditation/qualification.

Florida Department of Transportation. July 2013. "Construction Oversight Services (COS), Scope of Services, for I-4 Ultimate Improvements Project." Federal Project No: 0041 228I

This RFP describes DOT construction oversight requirements for a Design-Build-Operate-Maintain project. For this project, the contractor (Concessionaire) is responsible for providing and executing a comprehensive QC/QA quality management plan for the project. The owner through its Consultant is responsible for independently verifying the materials quality, and performing verification testing and inspection and compliance audits. The Consultant is required to develop a risk-based audit plan to statistically evaluate the Concessionaire compliance with its QC/QA plan. The Consultant would be required to develop a Requirements Verification Database that will place higher value to high risk requirements and lower value to lower risk requirements. High risk items defined by FDOT include: Foundations, Bridge Structures, MSE Walls, Design Elements, etc. The plan is required to optimize the process by systematically combining the likelihood and consequence of failure to establish a prioritized strategy monitoring the Concessionaire operations related to QC/QA.

Florida Department of Transportation. Revised April 12, 2010. "Materials Manual, Florida Sampling and Testing Methods." Effective September 1, 2000.

The manual lists Florida Sampling and Testing Methods (FSTM). It shows the source of the testing method being AASHTO and ASTM as well as FSTM. Florida's Method numbers have the AASHTO number implied within its code, which helps to easy compare the methods.

Fussell, L., and Field, S. 2005 "The Role of the Risk Management Database in the Risk Management Process." 18th International Conference on Systems Engineering, Las Vegas, Nevada.

This article promotes the use of a risk register as an important tool in the risk management process. The authors state that the use of risk registers creates a better understanding of project risks as well as serving as an important communication tool for all involved parties. Also stressed is the need for the risk register to be tailored to the needs of the project.

Golder Associates, K. Molenaar, M. Loulakis, and T. Ferragut. 2013. "SHRP2 Guide for the Process of Managing Risk on Rapid Renewal Projects", Transportation Research Board of the National Academies, Washington, D.C.

This research report provides step-by-step guidance for project risk management. It provides detailed processes for risk identification, assessment, analysis, mitigation and monitoring. It contains appendices for risk checklists (with mitigation strategies) and a detailed project example. It also provides training materials.

Goulias, D., Karimi, S. January 22, 2013. "Material Quality Assurance Risk Assessment", State Highway Administration Research Report Maryland Department of Transportation and University of Maryland

This materials QA research report addresses risks related to materials QA, and provides good examples of current QA processes used by MDSHA for aggregate, precast concrete, structural steel, rebar, coatings, and neoprene strip seal, and how these processes could be improved. One recommended approach is to use a statistical percent within limits approach for graded aggregate base to balance payment risks. The report also addresses how to bring manufactured products more into conformance with 23 CFR 637 requirements.

Hylton Meier, H. 1991. "A Control Model for Assessing Quality Costs." Mid-American Journal of Business, 6(1), 40-44.

This article examines how accountants can provide cost information using the traditional quality-cost model along with expected value techniques so that managers may make more effective decisions to accomplish quality goals. It first describes traditional views of quality costs as a collection of costs from throughout the entire company, which is associated with the prevention, measurement and correction of problems arising from products or services that lack conformity to specifications. The new trend in quality is to focus on the prevention of defects, and not merely on their detection and correction (through a zero-defect culture instilled into every level of the organization). Prevention and appraisal costs are classified as being "voluntary" costs as they are generally approved as part of an organization's annual budgeting process. In contrast, correction costs are "involuntary" in that they cannot be directly controlled by management and are generally difficult to measure. The involuntary costs can be modeled with the expected value method, which is the amount to fix the problem multiplied by its probability of occurring. The article surmises that use of this method will provide a more accurate view of quality costs and ultimately demonstrate that more initial quality control expenditure is better in the long run.

Illinois Department of Transportation. 2009. "Project Procedures Guide; Sampling Frequencies for Materials Testing and Inspection." Bureau of Materials & Physical Research

The Project Procedures Guide describes the range of materials acceptance in Section 200. Either SHA or representative take the samples at the source or project site. Document addressed QC/QA programs for asphalt binder, emulsified asphalt, Portland cement, Precast Concrete products, and reinforcement bars/fabric and details are available through web-based system. No mention of NTPEP, but made reference to process to qualify for addition to the approved list for materials. Manufacturer's certifications are also used for acceptance for certain types of materials and products, and visual inspection is required on the project site when possible. Visual inspection is acceptable when sampling is impractical, destructive, or when small quantities are involved.

Illinois Department of Transportation. October 25, 2013. "Bureau of Materials & Physical Research Policy Memorandums."

This memo consists of 31 different Policy Memorandums that describe the acceptance procedure for each material. It is one of the most up-to-date guides and has a comprehensive policy for each material. The next indented memorandums are part this big memo.

Illinois Department of Transportation. Revised: February 4, 2013. "Performance Graded Asphalt Binder Acceptance Procedure." Bureau of Materials & Physical Research Springfield Policy Memorandums

This memorandum establishes a procedure whereby the production of a source may be accepted for use in Illinois, based on a uniform certified quality control program.

Illinois Department of Transportation. Revised: February 4, 2013. "Emulsified Asphalt Acceptance Procedure." Bureau of Materials & Physical Research Springfield Policy Memorandums

This memorandum establishes a procedure of acceptance of a certain production source in Illinois through certification or quality control program.

Illinois Department of Transportation. Revised: January 1, 2008. "Minimum Requirements for Construction Materials Testing Laboratories – Department Operated Laboratories." Bureau of Materials & Physical Research Policy Memorandum

> This memorandum establishes the minimum qualifications for materials testing laboratories operated by the Department. It applies to soils, aggregate, hot-mix asphalt (HMA), and Portland cement concrete (PCC) laboratories. In the Table 1, Minimum District Laboratory Tests, it presents all of the tests that IDOT does for QC and QA. It has a description of each test and has the standard (AASHTO, ASTM).

Illinois Department of Transportation. Revised: January 1, 2008. "Cutback Asphalt and Road Oil Acceptance Procedure Definitions." Bureau of Materials & Physical Research Springfield Policy Memorandums

> This memorandum establishes a procedure whereby the production of a source may be accepted for use on Illinois State based on a uniform certified quality control program.

Kentucky Transportation Cabinet. February 2009. "Info Tech, Trn•sport Site Manager® and LIMS Training Guide for Kentucky Transportation Cabinet", Instructor Edition

> This training guide provides information about the main functional areas of the Laboratory Information Management System (LIMS). It covers the complete construction and materials management system process from contract award to contract finalization. It provides an understanding of the general work flow for approved products approvals, materials sampling and testing, and materials inspection requirements.

Li, C. and Sun, A. October 12-14, 2008. "The Research of Economic Evaluation Project Risk Based on Monte Carlo Simulation." 4th International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China.

> In this paper the authors use Monte Carlo simulation techniques to provide economic evaluations of construction projects. The model is then used to predict the net present value and the internal rate of return for construction projects. This research is intended to help contractors find the estimate yield and profit for a project and, therefore, make more informed decisions on which projects to pursue.

Molenaar, K.R., Diekmann, J.E. and Ashley, D.B. 2006. "Guide to Risk Assessment and Allocation for Highway Construction Management." Report FHWA-PL-06-032, U.S. Department of Transportation, Washington, D.C.

> In 2004, a team of representatives from the Federal Highway Administration, State highway agencies, industry, and academia visited Canada, Finland, Germany, the Netherlands, Scotland, and the United Kingdom. The purpose of this International Technology Scanning Program study was to identify practices that might be evaluated and applied in the United States to improve construction management.

Molenaar, K., Gransberg, D., Datin, J. 2008. "NCHRP synthesis 376: Quality Assurance in Design Build Projects." Research sponsored by the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration. Published reports of the NCHRP by Transportation Research Board at Washington D.C., U.S.A.

> This synthesis provides the QA state of practice of different DOTs. It emphasizes on the responsibilities of the DOTs vis-a-vis the contractor in different delivery methods. Design Bid Build is compared to the different types of Design build.

Morse, W.J. 1993. "A Handle on Quality Costs." CMA Magazine, 67(1), 21.

> This article addresses four types of quality costs: prevention, appraisal, internal failure, and external failure. Thirty percent of US manufacturing costs is estimated to be from quality control (not including costs related to customer dissatisfaction). Cited is the "Taguchi quality loss function" which estimates cost of customer dissatisfaction and other hidden quality costs. To provide more action-oriented information, some organizations are using root-cause analysis to link quality costs to specific activities. The article

addresses value-adding vs non-value-adding activities, noting that many quality control processes are non-value-adding. Whether these non-value-adding costs should be removed is pondered. In closing, the article states quality cost concepts should be an integral part of total quality management.

Mostafavi, A., and D. M. Abraham. 2012. "INDOT Construction Inspection Priorities." Publication FHWA/IN/JTRP-2012/09, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. doi: 10.5703/1288284314669.

> This paper establishes an inspection protocol, staffing guide and a list of pay items to enhance documentation process. It provides a table summary of the risks identified through a survey. This probability of risks is allocated to different materials. The paper suggests less inspection to the less prioritized materials.

New Hampshire Department of Transportation. "Standard Specifications for Road and Bridge Construction." Retrieved from:
<http://www.nh.gov/dot/org/projectdevelopment/highwaydesign/specifications/documents/2010_Spec_Book.pdf>

> Section 700 of the Standard Specifications describes the range of acceptance methods that in addition to sampling and testing addresses Certificates of Compliance and a Qualified Product List (QPL). A definition for small projects is given for which sampling and testing requirements are modified. Details for the testing frequencies of a wide range of materials are described in section 703.3 of the Standard Specifications.

Office of Professional and Corporate Development Program Improvement Team. 2007. "Quality Assurance in Materials and Construction". National Review Program. Washington DC.

> According to a FHWA national program evaluation report (FHWA 2007) and various quality assurance stewardship reviews for 2003-2008, more than 34 DOTs use contractor test results in acceptance decisions, but a number of these DOTs lack the proper systems to verify contractor test data. Without these controls, the risks of accepting non-conforming materials are higher. The FHWA report recommends that risk-based evaluation tools should be developed to assess appropriate testing frequencies and risks for a variety of materials. The report also noted that the 23 CFR 637 needed to be updated to address alternative delivery methods, to more formally address construction inspection and processes for acceptance of manufactured materials, and to be more applicable to all federal-aid projects regardless of system, class, or type.

Plunkett, J.J., and Dale, B.G. 1988. "Quality costs: A critique of some 'economic cost of quality' models." International Journal of Production Research, 26(11), 1713.

> This article explains problems with different models based on a study of quality related costs. It concludes that many models are inaccurate, and doubts are cast on the concept of an optimum quality level corresponding to a minimum point on the total quality-cost curve. Theoretical prevention vs failure cost curves from different textbooks and training manuals are compared to actual data taken from a few companies. The authors found that there is not enough real data to validate models of quality costs and their relation to each other.

Rahman, M. and Kumaraswamy, M. 2002. "Joint Risk Management Through Transactionally Efficient Relational Contracting." Construction Management and Economics. 20(4): 44-54.

> This paper states that the appropriate contracting methods and documents of a construction project are dependent on the characteristics of the project. The paper claims that relational contracting and joint risk management are two methods to decreases costs and make projects ultimately more successful.

Schiffauerova, A., and Thomson, V. 2006. "A Review of Research on Cost of Quality Models and Best Practices." International Journal of Quality & Reliability Management, 23(6), 647-669.

This paper presents a survey of published literature about various quality costing approaches and reports of their success to provide a better understanding of cost of quality (CoQ) methods. The paper finds that CoQ approaches are not utilized in most quality management programs, however companies that do adopt CoQ methods are successful in reducing quality costs and improving quality for their customers. The CoQ method must fit the situation, environment, purpose, and needs of the company in order to be successful. The companies that do not use this approach may still have other methods that still address quality such as continuous improvement.

Schuyler, J. 2001. "Risk and Decision Analysis in Projects, 2nd ed." Project Management Institute, Newton Square, PA.

This book provides information for numerous topics within risk and decision analysis. Some of the topics include multi-criteria decision-making, decision trees, Monte Carlo analysis and sensitivity analysis among others. The book provides both conceptual and practical frameworks for the use of these techniques and methods. The book is designed as a textbook for a class devoted to risk and decision analysis.

South Dakota Department of Transportation. September, 2013. "Required Samples, Test, and Certificates."

This manual provides guidance for required sampling, testing and certification processes for materials incorporated into SDDOT projects. The manual specifically describes a 3-tiered process for certification of materials ranging from critical to non-critical. For example, Tier 1 is defined as material that is considered critical to safety or costly to replace. The certification requirements vary from certificates of compliance supported with test results to certified suppliers to umbrella certificates for component products of a system or assembly. Verification methods for certification ranges from sampling and testing to documented inspection, random audits or annual inspections of suppliers.

Strategic Highway Research Program SHRP 2 Renewal Project R07. March 2013. "Performance Specifications for Rapid Highway Renewal."

This SHRP2 research project addressed the importance of identifying and assessing risks related to QA, particularly for materials and product measurement and testing, but also for other methods of acceptance including certification and field inspection. The research report identified gaps related to measurement and testing technology, such as the level of accuracy and reliability of current measurement and testing technology that can limit the extent to which measured values reflect quality or performance. A related risk is that while measurements may be objective, the sampling may be inconsistent or not sufficiently representative of actual conditions. Another identified risk is making an incorrect acceptance decision and/or assigning the wrong pay adjustment. These are often referred to as the seller's risk (i.e., the risk to the contractor of having acceptable material or workmanship rejected) and the buyer's risk (i.e., the risk to the agency of accepting rejectable quality level (RQL) material or workmanship). After identifying risks, it is necessary to understand who assumes the risk (agency or contractor), the frequency or likelihood of its occurrence, and the likely impact of the risk should it occur (i.e., the consequence severity). It is also important to consider how each risk will likely manifest itself. In other words, risk to what (e.g., service, schedule, safety, capital cost, maintenance cost)?

The SHRP 2 R07 research also addressed technological advancements in testing that could potentially eliminate or minimize some previously identified risks. The implementation guidelines outlined an approach to optimization of key materials acceptance criteria using a tiered implementation approach and identifying advanced testing and acceptance practices for pavements, structures, and soils. The objectives of promoting advanced methods included placing more emphasis on properties known to affect durability and long-term performance, using test methods that would be more conducive to rapid, continuous sampling and testing, reducing the risk of incorrect acceptance decisions, and allowing for reduced verification or agency oversight.

Texas Department of Transportation. August 2010. "Guide Schedule of Sampling and Testing."

This guide illustrates that the Department's and the Contractor's risk of either rejecting "good" material or accepting "bad" material range from 20% to 40%. To reduce this risk, it recommends that the sampling rate be increased during initial production, high-variability materials and when tests do not meet specifications. A four-fold increase in testing frequency will generally reduce risk to approximately 5%.

Texas Department of Transportation. November 1, 2011. "Design-Build Quality Assurance Program Implementation Guide."

This guide provides a programmatic approach to QA for Design Build projects where the developer's test results are used in the acceptance decision, regardless of how the project is funded." The guide is designed to provide Texas' DOT personnel and consultants the procedures to implement a QA Program.

Texas Department of Transportation. July 25, 2011. "Quality Assurance Program for Design-Build Projects with an Optional 15-Year Capital Maintenance Agreement."

This program is designed as a guide for projects where the use of contractor test results can be part of the acceptance decision. Texas DOT (TXDOT) developed two types of acceptance procedures for Design-Build projects with optional maintenance agreements. The first type uses TXDOT-performed acceptance testing and inspection where only TXDOT testing and inspection results are used in the acceptance decision. The second type of acceptance is contractor-performed where frontline acceptance testing and inspection is performed by the contractor or Developer's CQAF (Construction Quality Assurance Firm). Under this approach, the contractor is required to submit a CQMP (Construction Quality Management Plan). Under contractor-performed acceptance, statistically-based QA tests and owner verification tests are the basis for acceptance with an Independent Assurance (IA) program, and periodic TXDOT independent audits of the contractors CQMP. For each project, the contractor may conduct a project-specific analysis of risks to determine levels of owner verification testing. The TXDOT QAP Implementation Guide defines 3 levels of verification tests based on material and test method. Level 1 testing is for analysis of parameters that are strong indicators of performance. Tests include compressive strength for structural concrete, percent soil compaction, and percent asphalt content. Owner verification testing is conducted at 10% frequency with F and t tests on a continuous basis. The p values from F and t tests are reported and tracked over time with critical p values set based on the level of significance of materials categories. Level 2 testing is for parameters that are thought to be secondary measures of performance (i.e. slump test for concrete. Level 3 provides observation verification for materials that require few QA tests for compliance or materials whose risk of failure does not affect long-term performance of the facility.

Texas Department of Transportation. 2004. "2004 Standard Specifications Book." Mixture Selection for Flexible Pavements.

This guide recommends designers different types of hot mix asphalt depending on factors such as traffic volume, loading characteristics, design speed and desired performance.

Transportation Research Board of the National Academies. May 2005. "Glossary of High Quality Assurance Terms." Third Update. Transportation Research Circular Number E-C074 May 2005

The circular provides a reference to common highway QA terminology. It lists abbreviations, symbols and references as a glossary for terms that are frequently misinterpreted, misunderstood, or generally confusing. It provides some diagrams as well to exemplify QA system elements or to detail accountability for quality, sampling or performance.

Transportation Research Board of the National Academies. 2013. "Glossary of Quality Assurance Terms." Sixth Edition. Transportation Research Circular Number E-C173 June 2013

The circular provides a reference to common highway QA terminology. It lists abbreviations, symbols and references as a glossary for terms that are frequently misinterpreted, misunderstood, or generally confusing. It provides some diagrams as well to exemplify QA system elements or to detail accountability for quality, sampling or performance.

Virginia Department of Transportation. June 2011. "Materials Manual: Chapter II – Methods and Frequencies of Sampling." Retrieved from < http://www.virginiadot.org/business/resources/Materials/bu-mat-MOI-II.pdf > (November 20, 2013)

This manual specifies the minimum requirements for QA samples. In this specific chapter the specification limits, frequencies and sample sizes depending on the material type and the use for that material.

Virginia Department of Transportation. 2008. "Materials Manual: Chapter VII – Materials Acceptance and Materials Notebook Program" Published June 2011. Retrieved from < http://www.virginiadot.org/business/resources/Materials/bu-mat-MOI-VII.pdf > (November 20, 2013)

This Chapter of the Materials Manual describes the uses of the Materials Notebook Program and specifies the differences of use for a Design-Bid-Build project against a Design-Build project. The acceptance procedures and the necessary documentation needed are described as well. It allows the SME to override the requirements of the Notebook, and provides different responsibilities and requirements based on project type (a)Design-Bid-Build, Rest Areas, Minimum and No Plan Projects, FHWA Safety Improvement Projects and Electrical Installations; (b) Design-Build, Public-Private Partnerships, Local Assistance and Municipally Administered Projects; and (c) State Forces performing work). Details for individual materials requirements are outlined in the Standard Specifications.

Ward, S.C., Chapman, C.B., and Curtis, B. 1991. "On the Allocation of Risk in Construction Projects." International Journal of Project Management, 9(3): 140-147.

According these authors, an organization's willingness to take on a risk in a construction project is based on their ability to charge a premium for that risk. The paper shows what some of the implications of risk allocation are and outlines the four response options for a party bearing a risk. The authors argue that appropriate risk allocation leads to better overall project risk management and therefore more successful projects.

Washington State Department of Transportation. August 2013. "Construction Manual." Engineering and Regional Operations Materials Laboratory. M 41-01.15

It is a comprehensive manual that establishes the test procedures and objectives for all the highway construction in Washington State. The manual is consistent with WSDOT Standard Specifications and the Materials Manual as well.

Washington State Department of Transportation. August 2013. "Materials Manual." Engineering and Regional Operations Materials Laboratory.

A comprehensive manual that establishes the test procedures for all the highway materials with Quality System concerns of AASHTO. It divides the materials in the table of contents by: Aggregate, Bituminous Cement, Hot-Mix Asphalt, Cement, Chemical, Concrete, Electrical and Traffic, Geotechnical-Soils, Geotextile and Steel, Paint, Pavement Soils and Standard Practice.

Washington State Department of Transportation. 2013. "Standard Specifications for Road, Bridge, and Municipal Construction 2014." M 41-10

The document presents the baseline for the work that is delivered to the public by the Washington State Department of Transportation. It reflects WSDOT's philosophy of risk allocation to provide the lowest final cost to the State's transportation needs. Finally it provides the acceptance procedures and statistics.

Washington State Department of Transportation. 2013. “State Materials Laboratory AASHTO Accreditations” < http://www.wsdot.wa.gov/business/materialslab/qualityassuranceprogram.htm> (October 25, 2013)

The Washington State Department of transportation shows its AASHTO accredited laboratories and in which methods are those laboratories accredited.

Wideman, R.M. 1992. “Project and Program Risk Management: A Guide to Managing Project Risk and Opportunities.” Project Management Institute, Newton Square, PA.

This handbook is published as part of the Project Management Body of Knowledge. It provides an understanding to the nature of risk and provides methods for reducing a project’s risk exposure. The handbook includes tools and techniques for risk identification, risk assessment, contingency management and risk mitigation.

Williams, T.M. 1994. "Using a Risk Register to Integrate Risk Management in Project Definition." International Journal of Project Management 12(1): 17-22.

This paper found that the risk register was becoming central to any successful risk management program. The paper describes an integrated risk analysis and management framework that is based around the use of a risk register. This framework assists managers by making the risk register a tool in making decisions for risk management plans and risk transference.

Wisconsin Department of Transportation. 2013. “Construction and Materials Manual. Chapter 8: Materials Testing, Sampling, Acceptance.” Retrieved from < http://roadwaystandards.dot.wi.gov/standards/cmm > (November 19, 2013)

This comprehensive manual states the procedures for approval of materials, quality management program, independent assurance program, quality verification, QA and QC for all the different materials. It describes the price reductions due to nonconforming materials or testing. The CMM Chapter 8 includes documentation requirements for different acceptance types and differentiates between approved materials (i.e. from an approved source or supplier) and acceptance of materials through inspection or testing when incorporated into the project. Wisconsin DOT (WisDOT) includes the full range of acceptance levels and types for different materials incorporated into projects. Different frequencies and scope of sampling, testing, and inspection are utilized as needed or appropriate for adequate control of quality and compliance with specifications. WisDOT identifies a listing of low risk or non-critical materials that may be accepted through visual inspection and not require documentation

Wyoming Department of Transportation. 2012. “Materials Testing Manual.” DOT Number 108.0 Materials Acceptance – Manufactured Products: Materials Certifications, Form T-168 – Certification of Materials

This manual ensures materials meet applicable WYDOT requirements for acceptance. Forms exist for construction testing and certification requirements. Sampling and testing frequencies are identified in Form T-128, manufactured products accepted by certification uses Forms T-168 and T-131. Verification acceptance of certain materials and manufactured may also utilize Form T-132 in some instances. Qualified suppliers are also identified for certain materials and are identified on the agency website.

APPENDIX B: DEFINITIONS

B.1 Quality Assurance Terms

Acceptance: the agency's process of determining whether or not to accept or reject a product (If contractor test results are used to support the acceptance decision, the agency's acceptance process includes contractor testing, agency verification and validation, and possibly dispute resolution).

Dispute resolution: for QA programs, the process to address the resolution of discrepancies that may exist between QC sampling and testing used in the acceptance decision and the agency's verification sampling and testing.

Independent assurance (IA): unbiased and independent evaluation of all sampling and testing procedures to assure the reliability of data used in the QA program. IA ensures that sampling and testing is performed by qualified personnel using proper procedures and properly functioning and calibrated equipment.

Inspection: The act of examining, measuring, or testing to determine the degree of compliance with requirements.

Qualified (or accredited) laboratory: laboratories that are capable, as defined by a program established by the agency, to conduct sampling and testing for acceptance or IA purposes.

Qualified sampling and testing personnel: personnel who are capable, as defined by a program established by the agency, to conduct sampling and testing for acceptance or IA purposes.

Quality assurance (QA): All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service, including the elements of quality control (QC), independent assurance (IA), acceptance, dispute resolution, laboratory accreditation, and personnel certification.

Quality control (QC): The system used by a contractor to monitor, assess and adjust its production or placement processes to ensure that the final product will meet the specified level of quality. QC includes sampling, testing, inspection, and corrective action (where required) to maintain continuous control of a production or placement process.

Validation: (1) The process of confirming the soundness or effectiveness of a product (such as a model, a program, or specifications) thereby indicating official sanction; (2) The mathematical comparison of two independently obtained sets of data (e.g., agency acceptance data versus contractor data) to determine whether it can be assumed they came from the same population [The *validation* of a product often includes the *verification* of test results.]

Verification: The process of testing the truth, or of determining the accuracy of test results, by examining the data or providing objective evidence, or both.

B.2 Project Delivery Methods

Design-bid-build: the traditional delivery system for the public sector in which the owner contracts separately with a designer and contractor.

Design-build: a project delivery system in which an entity provides both design and construction services under a single contract.

Public-Private-Partnership/Concessionaire: a project delivery system where an entity or a developer invests in a project and provides financing and integrated services to design, construct, operate, and maintain a roadway or transportation facility in return for tolls or some other compensation under the operating or concession agreement.

APPENDIX C: SURVEY RESULTS

Respondent Contact Information:

Agency Name:	Position/Title:
Alabama Department of Transportation	Asst. Materials and Tests Engineer
Alabama Dept. of Transportation Bureau of Materials and Tests	Testing Engineer
Arizona DOT	Materials Group - Quality Assurance Manager
Arkansas State Highway and Transportation Department	Materials Engineer
California Department of Transportation	Senior Bridge Engineer
Caltrans	District Material Engineer
Caltrans	
ConnDOT	Principal Engineer Materials
Delaware Department of Transportation	Chief Materials & Research Engineer
Florida DOT	Director, Office of Materials
GDOT	Testing Bureau Chief
Illinois Tollway	Deputy Program Manager of Materials
Indiana Department of Transportation	Manager
Iowa DOT	Materials Testing Engineer
KSDOT	Chief, Bureau of Research
KY Transportation Cabinet	Director, Division of Materials
LADOTD	Materials Engineer
Maine Department of Transportation	Director, Materials Testing and Exploration
MassDOT	Civil Engineer Materials

Agency Name:	Position/Title:
MD State Highway Admin.	Division Chief, Materials Management
Michigan Department of Transportation	Concrete Operation and Materials Engineer
Mississippi Department of Transportation	Assistant Chief Engineer - Operations
Missouri DOT	Physical Laboratory Director
Missouri DOT	Construction and Materials Liaison Engineer
Montana DOT	Testing Engineer
MTO	Head, Bituminous Section
NC DOT	State Materials Engineer
Nebraska Department of Roads	State Construction Engineer
New Mexico Dept. of Transportation	Materials/Testing Engineer
NJDOT	Manager, Bureau of Materials
NYSDOT	CE3 - Concrete Program Manager
Ohio DOT	Administrator, Office of Construction Management
Ohio DOT	Structural Welding Engineer
Ohio DOT	Administrator, Office of Materials Management
Oklahoma DOT	Assistant Materials and Research Engineer
Oregon DOT	Quality Assurance Engineer
PennDOT	Chief Chemist
PennDOT	Construction Quality Assurance Section Chief
Peoples	State Materials Engineer
PORT AUTHORITY OF NEW YORK & NEW JERSEY	CHEIF OF MATERIALS ENGINEERING

Agency Name:	Position/Title:
Rhode Island Department of Transportation	Associate Chief Engineer
Roads Maritime Services NSW Australia	Manager Delivery Strategy
South Carolina DOT	Quality Assurance Engr.
Teichert Materials	Q/A Supervisor
Texas DOT	Deputy Director, Construction Division
TN Department of Transportation	C.E. Manager II
Utah DOT	State Materials Engineer
Virginia Dept. of Transportation	State Materials Engineer
Virginia DOT	Assistant State Materials Engineer
Washington State DOT	State Materials Engineer
Wisconsin Department of Transportation	Quality Management Program Engineer
WisDOT	Materials Lab Supervisor

Statistic	Value
Total Responses	63

1. Please select any of the following characteristics that your agency uses to determine the materials acceptance procedures and protocols for a project (please select all that apply):

#	Answer		Response	%
1	Project Type (grading, paving, bridges, etc.)		38	64%
2	Facility Type (Interstate, primary, secondary, etc.)		23	39%
3	Quantity of Materials Involved		48	81%
4	Project Delivery Type (design-bid-build, design-build, etc.)		28	47%
5	Funding Source		15	25%
6	Criticality of Materials (related to safety or performance of end product)		39	66%
7	Other		6	10%

Other (Comments):

(TX) All projects are treated the same regardless with QA frequencies as a function of number of tests per amount.

(OH) Acceptance Procedures are uniformly applied across all projects. But not all materials are accepted in the same manner

(RI) Our 'Master Schedule for Testing' determines parameters for each item regardless of project type, funding, size, etc.

(MT) All projects are treated the same and according to our guide schedule. In DB and PPP we hire a consultant to do a min of 10% of guide scheduled test for verification to comply with CFR

(DE) Acceptance procedures are the same for all projects regardless of size/funding source/type. The number of tests is based on the quantity of materials used on each project and therefore varies based on the size of the project.

2. Please select any materials management and tracking systems used in your agency for statewide materials management and for defining project materials QA requirements? (Please check all that apply)

#	Answer		Response	%
1	AASHTOWare (Site manager, etc.)		24	41%
2	Commercially or internally designed Laboratory Information Management System (LIMS)		26	44%
3	Spreadsheet, ledger, etc.		23	39%
4	No formal system		2	3%
5	Other		14	24%

Comments from Question 2

Commercially or internally designed Laboratory Information Management System (LIMS) (please describe):

(Port Authority of NY & NJ) Internal HiCAMS (Highway Construction and Materials System). Tracks receipt, payment, and acceptance of materials including contract administration and all inspection, sampling and testing of materials.

(NY) Internally developed LIMS to supplement SiteManager

(KS) Internal LIMS; CMS, similar to Site Manager

(WI) Atwood Systems - Materials Reporting & Tracking System

(AZ) ADOT uses internally designed laboratory databases for reporting/storing data

(AZ) Internal designed and maintained databases

(MI) Materials Testing System

(IA) In the process of internal development of a LIMS

(WI) Materials Tracking System, Materials reporting System and Materials Information Tracking

(IL) IMIRS program creates a database for all materials QC/QA data.

(ME) Internally designed Oracle database w/Access front end. Contains all materials sampling/testing data since 2002.

(FL) Modified Off the shelf system. Currently constructing a new database form the ground up.

(AK) Internally designed data base for central laboratory

(TX) Internally written in PowerBuilder

(VA) Materials Information and tracking system for hot mix asphalt testing and dense graded aggregate base materials. Materials Manual of instruction contains acceptance procedures for all materials. The link is: http://www.virginiadot.org/business/materials-download-docs.asp

(PA) Several, a LIMS like system we just implemented (eCAMMS), as well as others for fabricated structural steel, precast and pre-stressed concrete (EQMS), An Electronic State Book (ESB) for asphalt testing

(VA) We recently deployed a web based system for capturing asphalt concrete and central mixed aggregate production laboratory data

(GA) GDOT developed Field Data Collection System

(AK) Internally Designed

(AL) Currently developing our own program but are still relying on site manager at the present.

(WA) WSDOT Computer Applications

(WA) WSDOT Mats Lab Computer Applications http://wwwi.wsdot.wa.gov/matslab/default.htm

(MD) Developing Materials Management System and QA Material Processes Manual

(RI) Access databases developed in-house.

(MD) Custom made program as part of materials management system QA materials processes manual, http://ww.roads.maryland.gov/omt/qamanual.pdf

(LA) Matt system central data warehouse is being phased out

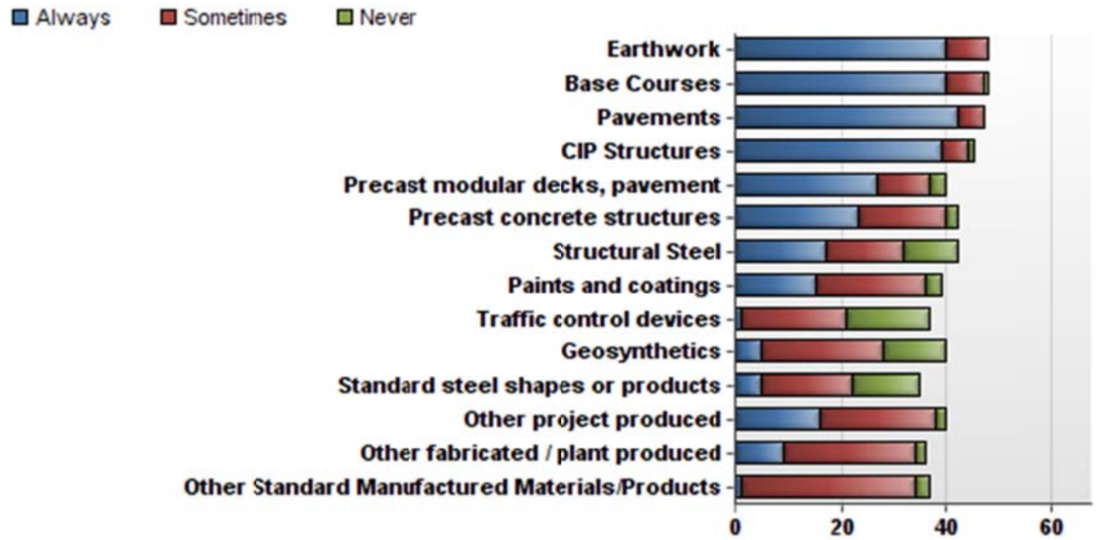
(AU) RMS Auon Database

(MD) In the process of Developing a Materials Management System

(CA) Written records at the lab or satellite lab

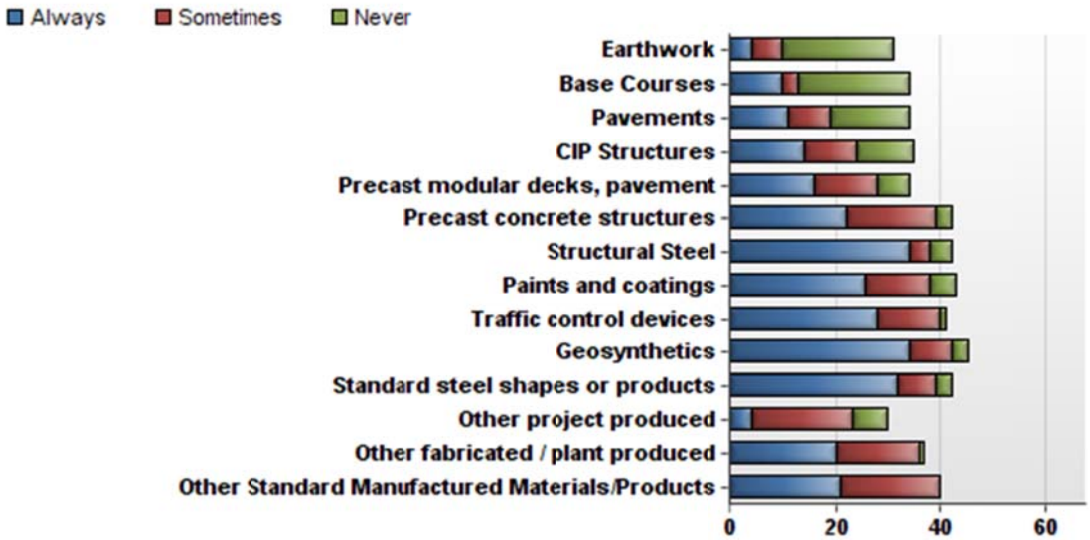
3. Questions 3.1 and 3.2 ask how your agency typically accepts materials for high (3.1) or low (3.2) profile projects considering a cross-section of materials (i.e. project-produced, fabricated/plant-produced, and standard manufactured products). If multiple levels of acceptance are used, please check all applicable acceptance methods and use the space provided for additional comments or clarifications.

3.1. Sampling and Testing



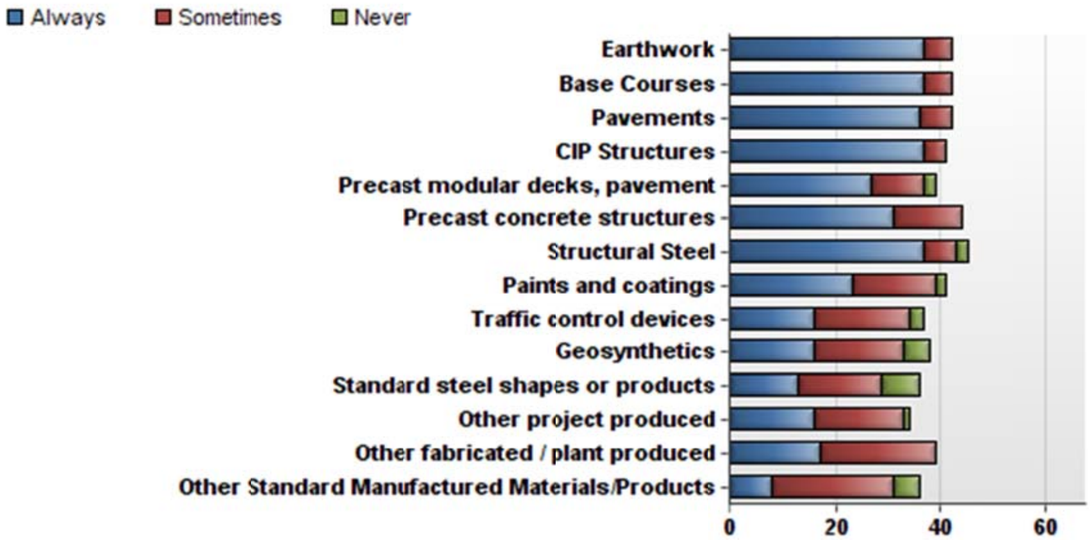
#	Question	Always	Sometimes	Never	Total Responses
1	Earthwork	40	8	0	48
2	Base Courses	40	7	1	48
3	Pavements	42	5	0	47
4	CIP Structures	39	5	1	45
7	Precast modular decks, pavement	27	10	3	40
8	Precast concrete structures	23	17	2	42
9	Structural Steel	17	15	10	42
12	Paints and coatings	15	21	3	39
13	Traffic control devices	1	20	16	37
16	Geosynthetics	5	23	12	40
17	Standard steel shapes or products	5	17	13	35
18	Other project produced	16	22	2	40
19	Other fabricated / plant produced	9	25	2	36
20	Other Standard Manufactured Materials/Products	1	33	3	37

3.1. Certification



#	Question	Always	Sometimes	Never	Total Responses
1	Earthwork	4	6	21	31
2	Base Courses	10	3	21	34
3	Pavements	11	8	15	34
4	CIP Structures	14	10	11	35
7	Precast modular decks, pavement	16	12	6	34
8	Precast concrete structures	22	17	3	42
9	Structural Steel	34	4	4	42
12	Paints and coatings	26	12	5	43
13	Traffic control devices	28	12	1	41
16	Geosynthetics	34	8	3	45
17	Standard steel shapes or products	32	7	3	42
18	Other project produced	4	19	7	30
19	Other fabricated / plant produced	20	16	1	37
20	Other Standard Manufactured Materials/Products	21	19	0	40

3.1. Inspection



#	Question	Always	Sometimes	Never	Total Responses	Mean
1	Earthwork	37	5	0	42	1.12
2	Base Courses	37	5	0	42	1.12
3	Pavements	36	6	0	42	1.14
4	CIP Structures	37	4	0	41	1.10
7	Precast modular decks, pavement	27	10	2	39	1.36
8	Precast concrete structures	31	13	0	44	1.30
9	Structural Steel	37	6	2	45	1.22
12	Paints and coatings	23	16	2	41	1.49
13	Traffic control devices	16	18	3	37	1.65
16	Geosynthetics	16	17	5	38	1.71
17	Standard steel shapes or products	13	16	7	36	1.83
18	Other project produced	16	17	1	34	1.56
19	Other fabricated / plant produced	17	22	0	39	1.56
20	Other Standard Manufactured Materials/Products	8	23	5	36	1.92

3.1. Additional comments

(OH) We make no differentiation between large or small or high or low profile projects. All are treated the same.

(NY) Materials from sources frequently require certifications regardless of Dept. Sampling/ testing. Inspection of materials as delivered to projects is very common for most products. Materials inspection at production facilities is common but may be accepted by certification on certain days when manpower isn't available to perform sampling /testing / inspection.

(KS) Difficult to say for the open-ended categories (other...). Precast modular - KSDOT is just getting into this area.

(OH) Ohio ODT samples and tests and accepts certifications according to the Ohio "Sampling and Testing Manual" and the "Construction Administration Procedures Manual"

(WA) CIP Structures: For Structural Concrete (4000 psi plus) Testing and Sampling would occur, but for 3000 psi concrete there are applications where sampling and testing are not done and acceptance is by certification. Precast Concrete Structures: All sampling and testing is performed by fabricator and test results reviewed and WSDOT Fab Insp. Structural Steel: Fabricator provides Weld UT, Radiographic file, mag particle testing results which are reviewed by WSDOT Fab Insp Standard Steel Shapes and Products: For Structural Fasteners (high strength bolts, nuts and washers) sampling and testing is done by WSDOT, for standard steel shapes no sampling and testing done.

(OH) Most all of our materials are covered under a Certified Supplier/Fabricator program or a Qualified Products List. With the certified supplier/fabricator programs the company becomes certified, random inspections are performed at the plants, and verifications samples are taken at the job sites or plant visits.

(AZ) Clarification - For some project produced materials, certifications are required for components of the material, i.e. asphalt binder certification required for Asphalt Pavement, but the final Asphalt Pavement is accepted by sampling, testing and inspection.

(IL) Paint coatings and geosynthetics are controlled by our sister agency, IDOT, and rarely sampled and pre-certified.

(MI) Inspection is always performed when material is received on project for correct type, paperwork and visually inspected for damage

(TN) We perform verification testing on all items accepted by certification

(MT) We consider structural steel to cover sign supports and bridges. Assumed the standard steel shapes or products meant roadside steel such as guiderail support. Have not yet got a reply from the Traffic Office - will forward if information obtained.

(FL) Pre-stress products (beams and pile) are inspected and tested at the yard. They are accepted at the job site if the certification stamp is on the member.

(RI) 1. Full time Acceptance testing at ready-mixed concrete, precast/pre-stress concrete and bituminous plants during production by State inspectors. 2. State requires Quality Control inspection / testing by the contractor (usually independent firm) for soils, asphalt, and concrete to mimic acceptance frequencies on some large projects on a trial basis.

(AU) Full ISO 9001 - since 1987

(TX) We have a combination of source sampling and testing, certification, inspection, and QM programs. Project site is final inspection and can reject, especially if damaged in shipment.

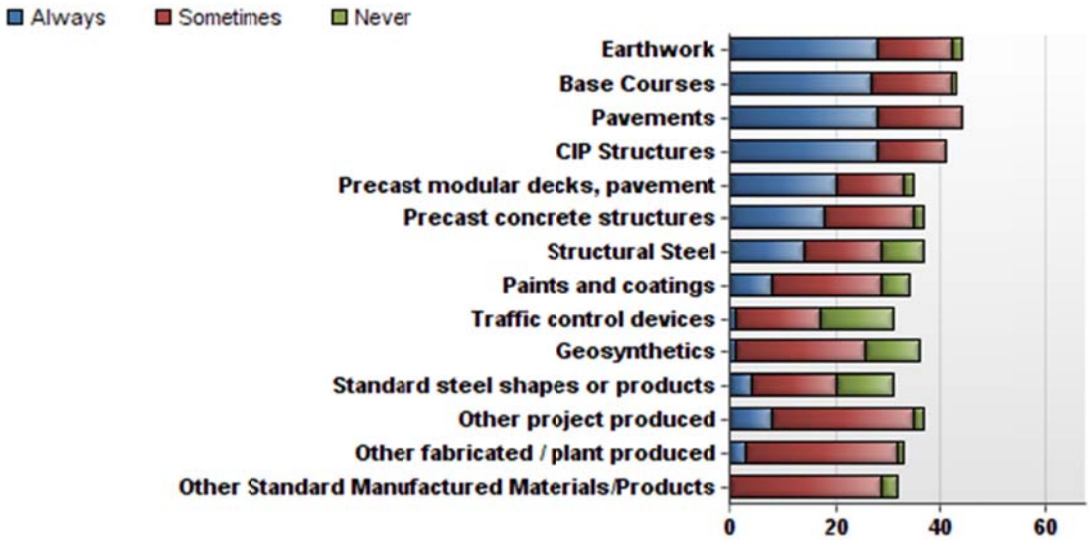
(VA) Virginia's overall acceptance program is the same for all design bid build projects. We determine risk related to materials and testing frequencies. In Design Build and Public Private Partnerships risk per project is taken into account. The materials testing responsibility is shifted in Design builds and P3 projects with more contractor quality control testing and layers of Quality Assurance management by Design builder and owner.

(GA) We always sample and test construction materials asphalt, concrete, base materials for acceptance and they must come from an approved source. Other products, precast concrete, structural steel, we accept factory certs but we do perform inspections on-site and at the plant.

(CA) Certification in multiple ways - Certify material testers, and Certificate of Compliance for material that is not tested nor inspected, however random testing is done, and selected testing is done if the material is suspicious.

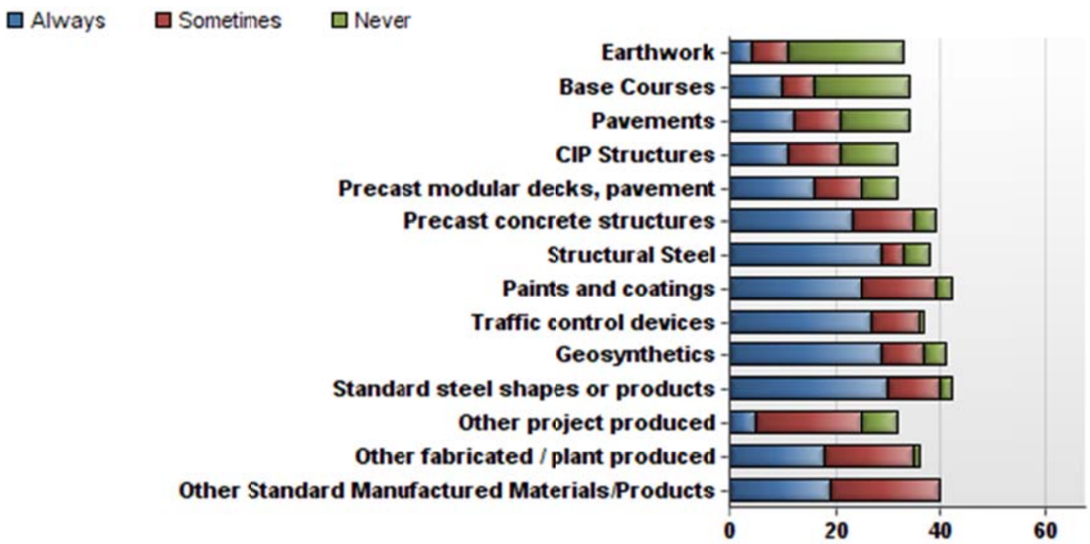
(DE) We consider the risk of failure and probability of failure in allocating our resources.

3.2. Sampling and testing



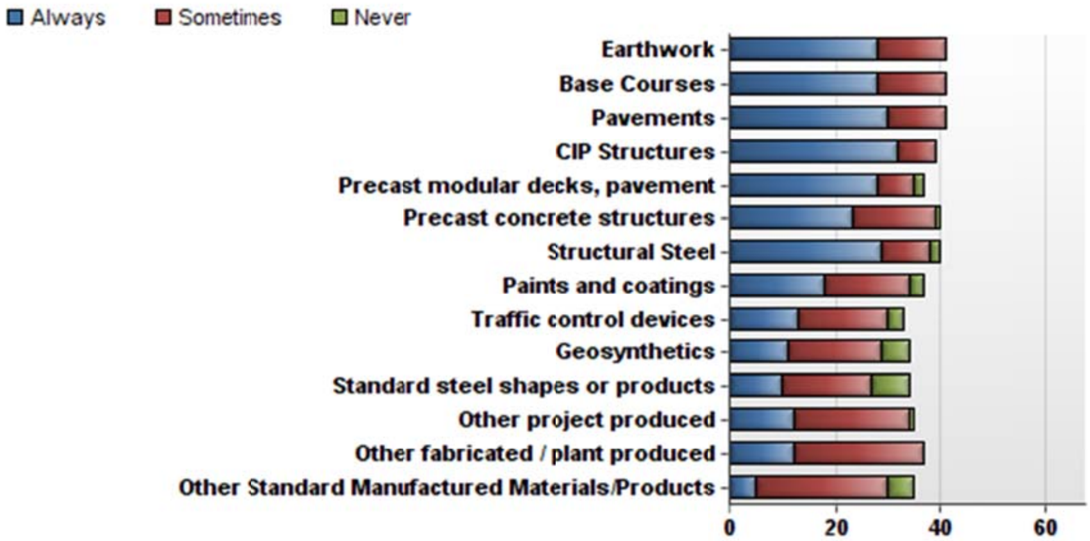
#	Question	Always	Sometimes	Never	Total Responses
1	Earthwork	28	14	2	44
2	Base Courses	27	15	1	43
3	Pavements	28	16	0	44
4	CIP Structures	28	13	0	41
7	Precast modular decks, pavement	20	13	2	35
8	Precast concrete structures	18	17	2	37
9	Structural Steel	14	15	8	37
12	Paints and coatings	8	21	5	34
13	Traffic control devices	1	16	14	31
16	Geosynthetics	1	25	10	36
17	Standard steel shapes or products	4	16	11	31
18	Other project produced	8	27	2	37
19	Other fabricated / plant produced	3	29	1	33
20	Other Standard Manufactured Materials/Products	0	29	3	32

3.2. Certification



#	Question	Always	Sometimes	Never	Total Responses
1	Earthwork	4	7	22	33
2	Base Courses	10	6	18	34
3	Pavements	12	9	13	34
4	CIP Structures	11	10	11	32
7	Precast modular decks, pavement	16	9	7	32
8	Precast concrete structures	23	12	4	39
9	Structural Steel	29	4	5	38
12	Paints and coatings	25	14	3	42
13	Traffic control devices	27	9	1	37
16	Geosynthetics	29	8	4	41
17	Standard steel shapes or products	30	10	2	42
18	Other project produced	5	20	7	32
19	Other fabricated / plant produced	18	17	1	36
20	Other Standard Manufactured Materials/Products	19	21	0	40

3.2. Inspection



#	Question	Always	Sometimes	Never	Total Responses
1	Earthwork	28	13	0	41
2	Base Courses	28	13	0	41
3	Pavements	30	11	0	41
4	CIP Structures	32	7	0	39
7	Precast modular decks, pavement	28	7	2	37
8	Precast concrete structures	23	16	1	40
9	Structural Steel	29	9	2	40
12	Paints and coatings	18	16	3	37
13	Traffic control devices	13	17	3	33
16	Geosynthetics	11	18	5	34
17	Standard steel shapes or products	10	17	7	34
18	Other project produced	12	22	1	35
19	Other fabricated / plant produced	12	25	0	37
20	Other Standard Manufactured Materials/Products	5	25	5	35

3.2. Additional comments

(MT) See previous comment.

(NY) Lesser quantities of materials often accepted by certification more frequently due to manpower shortages.

(KS) KSDOT does not specify QC/QA when project quantities drop below 5,000 tons for HMA and 5,000 square yards for concrete pavement.

(OH) Same as 3.1

(WA) Earthwork/Base Course: Project Engineer has ability to eliminate sampling and testing on small quantities of aggregate and earth work so testing may not occur every time.

(OH) We do not differentiate between low and high profile jobs with our standard material acceptance processes. These answers should be the same as for question 3.1

(AZ) Same as for large projects

(OH) Most all of our materials are covered under either a certified supplier/fabricator program or a qualified product list (QPL). With the certified programs the company becomes certified, random inspections are performed at the plants, and verification samples taken at the job sites or plant visits. ***NOTE: This same information would apply to our High Profile jobs. I clicked out of that question before completing the answers. If for some reason I can't go back in this survey I wanted to get this information out.*** ***Note: this same information would apply to our large

(TN) We perform verification testing on all items accepted by certification.

(MT) Same comment provided in 3.1 applies

(FL) We have "streamlined specifications" for projects less than $2 million less than 2,000 tons of asphalt. We have performance based frequency reductions for asphalt concrete and density on earthwork.

(RI) 1. Chart above shall mimic Item 3.1 as regardless of project size, our Master Schedule for Testing is specified.

(MD) Geosynthetics - NTPEP certification results

(LA) Same as previous

Full QA ISO 9001 since 1987

(TX) Generally the same as large projects. Final inspection is always field responsibility.

(VA) Virginia's overall acceptance program is the same for all design bid build projects large or small. We determine risk related to materials and testing frequencies. In Design Build and Public Private Partnerships risk per project is taken into account. The materials testing responsibility is shifted in Design builds and P3 projects with more contractor quality control testing and layers of Quality Assurance management by Design builder and owner. In locally assistant projects there is a tiered approach depending on the revenue stream. For example is the project federal funded or on the IHS or is local and state money used for project and will the final structure or pavement to be maintained by locality.

(GA) Same as before, we test roadway materials or require consultant field technicians hired by the city or county to meet our sampling and testing frequencies. All manufactured products must come from an approved source. Project inspectors must inspect the installation of the products.

(CA) Certification can refer to Certification of Testers, and Certificate of Compliance when inspection or testing is not performed, however random testing can be done, and is typically done when materials seem suspicious.

(DE) The profile of the project has little effect on our decision to inspect or not. A small bridge failure is no less a bridge failure than a large bridge failure.

(MI) Mississippi maintains a list of materials and the quantities in which the sampling and testing requirements are modified due to the fact that a small quantity of the material is to be used on the project.

(AU) Full ISO 9001 - since 1987

(CA) Certification in multiple ways- Certify material testers, and Certificate of Compliance for material that is not tested nor inspected, however random testing is done, and selected testing is done if the material is suspicious.

Statistic	Value
Total Responses	21

4. Please indicate whether statistically-based specifications using random sampling and lot-by-lot testing, and payment adjustment systems are used in your materials QA program?

#	Answer		Response	%
2	Yes		50	98%
3	No		1	2%
	Total		51	100%

4.1. For what materials or products are these processes used?

#	Answer		Response	%
1	Earthwork		12	25%
2	Base courses (granular or other)		17	35%
3	Asphalt pavement		46	96%
4	Concrete pavement		32	67%
5	Structural Concrete		20	42%
6	Other		3	6%

Other:

(MT) Binder

(CA) Mechanical Couplers

4.2. Does the acceptance plan utilize a payment adjustment system with a Percent within Limits (PWL) or other methods?

#	Answer		Response	%
1	Always		20	42%
3	Sometimes		22	46%
5	Never		6	13%
	Total		48	100%

Always:

(MT) P = (TL + aR - Xn) x F or P = (Xn + aR - Tu) x F

(AZ) PWL

(MO) For asphalt & concrete pavement not for base courses

(MD) PWL

(UT) HMA Pavements

(MI) Asphalt does not utilize PWL to determine pay factors. Structural Concrete utilizes a modified PWL

Sometimes:

(NJ) Except we use Percent Defective (PD) because we're pessimists

(WI) Concrete

(AL) Pay for HMA/WMA

(IL) For large quantity concrete pavements, performance related specifications with pay factors will be applied in 2015.

(RI) Asphalt only.

(LA) For asphalt

(OR) PWL is used for our asphalt and base aggregate products

(VA) Payment adjustment system for dense graded aggregates and hot mix asphalt is performed using statistics.

(PA) Bituminous

(OK) Not PWL

(CA) Based on project size and location

(DE) Hot-mix asphalt - yes, Density HMA - No, PCC thickness – No

Never:

(TX) No PWL. Penalty/Bonus apples to slot/lot

5. Do you utilize contractor QC data in the acceptance decision? (Please elaborate)

#	Answer		Response	%
1	Always		10	21%
3	Sometimes		29	60%
5	Never		9	19%
	Total		48	100%

Always:

(KS) What are you wanting to know?

(AL) In asphalt.

(MO) QC data acquired from sublot testing provides the basis for pay factor calculations and acceptance.

(MO) Provided QA compares with QC results

(CT) For HMA only

(AU) QA

(OR) Contractor testing is used for payment unless verification testing does not validate their testing

(MI) For asphalt pavement and structural concrete

Sometimes:

(Port Authority of NY&NJ) QMS for HMA

(NY) Only tied to Design Build operations w/ Statistical validation by Dept.

(AL) HMA - QC compared to QA, If QC & QA compare for % Pay, use QC results, if they don't compare Referee tests are sent to Central Lab for Testing. M&T test results are then compared to QC, if same pay factor calculated, QC results used, if not M&T results used for pay determination.

(WA) WSDOT Uses Contractor testing data in Design Build Projects for Payment as long as WSDOT QV testing verifies test results. For Design Bid Build projects WSDOT does all testing for payment.

(OH) Samples usually used for pwl pay factors but sometimes QC data may be utilized.

(MI) Only to engage dispute resolution process

(IL) Pay factors for concrete material properties (strength and air) may be based on some of the QC data in addition to QA data.

(TN) Only when making the decision to allow for concrete curing in the event of low cylinder breaks.

(ME) Only on Design-Build projects

(KY) Asphalt pavements

(MD) If it matches state results

(TX) Only on DB and PPP projects. We would perform or contract for OV to meet CFR requirements.

(UT) Only in dispute resolution

(VA) Dense graded aggregates plant sampling and testing for gradation and atteberg limits. Hot mix asphalt plant testing for asphalt content, volumetric and gradation along with field density using nuclear gauge.

(PA) QC data for density, concrete slump, air and temperature, non-destructive testing for structural steel. Small quantities, such as bituminous scratch courses accepted on certification.

(GA) The contractor performs acceptance sampling and testing at all of the asphalt plants.

(CA) In some concrete projects and HMA

(IN) Miscellaneous material from Certified Plants

Never:

(MT) We used to use QC but have moved to QA. There may still be some decisions that have not yet changed over to QA. We use QA data or referee for acceptance if testing is used.

6. Does your agency use alternative project delivery methods (e.g. Design-Build, warranty, or maintenance contracts)?

#	Answer		Response	%
1	Yes		40	80%
2	No		10	20%
	Total		50	100%

6.1. What alternative project delivery methods does your agency use?

#	Answer		Response	%
1	Design-Build and variants		40	100%
2	Warranties - please specify for which materials (i.e. project produced, plant fabricated, manufactured, other)-		14	35%
3	Long term maintenance		8	20%
4	Other		6	15%

Warranties -please specify for which materials (i.e. project produced, plant fabricated, manufactured, other):

(MT) Chip seals only

(Port Authority of NY&NJ) 12 month guarantee materials and workmanship issues

(OH) Various

(TN) We have tried a limited number of warranties in the past but none currently. We are currently trying a maintenance contract for sections of roadways. This contract is not associated with a construction project. Other is CMGC Construction Manager General Contractor

(ME) On DB projects, 5 yr. pavement warranty; 5 or 10 yrs. on bridge items.

(MT) Warranties are on everything. We have a one year general warranty and on specific projects there are 2, 3, 4, 7 and even to 30 years on some.

(FL) Asphalt, Concrete Pavement, Landscaping, signals and lighting, Bridge Components -joints and bearing pads

(TX) Very few warranties. Micro surfacing and some performance periods for pavement markings. PPP - finance, acquire ROW, design, build, maintain. These are PPPs. Usually about 50 years.

(UT) Paint, Bridge Deck Surface Treatments

(PA) Bituminous. Long term maintenance above is a P3 project we're currently putting together for the replacement of over 500 bridge structures.

(CA) Pavement and pavement preservation

(MI) Mississippi has utilized warranties for asphalt and concrete pavement in the past

(OH) We now have an Office if Innovative Delivery who is looking at many different ways.

(RI) LEAP (Local Enhancement Assistance Project) / General Enhancements - small specialized projects for towns or organizations

(IN) P3

(TN) We are currently trying maintenance contracts for sections of roadways. This contract is not associated with a construction project. Other CMGC Construction Manager General Contractor

(TX) PPP- finance, acquired

6.2. Do project delivery methods alter your standard procedure for materials QA?

#	Answer		Response	%
1	Not at all		17	44%
2	Materials QA is modified (please elaborate)		20	51%
4	Don't know		3	8%

Materials QA is modified (please elaborate):

(NY) When large quantities used, QC data may be used as part of acceptance, Owner verification required and statistical methods used

(MO) The design-build team proposes the quality control plan which is must be agreed upon by the DOT.

(WA) Design Build has Contractor QC and QA testing and is used for payment, while WSDOT does QV testing for verification of contractor test results.

(AZ) Very little

(AZ) There is only one project that I know of that altered the QA processes and that occurred many years ago

(MA) Material quantities are developed as the project progresses

(MO) On large projects QC by contractor, QA by hired company and agency performs audits

(ME) DB hires a testing firm to perform tests used in Acceptance decision, with DOT verification.

(MT) Less testing of materials. Acceptance based when possible on the performance of the product over time for warranty contracts.

(FL) For Public Private Partnership Projects

(KY) Design-build projects seldom provide specific material bid items and quantities, so sampling frequencies must be adjusted accordingly

(MD) On design build mega projects (ICC, WWB)

(LA) See website for design build QAP

(TX) In DB and PPP contractor responsible for acceptance using guide schedule. TXDOT conducts or hires consultant for OV at min of 10% of our guide schedule to satisfy CFR.

(UT) Contracting group hires an Independent Qualification Firm that tests at normal MSTR, Department correlates at set percentage usually 10%

(VA) Contractor performs QC. QA manager performs IA and verification testing. DOT or Owner performs IA and Verification testing

(PA) For P3 it will

(GA) The developer hires a consultant to perform acceptance sampling and testing. The owner hires and engineering firm to act as the DOT to hire consultant techs to perform verification.

(CA) Under our new Pilot Program, The Design-Builder performs additional quality verification of the quality control, and the Department's quality assurance/verification program uses this as part of its quality assurance.

(OH) They haven't yet but not sure going forward

7. Do you have a tiered or risk-based acceptance program for materials QA or any practices in place to optimize QA based on the criticality of materials (e.g. adjusting the type or frequency of tests, or methods of acceptance)?

#	Answer		Response	%
1	Yes (please describe the program)		21	45%
2	No		26	55%
	Total		47	100%

Question 7 Comments: Yes (please describe the program)

(MT) We performed a one time risk analysis/risk assessment several years ago to update our sampling and testing procedure.

(NY) Low risk on Approved List only, moderate risk may have some minor level of sampling testing, high risk requires sampling and testing

(NJ) Informal program with engineering judgment on reducing sampling rates

(WA) Materials that have been identified as a lesser risk (off the roadway type applications) the WSDOT Project Engineer may modify the standard materials approval and acceptance criteria to a less stringent requirement.

(AZ) In our QA sampling guide we designate the frequency and methods of acceptance for material type. Frequency of sampling is increased for some critical items in asphalt pavements and structural concrete.

(ME) 4 different Acceptance methods for HMA; 3 different for PCC, based on type, size of project.

(MT) For low complexity work with a short service life we may reduce or eliminate QA practices for performance requirements.

(FL) Performance based frequency reduction for concrete, asphalt and density on earthwork

(MD) Material QA is based on a minimum frequency of testing, state can increase frequency as required to assure quality of material

(LA) Somewhat for design build projects

(TX) Our frequently of guide scheduled testing is based on criticality, variability, etc.

(SC) Nothing is a written specification, but our managers can increase/decrease frequency of tests if needed

(VA) Aggregate quality testing, pavement markings and precast items.

(PA) Small quantities are typically accepted on the basis of certification alone.

(GA) If we have testing discrepancies and we obtain six inch cores from the roadway to perform ac and gradation analysis on the asphalt mixture the tolerance band gets tighter.

(CA) Structures items and some pavement items

(DE) It is not a formal program, but failure critical items are often tested at a higher rate. For instance, 8000 psi PCC gets more frequent testing in practice but it is not written.

(CA) We perform risk assessments based on a tier priority list for materials, ranging from a value of 1-4, with 1 being the material with the highest consequence of failure.

7.1. Please indicate which materials QA acceptance methods are tiered or risk based:

#	Answer		Response	%
1	Sampling and testing		18	90%
2	Certification of materials		7	35%
3	Plant certification		6	30%
4	Inspection		15	75%
5	Other (comments)		3	15%

Comments:

(VA) Combination of all these depending on Material

(CA) Some sampling, testing and inspection is waived based on perceived lack of risk

(DE) None

8. Please estimate the percent of your program budget allocated to materials QA (i.e. testing, certification, and inspection).

#	Answer	Min Value	Max Value	Average Value
1	Percent of budget to materials QA	0.00	73.00	11.95

9. Do you or any of your qualified producers/suppliers maintain a database of QA costs?

#	Answer		Response	%
4	Yes		8	17%
5	Don't know		24	50%
6	No		16	33%
	Total		48	100%

10. Do you or any of your qualified producers/suppliers maintain a database of percent defects for materials or products?

#	Answer		Response	%
4	Yes		14	30%
5	Don't know		20	43%
6	No		13	28%
	Total		47	100%

11. Are you willing to provide additional information and/or participate in a focus group or interview? (Check all that apply)

#	Answer		Response	%
1	Yes, I am willing to provide additional information		38	81%
2	Yes, I am willing to participate in a focus group or interview.		21	45%
3	No		6	13%

13. Please provide any links

Text Response:

(OH) http://www.dot.state.oh.us/Divisions/ConstructionMgt/Pages/default.aspx

(WA) Note: Don't have an estimated number for amount budgeted for QA.

(OH)http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Pages/ProposalNotesSupplementalSpecificationsandSupplements.aspx, http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Pages/2013-Online-Spec-Book.aspx

(AZ) ADOT Materials Quality Assurance Program - http://www.azdot.gov/docs/default-source/businesslibraries/qa-program-0114.pdf?sfvrsn=18

(IA)http://www.iowadot.gov/erl/current/IM/content/205.htm

(CT) http://www.ct.gov/dot/lib/dot/documents/dpublications/dmt-manual_2009_v2.pdf

(FL) http://www.dot.state.fl.us/Specificationsoffice/Implemented/Workbooks/History/Default.shtm

(RI) Master Schedule for Testing document and templates available on the right hand side of: http://www.dot.ri.gov/engineering/materials_research/index.asp

(MD) http://www.roads.maryland.gov/omt/qamanual.pdf

(LA) The data collected was taken from our Matt System. I only have the hard copy with failure rates.

(AU) Business as usual in percentage of budget to QA

(TX) http://ftp.dot.state.tx.us/pub/txdot-info/cst/guide_schedule.pdf

(OR) http://www.oregon.gov/ODOT/HWY/CONSTRUCTION/pages/mftp_manual.aspx

(SC) http://www.scdot.org/doing/technicalPDFs/supTechSpecs/SC-M-400_10-13.pdf

(VA) http://www.virginiadot.org/business/materials-download-docs.asp

(PA) Our specifications are available on line at www.state.pa.us

(IN) www.in.gov/indot, Materials Management Information

(DER) www.der.sp.gov.br

14. Please identify if there are other individuals within your agency or other outside organization that would have an interest in this research and would have anything to share. Contact Information:

Name:	Agency Name:	Position/Title:	Contact Phone:	Contact email:	Comments / Other
Lisa Zigmund	Ohio DOT	Administrator, Office of Materials Management	614-275-1300	Liasa.Zigmund@dot.state.oh.us	
Brett Trautman	Missouri DOT	Physical Laboratory Director	(573) 751-1036	Brett.trautman@modot.mo.gov	
Lisa Zigmund	Ohio DOT	Administrator, Office of Materials Management	614-275-1351	lisa.zigmund@dot.state.oh.us	
Steve Krebs	Wisconsin DOT	Chief materials engineer		steven.krebs @dot.wi.gov	
Dr. William Vavrik	Applied Research Associates	Principal Engineer	217-239-9690	wvavrik@ara.com	ARA is our pavement / materials management consultant who developed our database program (IMIRS) and is developing our performance related specifications in coordination with the FHWA.
David Ahlvers	Missouri DOT	State Construction and Materials Engineer	(573) 751-7455	David.Ahlvers@modot.mo.gov	
Tim Smith	MD SHA	Director, Office of Materials Technology	4435725032	tsmith2@sha.state.md.us	Materials management system being developed to maintain a database of producers/suppliers
Harold Paul	LADOTD	Director of LTRC	2257679101	Harold.Paul@la.gov	

Name:	Agency Name:	Position/Title:	Contact Phone:	Contact email:	Comments / Other
David Belser	TxDOT	Technical Operations	512-506-5803	david.belser@txdot.gov	
Robert Stewart	Utah DOT	Quality Manager	801 440 5746	rstewart@utah.gov	
Larry Johnson	GDOT	Testing Management Branch Chief	404-608-4811	ljohnson@dot.ga.gov	
Victor Zengler	Caltrans	Plant Services Supervisor	562-345-3126	victor.zengler@dot.ca.gov	
Dan Speer	Caltrans	Supervising Bridge Engineer	916-227-7016	dan.speer@dot.ca.gov	

APPENDIX D: INTERVIEW QUESTIONNAIRE

Questionnaire

NCHRP 10-92, Optimizing the Risks and Cost of Materials QA Programs Interview Form – DOT State: Contact Information: Review Team: Date:	
Discussion Point	Objective
A. General Information	Understand DOT organizational structure for materials QA Understand how materials QA is internally managed Understand how industry affects materials QA practices Identify materials QA manuals and guidelines Identify qualifications requirements for lab and technician staff Identify and understand automated systems for materials management

Discussion Topics:

1. Administration of materials QA Program (Central Office, District, Other):
    - Does your agency have dedicated central office materials division staff responsible for materials QA?
    - If so, what are the responsibilities of the materials division/staff?
    - What is the hierarchy of materials QA administration (i.e. under Construction versus reporting directly to a Chief Engineer)?
    - Is materials QA always performed by DOT staff or do you use Consultants (e.g. CEI, private labs) for QA?
2. Do contractors or producers/suppliers or industry groups provide input or contribute to current materials QA practices?
3. DOT guidelines/manuals addressing materials QA for DOT projects
    - Identify the guidance that your agency maintains (i.e. manuals or guidelines for materials QA) that define acceptance requirements for a project?
    - Do these manuals or guidelines incorporate the requirements of 23 CFR 637 Subpart B for all construction-related materials?
    - If not, do materials QA requirements change for different project or material types?
4. What qualifications programs are required for laboratory and technician staff (i.e. national or regional certification standards)?
5. Does your agency rely on an automated materials management system? If so, please describe the automated systems/programs you use for materials QA (e.g. sampling and testing schedule or record of materials) for a project?
    - Who manages the system?
    - Who can enter data?
        - Do contractors, producers, or CEI consultants have access or rights to enter data?
    - What specific project inputs are required to generate a materials QA schedule for a project?
    - What materials QA information does the output provide?
    - Is it an off-the-shelf or custom designed database?
    - Can the input data be imported from Excel or similar spreadsheet program?
    - Can the output be exportable to Excel or a similar program?

Responses:

1.
2.
3.
4.
5.

Optimizing the Risk and Cost of Materials QA Programs				
Discussion Point	Objective			
B. Materials Acceptance Hierarchy and Categories	Identify the range of materials QA acceptance practices and standard criteria for determining materials QA acceptance methods			
1. What are the major materials categories and how are these materials generally accepted in your standard materials QA program? Check where appropriate				
Example Major Materials Category/Classifications	Primary Materials QA Acceptance Method			
	Sampling and Testing	Certification	Inspection	Other
Project-Produced				
Earthwork				
Base Courses				
Pavements				
CIP Structures				
Other				
Fabricated Structural Materials/ Plant-Produced				
Fabricated Structural Steel and Coatings				
Precast/Prestressed Concrete Structural Elements				
Other				
Standard Manufactured Materials/Products				
Binders and Cements				
Geosynthetics				
Paints and Coatings				
Traffic Control Devices				
Standard Precast Concrete Items (Concrete Pipe, Manholes, Barriers, MSE Wall Panels)				
Standard Steel Shapes/Products (Anchor Bolts, Rebar, Grates, SIP Forms, Sheeting, and Piles)				
Electrical, Signals, etc.				
PVC, fiber reinforced polymers				
Pavement markings				
Other				
Note: If multiple acceptance methods apply, indicate what additional methods may be combined with primary method?				

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	Objective
Comments: 1.	

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	**Objective**
C. Materials QA Acceptance Criteria	Identify criteria that modify standard materials QA acceptance practices

1. What are the factors that may modify the level or types of QA and acceptance methods?
   - ☐ Project size, type, complexity, service level (e.g. ESAL)
   - ☐ Small or large material quantity
   - ☐ Project delivery method (i.e. Design-Build, warranty)
   - ☐ Use of contractor/producer QC test data in acceptance decision
   - ☐ Material/Product criticality
   - ☐ Other
2. What project characteristics modify materials QA or acceptance?
   a. Project size/complexity?
      i. For what materials/product types?
   b. Service levels for materials (design ESALS)?
   c. Other?
3. If material quantity is a criterion for modifying QA,
   a. For what materials/product types?
   b. What criterion (i.e. small quantity/project, large quantities)?
   c. How is materials QA modified (i.e. sampling frequency, properties, test methods)?
4. Does alternative project delivery modify materials QA or acceptance? If so, how?
   a. For what alternative methods (i.e. Design-Build, warranty)
   b. Materials QA and acceptance testing?
   c. Increased use of contractor QC test data?
   d. Reduced verification testing?
   e. Greater use of certification?
   f. Other?
5. How do DOTs rationalize QC versus QA data using methods such as statistical analysis; sample chain of custody for payment-related items; dispute resolution, etc.?
6. Are incentives/disincentives used based on the degree of conformance/non-conformance with specifications (i.e. QC or QA requirements) and for what materials or properties?
7. Does the use of contractor/producer QC test results or data in acceptance affect the levels of DOT acceptance testing?

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	**Objective**
Responses: 1. 2. 3. 4. 5.	

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	**Objective**
D. Materials QA Risk	Assess the risk of materials and how the risks might affect the level of materials QA and associated internal (and external) costs of QA

Discussion Topics:

1. For the major materials categories, what are the risks related to non-compliance or failure of materials or products?
   a. Project-produced
   b. Fabricated or plant-produced
   c. Standard manufactured products
2. Assess these risks in terms of likelihood or frequency of occurrence in your program and impacts that would occur related to failing or non-compliant materials.
   a. Safety (of highway user)
   b. Premature failure (reduced service life)
   c. Cost of repair or replacement
   d. Payment deduction or adjustment based on degree of conformance
   e. Other
3. Does perceived material/product risks modify your current materials QA acceptance program?
   a. Is your current system of materials QA acceptance practices risk-based?
   b. If so, what risk criteria is used (i.e. safety, cost of replacement) to determine the level of acceptance used?
      i. Do more critical materials require more materials QA (and vice versa)?
      ii. Are payment adjustments used as part of the acceptance decision and if so, for what materials, and how are adjustments determined?

Responses:

1.
2.
3.

Optimizing the Risk and Cost of Materials QA Programs

Discussion Point	Objective
E. Criteria for QA sampling and testing of project-produced materials/products	Identify the key properties for project-produced materials QA sampling and testing for acceptance, and what criteria may modify QA acceptance

1. What are the key acceptance properties and test methods for major materials categories?

Example Major Materials	Example Standard Materials QA Acceptance Criteria			
	Acceptance Property	Measurement Method	Sampling Location & Frequency	Test Method
Earthwork/Processed Base				
☐	Gradation	Sieve analysis	Source, 1/500T	AASHTO T2/27
		Other		
☐	Moisture/Density	Proctor		AASHTO T99
		Other		
☐	Density	N-Gauge	Field, 1/1500ft	AASHTO T238
		Other		
☐	Strength/Stiffness	LWD	Field,1/1500ft	ASTM E2583
		Other		
☐	Bearing	DCP (M_r)	Field, 1/1500ft	ASTM D6951
		Other		
Asphalt Pavement				
☐	Gradation	Various		AASHTO T27
☐		Other		
☐	AC Content	Lab compacted	Field, 1/sublot	AASHTO T308
☐		Other		
☐	VMA	Lab compacted	Field, 1/sublot	AASHTO R35
☐		Other		
☐	Air Voids	Lab compacted	Field, 1/sublot	AASHTO T269
☐		Other		
☐	Compaction	N-Gauge	Field, 1/sublot or 5/lot	AASHTO T269/ ASTM D2950
☐		Other		
☐	Joint Compaction	Cores	1/sublot or 5/lot	AASHTO T269
		Other		
☐	Other			

Optimizing the Risk and Cost of Materials QA Programs				
Discussion Point		Objective		
Concrete Pavement				
☐	Strength (compressive/flexural)	Cylinders/Beams (Maturity Method)	Field/Lab, 1/sublot or 5/lot	AASHTO T 140, T 97, T 325
☐		Other		
☐	Gradation	Various		ASTM C33
☐		Other		
☐	Air Content	Pressure Meter	Field/Lab	AASHTO T152/ ASTM C231
☐		Other		
☐	Slump		Field	AASHTO T 119
☐	W/C Ratio	Microwave	Field	
☐	Permeability	Rapid Chloride Ion or Surface Resistivity	Field	AASHTO T 277 (ASTM C1202)
☐		Other		
☐	Dowel Bar Alignment	GPR	Field, 5% joints/lot	
☐		MIT Scan		
☐		Other		
☐	Other			
Structural Concrete				
☐	Strength (compressive/flexural)	Cylinders/Beams (Maturity Method)	Field/Lab, 1/sublot or 5/lot	AASHTO T 140, T 97, T 325
☐	Gradation	Various		ASTM C33
☐		Other		
☐	Air Content	Pressure Meter	Field	AASHTO T152/ ASTM C231
☐		Other		
☐	Permeability	Rapid Chloride Ion or Surface Resistivity	Field	AASHTO T 277 (ASTM C1202)
☐	Other			

2. Are there any acceptance properties that are specifically indicative of performance?
3. Are there any properties that you are considering for future use for acceptance?
4. What materials properties are used for statistical analysis and pay adjustments, if any?
5. What key acceptance properties, sampling frequency, or test methods would be modified based on project characteristics, material quantity, materials criticality, project delivery method, or other criteria?

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	Objective
Responses: 1. 2. 3. 4. 5.	

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	Objective
F. Alignment of DOT materials QA acceptance with 23 CFR 637	Identify how 23 CFR 637 is implemented and whether contractor/producer QC test results are utilized for acceptance

1. Does your materials QA acceptance program include the following in accordance with 23 CFR 637 Subpart B for projects using federal-aid:
   a. A frequency guide for verification sampling and testing adapted to specific project conditions?
   b. The location in construction or production operation where sampling and testing is performed? If so, how is the location determined?
   c. Specific properties or attributes to be inspected or tested that reflect the quality or performance of the finished product?
2. Are contractor/producer QC test data used in the DOT materials acceptance decision?
   a. If so, for what materials or products?
      i.
      ii.
   b. How are contractor/producer personnel and laboratories qualified for sampling and testing purposes?
   c. Has the use of contractor QC test data resulted in materials QA cost or internal resource savings?
3. How is the frequency of DOT verification testing determined?
   a. Does the frequency of verification testing change (more or less) depending on the material or product type?
   b. Does the frequency of verification testing change based on the project delivery method (i.e. Design-Build, Design-Build-Maintain, warranty)
4. How is Independent Assurance (IA) implemented?
   a. Is it a project-by-project or a system wide approach?
   b. If a system approach, has it resulted in cost savings?
   c. If a systems approach, how often are technicians IA tested for their areas of certification; and are equipment checks/calibrations tracked and at what frequency?
5. Do your non-federal aid projects follow the same procedures for materials QA?
   a. If no, how do your procedures differ?

Responses:
1.
2.
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4.
5.

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	**Objective**
G. Criteria for Materials QA Acceptance of fabricated materials by certification and/or other methods	Identify key criteria used to accept plant-produced or fabricated materials by certification or other methods and what criteria may modify QA acceptance for plant-produced or prefabricated materials.

Discussion Topics:

1. Provide examples of common plant-produced or fabricated materials/products
   - ☐ Precast concrete structures, (precast, prestressed beams, etc.)
   - ☐ Structural steel
   - ☐ Other
2. What QA methods or combinations of methods are commonly used for acceptance of fabricated or plant produced materials/products?
   - ☐ Approved or qualified product
   - ☐ Producer/supplier QMS certification or QC Plan
   - ☐ Material/product certification
   - ☐ QA Audit/inspection
   - ☐ Other
3. Do some producers/suppliers of fabricated materials/products use self- certification or a recognized certification program (i.e. NTPEP, ISO 9001 QMS) that requires less downstream agency verification (i.e. testing, inspection, QA audit or other acceptance practices)? If yes, for what types of materials/products?
4. Do some plant-produced or fabricated materials/products have different levels of agency acceptance (i.e. verification testing, inspection, QA audits or other) based on factors including criticality of products or project delivery method?
5. If yes, how is acceptance modified based on criticality of products or other factors?

Responses:

1.
2.
3.
4.
5.

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	Objective
H. Criteria for Materials QA Acceptance of Standard Manufactured Products	Identify key criteria that may modify QA acceptance practices for standard manufactured products

Discussion Topics:

1. What are common examples (or categories) of standard manufactured products
   - ☐ Binders and Cements
   - ☐ Geosynthetics
   - ☐ Roadside Safety Devices
   - ☐ Standard Precast Concrete Shapes
   - ☐ Standard Steel Shapes
   - ☐ Traffic Control Devices
   - ☐ Other
2. What are the requirements for a material/product on your approved or qualified products list?
   - ☐ Certified plant/supplier
   - ☐ NTPEP
   - ☐ QA Audit (plant or source)
   - ☐ Inspection
   - ☐ Periodic re-certification
   - ☐ Other
3. What QA methods or combinations of methods are generally used for acceptance of standard manufactured materials/products?
   - ☐ Approved or qualified product
   - ☐ Manufacturer certification
   - ☐ Inspection
   - ☐ QA audit
   - ☐ Other
4. Do some standard manufactured products require less rigorous agency QA (i.e. desktop or visual inspection only) if product is qualified or manufacturer is certified (e.g. ISO 9001 or other) or manufacturer provides a warranty?
5. Do agency QA acceptance practices vary based on the criticality of the manufactured product or other factors?
6. If yes, what criteria determine the criticality of the products and how is QA modified based on criticality or risk?

Responses:

1.
2.
3.
4.
5.

Optimizing the Risk and Cost of Materials QA Programs	
Discussion Point	Objective
I. Materials QA Cost	Assess the relative cost of materials and the associated internal (and external) costs of Materials QA

Discussion Topics:

1. Does the DOT have data or records documenting materials QA costs for construction that is used for project estimating purposes or for entire program?
2. Does the DOT estimate the costs of materials QA as a percentage of bid items or program cost, or is it a separate line item in the internal estimate for a project?
3. Do costs for materials QA (either as a % or as a line item) vary based on the materials QA requirements for material acceptance? If so, how are the costs calculated for:
    a. Sampling and testing protocols (including field and lab testing)?
        i. Earthwork
        ii. Asphalt
        iii. Concrete
        iv. Other
    b. Agency certification of materials/products?
    c. QA audit/Inspection (plant, field, desktop)?
    d. Combinations of the above?
4. Do the materials QA costs include the external costs related to:
    a. Consultant CEI services?
    b. Contractor/Producer quality management (i.e. QC plant and field testing and inspection)?
    c. Approved products testing?
    d. Manufacturer or other certifications?
5. If not, how are external QA costs accounted for in the project budget?
6. As part of data collection, we also want to reach out to a local supplier/producer to better understand their internal cost of materials QA. Would you recommend a particular industry contact?

Responses:

1.
2.
3.
4.
5.
6.

List of Abbreviations and Terms

ACI. American Concrete Institute

AASHTO. American Association of State Highway and Transportation Officials

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 [FHWA-NHI-08-067]

AMRL. AASHTO Materials Reference Laboratory

ASTM. American Society of Testing and Materials

CCRL. Cement and Concrete Reference Laboratory

CEI. Construction Engineering and Inspection Services

CFR. Code of Federal Regulations

CMM. Construction and Materials Manual

CRSI. Concrete Reinforcing Steel Institute

CQAF. Construction Quality Assurance Firm

CQMP. Construction Quality Management Plan

DB. Design-Build project delivery method where a single entity provides project design and construction services and the DB contractor is responsible for developing and executing a Quality Management Plan.

DBB. Design-Build-Build project delivery method is the traditional delivery method for highway construction

DOT. Department of Transportation

EP Curve. Expected Pay Curve; A graphic representation of an acceptance plan that shows the relation between the actual quality of a lot and its EP (i.e., mathematical pay expectation, or the average pay the contractor can expect to receive over the long run for submitted lots of given quality)

ESAL. Equivalent Single Axle Load

Fabricated Structural Materials. Major structural materials or items produced specifically for an individual construction project by a material fabricator. The materials are normally mass produced under highly controlled and automated manufacturing conditions. The materials arrive at the site in a solid, finished state, and require little or no work after installation. [AASHTO R38-10]

FHWA. Federal Highway Administration

HMA. Hot Mix Asphalt

IA. Independent Assurance are activities that are an unbiased and independent evaluation of all the sampling and testing procedures used in the acceptance program. The purpose of an IA system is to assure the reliability of all data used by the agency in the acceptance determination including agency verification data and contractor QC data. The results of IA testing should never be used in the acceptance decision

Inspection. The act of examining, measuring, or testing to determine the degree of compliance with requirements

ISO 9001. The international organization for standardization, ISO, standard 9001 sets out the criteria for a quality management system including requirements for certification. Many organizations (e.g. producers and suppliers) are ISO 9001 certified and implement a QMS for the production of materials and products

MARTCP. Mid-Atlantic Region Technician Certification Program

MSTG. Minimum Sampling and Testing Guide. Generic or project specific listing of materials and minimum size and frequency of sampling required, along with associated tests performed

NCRMA. National Concrete Ready Mix Association

NETTCP. Northeast Transportation and Training Certification Program

NICET. National Institute for Certification in Engineering Technologies

NPCA. National Precast Concrete Association

NTPEP. National Transportation Product Evaluation Program managed through AASHTO

OC Curve. Operating Characteristic Curve; A graphic representation of an acceptance plan that shows the relationship between the actual quality of a lot and either (1) the probability of its acceptance (for accept/reject acceptance plans) or (2) the probability of its acceptance at various payment levels (for acceptance plans that include pay adjustment provisions) [TRB Circular EC-074]

PCCP. Portland Cement Concrete Pavement

PE. Project Engineers

Project-Produced Materials. Major items produced directly for an individual construction project by the contractor or a material producer. The production process for the material occurs either at the project site or at a production plant located in close proximity to the project site. The materials typically require subsequent mixing, compaction, finishing, or curing. [AASHTO R38-10]

PPP. Public-Private Partnership project delivery method

PWL. Percent within Limits acceptance methodology

QC. Quality Control is the system used by a Contractor/supplier to monitor, assess, and adjust their production or placement processes to ensure that the final product will meet the specified level of quality

QA. Quality Assurance includes 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 that the quality of a product or facility will perform satisfactorily in service. The current QA definition addresses the overall problem of obtaining the quality of a service, product, or facility in the most efficient, economical, and satisfactory manner possible. [TRB Circular EC-074].

QPL. Qualified Project List (also referred to as Approved Product List)- Listing of products and materials approved by the agency for use

QML. Qualified Manufacturers List is a listing of manufactures or suppliers qualified by an agency to provide materials or products

QMP. Quality Management Plan is a Contractor developed plan to meet QA requirements for DB projects (i.e. roles and responsibilities, sampling and testing, certification, inspection)

QMS. Quality Management System (associated with ISO 9001 certification of producers and suppliers)

SHA. State Highway Agency

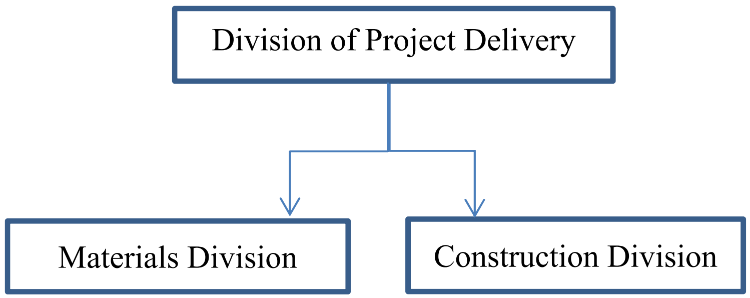
SME. State Materials Engineer

Standard Manufactured Materials. Standard items are produced routinely (i.e. not for a specific project) by a manufacturer. The materials are normally mass produced under highly controlled and automated manufacturing conditions. The materials are stable and have little potential for alteration when transported properly, and arrive at the site in a solid, finished state, and require only installation. [AASHTO R38-10]

Verification. The process of testing the truth, or of determining the accuracy of test results, by examining the data or providing objective evidence, or both. [Verification sampling and testing is part of an acceptance program to verify contractor testing used in the agency's acceptance decision).] [TRB Circular EC-074]

WAQTC. Western Alliance for Quality Transportation Construction

APPENDIX E: STATE INTERVIEW SUMMARY

State/ Contact Information	Interview Summaries
Florida (FDOT) Timothy J. Ruelke, P.E. Director, Office of Materials Florida Department of Transportation Timothy.Ruelke@dot.state.fl.us Date 5/27/14	**General Information** FDOT materials organized into a central office responsible for general policy and procedures and 8 Districts responsible for materials QA on projects in each district. The central office assists the districts, but the management is decentralized in the execution of materials QA. More generally FDOT organized as:  The standard specifications include the requirements for QC testing, verification testing, and a resolution process for issues related to QA FDOT uses an approved supplier approach for QC of Redi Mix plants and asphalt plants. They must meet the requirements and criteria specified by FDOT for an approved supplier. The District staff will periodically audit/inspect the plants to assure they continue to meet the approved supplier requirements. Aggregate suppliers have to upload their data to FDOT system to maintain approved supplier status. Contractors must use FDOT pre-approved suppliers for their projects **Optimization Strategies or Streamlining of Materials QA** For small quantities, FDOT may use visual inspection, or for <200T or <$2M, the frequency of testing may be reduced. FDOT also uses a streamlined payment process (Lump Sum)

State/ Contact Information	Interview Summaries
	Criticality of inspections are much higher for pre-stressed beams, piles, steel beams or similar safety critical structural elements **<u>LAP Specifications</u>** FDOT implements "Streamlined" specifications for local agency projects (LAP) that don't qualify as requiring standard FDOT specifications. These streamlined specifications are called the "Big 4". FDOT in a 2014 bulletin defines 4 classes of projects: • Class A: On SHS • Class B: Off SHS with value of $10M or greater • Class C: Off SHS Bridge defined as having a length of more than 20' (including multi-span box culverts). • Class D: All remaining off-SHS projects FDOT defines three types of construction administration applicable to local projects: • Type I: Use FDOT standard specifications and STRG and materials/construction requirements • Type II: Use either approved local agency specifications or pre-approved FDOT LAP "Big 4" specifications • Type III: Use either Type I or II The LAP must use Type I for Class A-C projects, and can use Type II streamlined specs for Class D projects **<u>Other Optimization Strategies</u>** For Section 346 Concrete specs, the sampling frequencies are cut in half. For Section 347 Non-structural concrete specs; FDOT evaluates the risk and based on risk, may reduce sampling frequency FDOT uses CQC (Contractor Quality Control) Specs for Asphalt Superpave; Spec uses contractor test results in acceptance decision and PWL (percent within limits) for payment adjustments (I/D). FDOT does not use CQC specs for concrete **<u>Alternative Delivery</u>** For DB contracts, QC by contractor and QA by agency are specified. For P3 projects, verification shifts to the Developer, and FDOT does risk-based auditing. • For example, for the I- 4 Ultimate P3 Project: QC and QA may be reduced if 10 consecutive tests are

State/ Contact Information	Interview Summaries
	OK (performance-based frequency reduction) • Because structural concrete outlives the Concession Agreement, frequency of testing is reduced FDOT uses a standard 3-year asphalt pavement warranty specification • No bonding required, FDOT uses a "guarantee" approach (prequalification for future work contingent on meeting warranty requirements) • CQC with FDOT verification • FDOT thinking about backing off on QA • Performance based approach to QA o If can prove that the operation is under control, then frequency can be reduced or move to larger lots (i.e. from 2000 cu/yds. to 4000 cu/yds.) **Costs** The cost of testing in FDOT's opinion is insignificant compared to the cost of failure. The use of larger lots (reduced frequency) is a cost reduction strategy. Regarding the use of performance-indicating or performance-based tests, FDOT is still not there yet. **<u>Certification</u>** GPL (Guard Bridge Assembly) certification Wooden stand-off blocks Certification with mill analysis (tests) FDOT recognizes national certification standards • PCA - Prestressed Concrete Association – Certification of Pre-stressed Producers • NPA – National Precast Association **<u>Cost of QA</u>** • FDOT Materials and Research = .55% of SB • FDOT Applied Research Group = .4% • Materials QA (lab tests using consultant contracts) = 1.17% • CEI costs include field inspection, field density and making cylinders • Materials - all in testing and inspection amounts to 2% of project cost

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California (Caltrans) **Translab**, 5/21-22/14 John Babcock HQ Office Chief john.babcock@dot.ca.gov Daniel Speer METS-OSM Office Chief dan.speer@dot.ca.gov Jnex Youch Senior Bridge Engineer jack.youch@dot.ca.gov Bobby Petska CT MET OSM John Cammers CT-DES-SC Keith Hoffman CT-DES-METS Jim Sagar CT-DES-METS/GS james.sagar@dot.ca.gov Ken Darby CT-DOC-OCE ken.darby@dot.ca.gov Chris Cummings CT-NR-CONST Robert Stott CT-DES-SC Jose G. Reza CT Dist 4 Labs CA Industry Reps	**General** Caltrans does most of testing for acceptance. There are generally three general areas to classify materials: field-produced, plant-produced, and standard manufactured products. For plant-produced materials, Caltrans uses a risk based inspection with high priority and low priority materials/items. The state is organized into a HQ and 12 districts. Each District has a District Construction and District Materials Director. HQ is organized into Structures, Materials, and Construction. Caltrans has one Construction Manual and one Materials Manual. Construction Manual covers construction recordkeeping and Section 6 of the Construction Manual deals with job-produced materials. Additionally Caltrans maintains one Office Process and Procedures Manual, and more recently has developed a QA Program Manual for both job produced and fabricated items. In addition to then manuals, Caltans has standard specifications, and standard special provisions addressing materials QA. Caltrans indicated that many of the specifications that are referenced in their manuals date from the 1950s. Because of how the manuals have been updated, the specifications, frequencies, and procedures are spread out in a number of different documents. For example, Caltrans' QA program manual for construction provides standard specifications to be used in plant or project produced materials but the frequencies are described in the construction manual. To coordinate the construction process as well as QA, the manuals explain step by step what the staff should do once they are on site. Caltrans is moving towards clear and readily available specifications so that contractors better understand Caltrans' requirements. **QA for Local Public Agency (LPA) Projects** Caltrans maintains a Quality Assurance Program (QAP) Manual for LPA projects to provide QA guidelines for materials. The way Caltrans is delivering LPA projects is changing in the sense that locals now have increased control for delivering their projects. Locals have assumed this control through legislation giving them taxing authority. If on the SHS, the QA approach is very similar to Caltrans projects. Caltrans provides the QAP manual, and specifications and standards. Very few LPAs have their own specs and standards. Caltrans MET also maintains a source inspection quality website. Caltrans enters into Cooperative

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	Agreements with LPAs, which address the cost of QA. Caltrans staff provides oversight and consultant staff perform the work. No funding is provided for maintenance and operations. Although LPAs may be overseen differently, it is in most respects similar to Caltrans approach. LPAs usually ask for certifications, when applicable, and require a QMP from the consultant. Audits are performed of the paperwork for sampling and testing. LPAs (particularly in Northern CA) use Caltrans' specifications but they have their own budget and can make QA decisions by themselves. Caltrans is concerned by the way local agencies operate, first LPAs only fund improvements but no maintenance, secondly many rely on consultants to do most of the QA, and lastly some have their own customized specifications. These attributes of LPAs may confuse the contractor regarding the QC/QA expectations. **Caltrans QC Requirements** Caltrans has strong QC requirements for materials. The actual QA approach has no effect on the contractor's quality procedures. *"Our inspection is inconsequential to most of their QC process"* Rob Stott California test methods are moving towards adoption of broader standards (National Standards). They are in the process of modification to better define QC requirements and certification. **Alternative Delivery** Other trends include greater involvement in LPA, DB, and P3 projects. Caltrans follows a 90/10 rule, in other words, 90% of is done in house. The increased use of different project delivery methods such as Public Private Partnerships (P3) has effected changes in Caltrans' policies. To adapt to this new challenge, the agency has emphasized its position to rely on themselves (90% done in house, 10% through consultants), and provide only oversight to ensure projects are administered in a similar fashion to State requirements. The agency expressed its concerns about contract administration with alternative delivery methods, especially with the contractor rejecting their own loads (materials) and the way to empower inspectors doing the tests or rejecting batches. To reduce the agency's risk or to better allocate it to their suppliers, warranties have been used in some local agencies but in a project by project basis. The Districts customize their specs (non-standard special provisions) which may not be consistent with state

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	standards for QC/QA. **<u>Changing Materials QA Requirements</u>** New materials requirements are being introduced for recycled materials (asphalt and concrete) with new RAP mixes for both and specs based on volume of asphalt. AGC local chapter is involved with Caltrans in development of new specs. (ROCS Committee) Roadway materials will pay for IA and accredited labs. There are over 300 materials labs statewide Regarding testing, typically Caltrans will perform approximately 10% of total testing (i.e. 90% is contractor QC, 10% is Caltrans QA). For certain plant-produced materials (i.e. precasting), QC testing is more robust to reduce Caltrans QA. ACI certification not required. Regarding industry self-regulation, the industry is not particularly good at regulating their own materials. Certain materials more critical to performance, are for example, fracture-critical materials such as steel bridge girders and non-redundant steel piles. Redundant piles represent a lower risk, and should require less QC/QA. Acceptance Methods/Levels (i.e. testing, certification, inspection). The group agreed that the QA approach is project and District dependent. They provided some examples such as how redundant piles have different QA approaches, HMA acceptance methods changes with different quantities, geology, or traffic, or that an “authorized” or pre-approved material is sometimes inspected afterwards as well. For field-produced HMA pavement, Caltrans uses essentially three different construction processes: 1. Old style paving method 2. Section 39 method for 1-10k tons 3. HMA > 10k tons (750T 1/3 ratio of testing, grad., cores) The use of RAP has increased from RAP @ 15% to 40% on lower lifts & QA criteria has changed (i.e. Hamburg Wheel Deformation), superpave, PG asphalt Workmanship criteria also apply to field-produced (i.e. IRI) Caltrans also applies a **1-yr guarantee** on materials and workmanship for all construction

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	Standard manufactured products Authorized materials per METs website include: • Certified materials and additives • Proprietary Materials Also OSMPP (Office of Structures Materials Policies and Practices) has pre-approved materials Authorized materials are accepted through a Certificate of Compliance **Plant Inspection** Caltrans uses three levels of inspection based on risk and probability and consequence of failure. These are: • Continuous (F/T inspector at plant) • Intermittent (moderate risk items like signals and lighting pole installation) • Programmatic (lower risk items such as timber, cyclone fencing Fabricators typically have a QC manager. For Certified suppliers of pre- cast, Caltrans inspection will audit the QC process. Legislation requires each lab to follow same guidelines. Caltrans is adopting a risk-based approach to source inspection that shifts more risk to suppliers to self-regulate. There was an issue with welds on rebar, and risks involved resulted in contractor being barred from working in CA. Aggregate quarries require yearly certification. Field sampled materials are covered in Chapter 6 of manual Certificate of compliance is applicable to extremely reliable materials. National standards used for rebar (AASHTO NTPEP), NRMCA (Ready mixed concrete), ACI, and CPCPA and NPCA (precast), ACPA (concrete pipe), etc. **Cost of QA** Cost of QA includes the costs of testing, inspection, and administration. From a lab perspective, a materials testing estimate is required including # of testing hours. The QA (all in) cost target is 13% based on $10M. For smaller projects, the fixed rate is much higher, and for

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	larger projects lower depending on the materials. Of the 13%, QA costs are divided into roughly 50% are for lab costs (staff and admin.). Of the staff and administration and only about 13% of the administration costs are assigned to the functional units. [Chris Cummings] The process begins at District with estimates of resources in the design phase. For example, approximately 200 lab hours are resourced for an asphalt mix design. A work plan is developed for individual hours for District staff. Lab costs may include facility rentals, down time, overhead, and equipment maintenance. In some cases, multiple mix designs from a supplier can be used on one project or multiple projects. For well-defined QC, Caltrans is letting the contractor do more of the QC; 400 projects Regarding PCC source testing, sampling materials in quarries in winter (compiled on an annual spreadsheet) saves project testing. The cost of equipment/ expendable materials to supply lab can run $4M/yr. Regarding IA costs, there are two F/T staff at District for IA. Consultant inspection staff generally runs approximately 1-1/2 times the cost of in-house inspection. **Construction QA $** Construction staff QA runs about 15% of QA total. Of this, 7 ½% comprised of field inspection/testing based on historic data, and 3 ½% is the QA portion of field inspection/ testing 15% of projects involve roadway and structures --- this % could double in future [Jose Reza] Bay area projects experience 30% of total QA for RE support costs including travel for testing inspectors, field inspectors, field testers, and lab testing for PCC, HMA, and structures. This is significantly higher than other more rural Districts. **Contractor Comments/Recommendations** 1. Standardization of QA process throughout the state 2. Adopt a joint certification program using national certification standards based on AASHTO or other standards 3. Change business model to shift more responsibility to industry (suppliers) for quality

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	4. Better, faster turn-around of test results; timely test results for QA Superpave has changed the way industry does QA for job mix (JMF) based on VMA and gyratory mix, also RAP, warm mix, and RAZ. Contractors taking more responsibility for quality. Owners need to adapt with more appropriate QA practices. **Specification risks** Balancing buyers and seller risk for sampling and testing Determine what tests are truly important, and how many tests are needed for performance (statistical control) Analysis of spec tolerances to determine that tolerances are achievable and result in the desired quality level and performance. **Industry control (process control)** • Capable process - statistically under control • Marginal process - more heavily sampled • Experimental- continually sampled Variability of plant performance should be measured based on standard deviation **Optimization Strategies** • Eliminate unnecessary tests • Reduce number of tests (verification or QC) for under control materials tests on low risk materials • Standardized test methods • Increase use of certified materials/ certified suppliers • Less QA on low risk materials • Lower inspection levels (or programmatic auditing) by agency/Department **Caltrans Materials/Construction QA Optimization Initiatives** A. **Risk-based Method for Acceptance based on Project/Materials Type**. The Material Plant Quality Program (MPQP) certification is used for plant produced materials. The program assures that everything is scaled correctly by deploying inspectors through a risk based decision process that determines the level of inspection from programmatic, and intermittent, to continuous. High

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priority/high risk items are always inspected/tested at higher inspection levels. Project type also is considered in the evaluation, where higher profile or higher risk projects are subject to more rigorous QA.

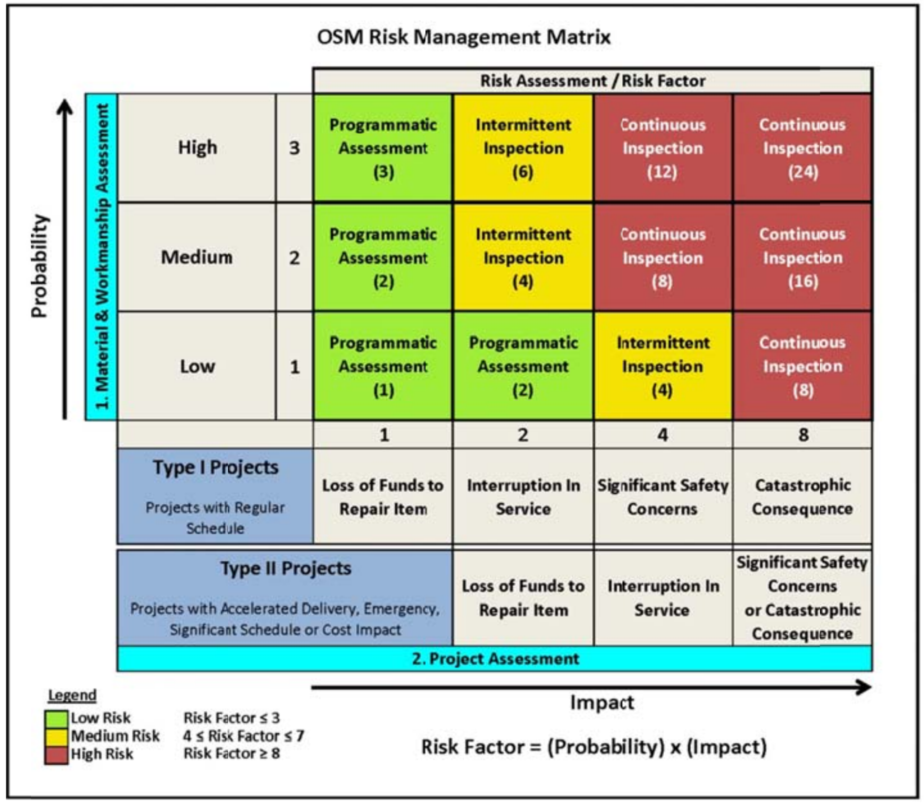

Figure 1. OSM/METS Risk-based Matrix Tool for Materials

B. **ISO Standards for Certification**. Caltrans does not accept ISO certifications however the Independent Assurance Manual, which they manage, has the authority to certify independent

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	engineers and laboratories. Certification agencies are not selected by Caltrans in a consistent manner. On the other hand, they want to become ISO 9001 compliant, even though not many of their suppliers are ISO-certified Caltrans shared additional documents including the draft CQA Manual for construction. This manual describes a process for drafting QA specifications using a risk-based tiered level listing for all the specification sections in the Caltrans Standard Specifications based on the consequence of failure. Given the tier level, and production mode (i.e. jobsite, fabricated, and manufactured), the specification can be developed further to define the appropriate QA plan that may involve certification, field testing and/or inspection. A jobsite produced material plan would include quality characteristics, sampling and testing methods, location and frequencies for testing, and acceptance criteria and limits.

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Washington DOT (WSDOT) 5/21/14 Kurt Williams State Materials Engineer 360-709-5410 WilliKR@wsdot.wa.gov 6/13/14 Jeff Carpenter State Construction Engineer Carpenter, Jeff CarpenJ@wsdot.wa.gov	WSDOT undertook a Materials Risk Analysis between 2002 and 2005 with the final report published in February 2010. The purpose of this risk effort was to define levels of QA from lowest to highest levels of QA effort, and then assess or rate materials risks (considering both likelihood and consequence of materials failing to meet specifications). Based on the risk ratings for materials derived through a Delphi process, WSDOT assigned a QA level to optimize or align the QA effort based on material risk. The follow-up interview discussed the WSDOT risk analysis study and WSDOTs risk-based approach to materials management as reflected in the WSDOT Construction Manual (Chapter 9, Materials) as a starting point. WSDOT is organized in to 6 regions. In term of functional responsibilities, materials QA include Construction (Division Manager) → Materials Lab (QA/IA → Region Labs (IA) → Inspectors. WSDOT also interacts with AGC, concrete aggregate suppliers, and ACPA for materials management policy. [Kurt Williams] WSDOT indicated that the current construction manual was revised based on the results of the risk analysis study. He pointed out that the frequency of testing may vary for a number of reasons associated with risk as explained in the manual. The Contractor typically is responsible for QC and Department for verification. For small quantities a testing frequency might be (1 test per 2000 tons). Testing frequencies are given in Chapter 9. For large quantities of materials under control (where QC tests are uniform), the QA frequency might adjust downward based on the uniformity of the test results (first 10 tests). Another example would be that very small quantities of a specific material may be accepted based only on visual acceptance. The Project Engineer also can use discretion regarding the acceptance of materials. As noted in Chapter 9: *The options that are available to the Project Engineer for approving and modifying the acceptance of materials are the following sections:* • *Section 9-1.1A Sampling and Testing for Small Quantities of Materials* • *Section 9-1.1B Reducing Frequency of Testing* • *Section 9-1.1C Project Engineer Discretionary Materials Acceptance* • *Section 9-1.1D Optional Approval/Acceptance for Materials* *The Reduced Acceptance Criteria Checklist (DOT Form 350-120) shall be completed and retained in the materials file when Reducing Frequency of Testing, Sampling and Testing for Small Quantities of Materials and Project Engineer Discretionary Materials Acceptance are invoked. All information requested on the checklist shall be filled in completely. Any items that do not require approval from the State Materials Laboratory and the State Construction Office may be approved at the Project Engineer level.*

	Considering field-produced, plant-produced, and standard manufactured materials/products categories, the WSDOT Materials Division has responsibility for QA of plant-produced materials. WSDOT maintains approximately 15-16 inspection staff (certified inspectors) performing random inspections checks at various plants and fabrication facilities (locally and throughout the US). WSDOT uses an internal system of ratings or evaluations of fabrication facilities which may affect the level of inspection. WSDOT also takes into account certifications of facilities such as PCI concrete certification. For standard manufactured products, WSDOT maintains a QPL and typically 5 years is time it takes to get qualified. Once qualified, DOT requires resubmittal and retesting periodically. **QA Cost** Programmatically, materials management QA cost (including labs, inspectors, QA staff) amounts to approximately $22M/year (assume that this cost is allocated across whole program). Additionally, each project has a QA component. The budget office maintains data on these costs. WSDOT provided the team with a standard schedule of billing rates for services and testing for all of the tests run in the lab. The 2014 rates included both hourly rates and estimated test times for tests and analyses of the material. The cost of QA for construction typically runs about 8-10% of project construction cost for Construction Engineering (CE). The plant inspection portion of the budget could amount to 10-15% of QA for construction. For standard manufactured products (i.e. rebar, reflective materials, pipe), certified by AASHTO NTPEP or other national standards, the industry bears the cost of material evaluations and certification as need to become qualified or maintain qualification on the QPL. [Jeff Carpenter} Construction provided additional input on construction QA verification and acceptance costs. Typically CE consultant contracts range from 8-10% of construction costs for a project. Approximately 30% of that amount (or 2-3% of construction) is for material QA acceptance. In response to the question regarding which materials generate the most QA effort/cost, typically pavements and/or structures amount to 40-50% of QA costs for typical projects depending on the scope. In general, anything fabricated would result in lower construction QA cost. Field-produced asphalt pavements typically require more CE attention to both quantities and QA. Structures may also drive the QA effort depending on the project type. The trend is that industry is assuming more QC/QA responsibility for field-produced pavements, performance concrete, etc. With more prescriptive requirements for contractor QC, the Department is focusing more on end-result testing. For DB projects, a consultant performs QA and the Department verification.

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Ohio (ODOT) Jeff Chandler Structural Welding Engineer Office of Materials Management Ohio Department of Transportation 614-466-4082 Jeffery.Chandler@dot.state.oh.us 5/13/14	**Organization** ODOTs Division of CM includes the offices of Materials Management and Construction Management Materials Management includes a CFR accredited Central Lab and District Labs that handle acceptance of materials. The website for materials management is found at link: http://www.dot.state.oh.us/Divisions/ConstructionMgt/Materials/Pages/default.aspx The site includes the: QPL (Qualified Products List), Approved List of Certified Producers and Suppliers, Training / Certified / Approved Personnel, ODOTs Virtual Warehouse (TE-24), and the CMRS Portal. Jeff covered the different approaches to acceptance of materials through the office of materials. 1. Qualified Products List (QPL) (http://www.dot.state.oh.us/Divisions/ConstructionMgt/Materials/Pages/QPL.aspx) a. By clicking on the Spec number one will find the companies. By clicking on the material description you will find submittal requirements. 2. Certified Suppliers: (http://www.dot.state.oh.us/Divisions/ConstructionMgt/Materials/Pages/CertifiedSuppliers.aspx) a. Click on the Supplements in the left column and our supplement specs which explain the submittal requirements and our basic QA program for each material. This is the supplement which explains the quality control plan submittal, along with our random inspection requirements we discussed. Supplement 1078 is for our structural steel fabricators. In this you will see it is different from the other certified supplier programs as we rate fabricators based on how they perform the work. The better ratings they receive the less inspection we perform. I would guess this could be titled a “risk based” program since we only audit standard ancillary bridge items (Level SF) while we inspect items that may be load carrying or are special Level UF and 1 thru 6). I copied the section of our Construction and Material Specifications which explains the different levels below. Supplement 1079 is pretty much the same and this is for Pre-stress Concrete beams. b. Click on the name of the material in the right column and the approved companies will come up. 3. Sampling and Testing Manual (http://www.dot.state.oh.us/Divisions/ConstructionMgt/Materials/2013-Sampling-and-Testing-Manual/Pages/default.asp The rating system used based on levels of fabricator qualification for Certified Suppliers is as follows:

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	513.03 Levels of Fabricator Qualification. There are eight levels of fabricator qualification. The Office of Materials Management will classify each fabricator at the highest level of fabrication it is qualified to perform.

Level	Description of Capabilities
SF	Standard fabricated members described and paid for as Item 516, 517, and 518 and detailed by standard bridge drawings. Material and fabrication acceptance by certification with random Department audits of the work and documentation.
UF	Unique fabricated members not covered by standard bridge drawings and not designed to carry tension live load. Examples include curb plates, bearings, expansion joints, railings, catwalk, inspection access, special drainage, or other products. Examples also include retrofit cross frames, retrofit gusset plates, retrofit lateral bracing, or other miscellaneous structural members not included in Levels 1 through 6. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, UF Level.
1	Single span, straight, rolled beam bridges without stiffeners, Secondary and Detail materials designed to carry tension live loads such as retrofit moment plates. Case II Loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
2	Multiple span, straight, rolled beam bridges without stiffeners. Case II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
3	Single or multiple span, straight, dog legged, or curved, rolled beam bridges including stiffeners. Case I or II Loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
4	Straight or bent welded plate girder bridges. Case I or II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.
5	Straight, curved, haunched, or tapered welded plate girder bridges. Case I or II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Levels 1 through 5.

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	6 — Truss bridges, fracture critical bridges, fracture critical members, or fracture critical components new or retrofitted. Case I or II loading. Quality assurance of shop drawings, material test reports, and inspection according to Item 513, Level 6. The website for certified materials contains the specifications relating to each certified material/product. Certified materials are used as a pre-approval process with different levels of testing depending on the materials. Structural steel girders and beams, and various ancillary items have different levels of testing as noted above. The levels range from certification with random audits (level SF) to QA of shop drawings, material test reports, and inspection based on the specification requirements. To become certified, a supplier must provide its QC plan, and meet requirements in Supplement 10-68 & TE-24. For DB projects, there is essentially no change to QA materials management requirements. ODOT is instituting a new program (EIMS) as a way to allow track hours for projects. Certification is used for ready mix QA. The Office of CM (Gary Angles) can provide information on construction QA processes, etc.

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Eileen C. Sheehy, P.E.
Manager, Bureau of Materials
New Jersey Department of Transportation
ph: 609-530-2307
eileen.sheehy@dot.state.nj.us</td><td>The NJDOT Bureau of Construction and Materials HQ is responsible for QA including pre-qualified materials on the QPL, plant inspection of fabricated materials, precast plants, etc.
The Regional Materials Engineers are responsible for all jobsite testing
The Products Group at HQ handles QPL, and plant inspections.
The IA group out of HQ performs IA at project or system wide level.

The criticality of materials is a primary criterion determining the level of QA. NJDOT has limited staff such that staffing levels determine the quantity of testing done.

NJDOT adjusts the frequency of QA testing based on quantity of materials. For example, for concrete pours <20yds, and for large volumes under control, the rate of testing is reduced.

Contractor QC is never used for acceptance

QA includes sampling and testing (field-produced materials), certification, and inspection.
Factors considered in determining the level of QA are:
• Criticality of the element (i.e. facture critical structural steel, pre- stressed elements, precast
• Quality of supplier,
• Quality of Consultant
NJDOT will adjust or cut back on testing or inspection (or audit), depending on these factors.

NJDOT uses certifications for acceptance (or reduced QA) for materials including Ready Mix, HMA, and aggregates

HMA pavement may involve specialty mixes or testing for fatigue, APA rut tests, overlay testing or beam fatigue. HDP pipe also.
Because NJDOT staff has been reduced, sampling and testing is reduced and subject to month to month decision making regarding prioritization of testing and inspection.

<u>QA Cost</u>
HQ testing is treated as an overhead expense. This includes labs, plant inspections, QPL certification, etc.
NJ uses as a rule of thumb 1% for Bureau of Materials and 1% for Regions This includes construction inspection at plants including precast and structural steel budgeted at 24hrs/day.</td></tr>
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	For job-specific QA, construction uses a formula to determine QA costs for field testing and inspection. Construction inspectors would perform inspections of deliveries of plant-produced (fabricated materials) for damage during shipping and checking seals, stamps, BC, etc. Construction inspectors may also take cylinder samples, perform density testing, rebar inspection, pour procedures, etc. Typically construction QA inspection ranges from 5-15% of project cost depending on the project materials requirements

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Texas (TXDOT) 5/12/14 Darren G. Hazlett, P.E. Deputy Director, Construction Division 512-416-2456 Darren.Hazlett@txdot.gov Follow-up 11/14/14 Interview Darren Haslett, David Belser, Jim Travis, Sid Scott, Cecil Jones	QC/QA is not % dependent on project $. QC/QA light for small quantities. Each DB and P3 is reviewed individually for QA requirements. DB includes 15 year (or other) maintenance agreements which will affect levels of QA. Contractor can do optional QC testing for enhanced process control. TXDOT uses a tiered approach for acceptance (does QV – quality validation). We went thru the guide schedule to determine what materials are most significant and are we most interested in. TXDOT conducted a risk workshop on the SH 130 DB project, consisting of 40 miles of roadway. SH 130 was not conducive to acceptance testing by TXDOT. We were not going to try to validate everything. The test procedures allows options and developed a tiered approach as follows: • Tier 1- Full F & T testing • Tier 2- Comparing tests to control chart with no f & t testing • Tier 3- Observation, observing QC tests to make sure it's done right For DB, TXDOT performs no QC (this is contractor requirement per their QMP) HDR- Weng Tam developed process **<u>Certification</u>** TXDOT certifies std. manufactured materials (i.e. asphalt rubber crack sealer) or other products that don't have a limited shelf life. Qualified producers must be re-qualified every two years. (moved away from qualified suppliers) If a producer is in the Producer/Supplier QA program (reduced risk), TXDOT will lower number of required samples, with limited verification. Rebar is NTPEP certified and TXDOT audits all test results For bridge beam suppliers, TXDOT used to do all of the testing and inspection. Now, if suppliers are certified per approved QC plan, TXDOT does audits and inspection (staff now at typically half of the original size) **<u>APL</u>** State bears the cost of testing conditioned upon acceptable material. Every 3 years APL must be renewed Contractor/Supplier will provide a sample for testing - test report form essential. If it doesn't meet the specifications, the contractor/supplier is charged for cost of testing

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	<u>**QA costs**</u> For bookkeeping - finance spreads out the cost of QA across all projects. For construction divisions, Site Manager captures costs for structural inspection (e.g. bridge beams, retaining walls), field inspection, stamps, etc. <u>**LA (Local Assistance) LA Program**</u> Smaller projects can't do statistical validation or acceptance testing Same practices used as for state projects TXDOT has an optimal standard guide schedule for testing (TXDOT DB QAP Guide) • HDR I2MS for DB with QA, QV real time test data • General data for quarterly FHWA reporting **11/14 Interview** **Darren Haslett, David Belser, Jim Travis, Sid Scott, Cecil Jones** **Introductions and meeting agenda:** Sid described the NCHRP project scope, and reviewed a summary of the interview responses to date that were included in the latest quarterly report. Then TXDOT further described its materials QA program **Current TXDOT Optimization strategies** The TXDOT Guide Schedule of Sampling and Testing provides the basis of their requirements. This document was revised based on the findings of a research effort that was completed in 2001 (project 1781), using a risk based approach by the UT Center for Transportation Research. TXDOT shared the report, entitled *Development of a Methodology to Determine the Appropriate Minimum Testing Frequencies for the Construction and Maintenance of Highway Infrastructure*. The research objective at the time was: *To develop a methodology for determining the optimal sample size and appropriate testing frequencies for construction materials on the basis of a statistically sound approach. By conducting a review of the state-of-the-art in testing procedures and frequencies used by various transportation departments and other agencies, a formula was established to define the relationship between required sample size and the parameters involved. Statistically, the optimal sample sizes or appropriate testing frequencies are primarily based on four issues: The variability of the quality characteristic being measured, the risks that a state DOT or a contractor is willing to take, the*

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	tolerable errors each is willing to accept, and the cost of the testing to be performed. A sensitivity analysis is conducted to show how sensitive the sample size is to the change of material variability, confidence level, and tolerable error. Using the data collected from TxDOT districts and the methodology developed under the project, the frequencies for certain TxDOT tests were developed and compared to the current TxDOT Testing Schedule. The study found a high level of risk, but the level of testing was not deemed practical so a preamble was inserted in the guide document noting that the risk to both the Department and the Contractor of either rejecting "good" material or accepting "bad" material ranges from 20% to 40%. . The decisions were based on the use of engineering judgment rather than cost based statistics due to the difficulty in capturing and tracking the cost of QA activities. They do, at times reduce the testing frequency once a process is under control, and for small quantities as described in sections 340 and 341 of the Std. Specs. For HMA, the lot size is increased which has the same effect of reducing frequency of tests. The specifications are being modified that will move these sampling frequencies closer together. Nonstructural concrete testing may be waived for small quantities (Section 421). TXDOT also reported that it does not use streamlined specifications for local agency projects as is the case for some DOTS. Local agencies generally reference TxDOT specs, and there is some level of oversight by TxDOT. The Materials Producer List (MPL) is a QPL for producers. Producers provide data initially to get on list, and periodically afterwards to stay on it. Sign sheeting, aggregates, and other materials are system based. The system does not preclude the use of materials not on the list, but producer must submit lot by lot quality data. Some materials are required to be on the MPL, such as sign sheeting, because of the time of testing and complexity. The criticality of the material is generally incorporated into the MPL. Qualification criteria for producers is identified in DMS 7300 that includes national and local certification programs. The state has moved towards QA with verification & audits for producers because of staffing reductions and risk assessment. The agency does still have a presence at some production facilities, such as prestressed concrete plants. In the past, the agency was performing QC, but have been moving towards QA with audits because of efficiencies realized that allows personnel to cover more than one plant, and focus on problem areas.

State/ Contact Information	Interview Summary
	Aggregate quality is monitored by producer and if varies, the sampling frequency is required to increase from 1 to 6 months to get back in control. For Hot Mix Asphalt, all must be certified in accordance with the TxDOT – Texas Asphalt Association joint program. Producers must be certified (e.g. PCI for concrete or HMA through TAA) in order to supply TXDOT projects. Systems are in place to address issues and irregularities, such as failure to test, fraud, etc. **Alternative Contracting** TXDOT experimented with use of contractor QC tests for HMA in acceptance decisions in 1993. It wasn't deemed workable and was discontinued in 2003. TXDOT now has implemented pay adjustments for certain pavement properties and uses ride specifications with payment adjustments with TII certified equipment. Initially the agency had a project-specific document that addressed quality management. The contractor hired a firm to perform QA, and the agency hired a firm to perform verification. F&t testing comparisons were made. From this, a stratified tiered program evolved. TxDOT terminology defines QA as contractor testing, and OV is the owner verification. A Design Build Quality Assurance Plan (QAP) document was subsequently developed where OV was performed on 10% of all testing performed by the contractor. The approach was to transfer more risk to the contracting firm. The contractors have been performing materials testing far in excess of the minimums identified in the Guide Schedule, causing the agency to perform significantly more testing than anticipated, thereby increasing their costs and staffing levels. After that experience of increased verification testing because of the number of tests run by the contracting firm, the process was modified to develop a tiered system and recommended levels, based on risk. Level 1 (highest level is currently soils, pavements, and structures). This was initially based on the perception of what testing is critical for work with a 15 year warranty. Currently, most Design-Build contracts have a 5 year mandatory warranty and TxDOT chooses whether or not to include additional 5year increments. The warranties typically address soils, pavements, drainage, and structures. A new process called COMA provides for a 25 year total maintenance requirement. The industry estimates warranty/maintenance costs based on net present value of future maintenance. This includes everything

State/ Contact Information	Interview Summary
	such as mowing, snow removal, animal removal, patching, planned and preventative maintenance, etc. This has created some issues about what needs to be performed on construction QA in order to comply with the provisions of the CFR. **Cost of QA** Costs of QA go up tremendously on DB and P3 projects, as there is no requirement re frequencies of QC TxDOT does not have test specific costs, but does have information from commercial laboratories about costs in the form of a statewide fee schedule. There are 16 contracts in place. They also have an internal fee schedule that is used when they perform testing for others, such as the toll authority, but it may not accurately represent typical project testing. **10-92 Risk Model** Sid Scott reviewed the model from Task 4 of the last quarterly report and asked for input from the participants. Observations and comments from the meeting participants are as follows: • In order to have meaningful numbers, lots of data is required. • TxDOT does not rate contractors (bullet 1 of step1) because it is very difficult to objectively accomplish. • TxDOT does short list contracting entities on Design-Build projects, but on traditional contracting if a contractor is on the list of prequalified bidders, they can submit a bid. • Some exceptions exist for bidding on specialty contracts, such as computerized signal systems, etc., that does limit the firms that can submit bids. • The participants felt that the model could be used once for the development of a minimum sampling guide (like their Guide Schedule) for use on a system basis. They did not feel that it would be used on a project basis routinely. • The model would help agencies understand the risk they are taking if resources are not available to optimize. • A general comment was made about the need to: 1. Identify the most critical items 2. Understand the consequence of failures 3. Use to understand the relative cost of testing vs., risk. • Suggested that the model be modified to accommodate the relative scale of costs for instances where hard data does not exist

State/ Contact Information	Interview Summary
	• Use programmatically rather than on a project basis • Questioned if maintenance costs can be fed back into the system In summary, TxDOT indicated that they did see benefit in the model and they could use it: • A tool to revise their Guide Schedule of Sampling and Testing • Approach would be to contract with a University to conduct the analysis • Serve as a reality check if the result dramatically increases the need for testing in order to minimize risk

State/ Contact Information	Interview Summary
Virginia (VDOT) 5/28/14 William R. Bailey III, P.E. Assistant State Materials Engineer Phone No. 804-328-3106 or Cell 804-350-3142 Bill.Bailey@VDOT.Virginia.gov	VDOT has a materials division and a construction division that handles materials QA The materials division consists of a Central Office with 55 staff and an accredited lab The Central office provides guidance to the district labs. There are 9 Districts, and 7 asphalt labs with District materials inspection staff. On the construction side, the construction division central office oversees the District construction staff Generally VDOT operates under the one program philosophy and as documented in the Materials Manual and the default approach is that the Department tests everything the same. NHS projects include federal funding and are subject to federal regulations re QA. The Materials Division website has documents (specs, manuals, and procedures) http://www.virginiadot.org/business/materials-download-docs.asp **Field-Produced Materials** The Materials Manual covers all materials. The major field-produced materials, soils, asphalt and concrete follow the manual's sampling and testing guide. For small quantities the frequency may be reduced Asphalt (Manual CH 5) testing is system based, and uses contractor test results in acceptance decision. Density is tested in the field and verification on based on taking so many cores per lot. Dense graded aggregates are also system based. VDOT does all testing in the field VDOT will use contractor test results for dense graded clean stone in modified acceptance (VDOT tests for LA Abrasion) for concrete per specs. **Fabricated materials** Fabricated materials are covered by QA staff supplemented with consultant inspection Weld tests are performed for steel. For Precast concrete and pipe, QA programs (VDOT criteria) involve certifying that work was done in accordance with the contractor's approved QC plan. Consultant inspectors are used to conduct quarterly inspections of plants and visual field inspections of fabricated materials/products (paperwork and QC stamp)

State/ Contact Information	Interview Summary
	QPL The QPL includes std. manufactured or pre-fabricated materials that take significant time to test and qualify – typically 2 years. VDOT uses NTPEP (Performance based testing) & get numbers to verify VDOT takes random samples of some materials, uses cut sheets for traffic devices by utility owners and accept by certification based on national standards. For metals, will analyze compliance with Buy America C- 25- Checks source of materials on approved list **Statistically based VTM** For asphalt and granular base VDOT can use contractor plant QC tests Pay adjustments are made for AC, and gradation, volumes are p/f. **Alternative Delivery (DB and P3)** (See VDOT Minimum Requirements for Quality Assurance and Quality Control on DB and Public-Private Transportation Act Projects, January 2012) When delivering DB/P3 and long-term maintenance contracts: • Contractor performs QC, same as for Asphalt • Contractor submits a QAP Plan, and performs QC and QA per plan • VDOT retains a QA manager (not under contractor), that essentially acts like the DOT • QA manager oversees project to assure that contractor performs verification testing • VDOT does 10% of verification 1/10 for assurance • In DB's of P3s, contractors have "equity" in project, VDOT doesn't act as sole owner LAP projects are modeled after DB when using test results Contractor test results are used and risk is considered depending on who maintains VDOT looks at risk based material performance. Aggregates are usually risk based. Quarries are rated based on quality data. Epoxy, guardrail, cement, fly ash, and other products may use modified acceptance based on certification and approved supplier source list. For admixtures, VDOT checks paperwork.

State/ Contact Information	Interview Summary
	<u>Cost of QA</u> Cost of QA is typically 4% of the project. In this instance QA represents lab costs for materials testing, and staff for Materials Division

State/ Contact Information	Interview Summary
Maryland State Highway Administration (MDSHA) 6/12/14, 9/25/14 Woodrow Hood Division Chief, Materials Management Office of Materials Technology Office 443-572-5020 Cell 443-474-2288 Woodrow Hood WHood@sha.state.md.us	MDSHA maintains a standard frequency guide for minimum testing frequencies which varies based on the criticality of the project (i.e. safety critical materials). Every material is handled the same way in guide. For asphalt pavements, contractor QC test results are used in acceptance if verification matches QC tests. For concrete pavement, QC is done by the SHA for 28 day cylinder breaks. QC is done by contractor for early breaks. IA is done by SHA MDSHA website has all relevant material QA resources: http://www.roads.maryland.gov/index.aspx?PageId=51 **Plant Inspection** For fabricated structural product inspection at plant, consultants provide oversight of QC testing and materials are also accepted by certification (MARTCP, AWS, CWE, and NTPEP). **Certification** Materials accepted by manufacturers' certification are based on inspection of test records, mill certs, and audits at spec frequencies. The inspector will review/spot check QC stamp by supplier along with visual inspection in field. For standard manufactured products on QPL, materials suppliers and manufacturers must have a good tracking system. QPL products may also be subject to random (unannounced) audits and potential additional forensic tests. Steel fabrication must be QC qualified to be accepted by certification Contractors must provide an approved producer of mix designs (HMA) If not an approved supplier, supplier must submit an approved QC plan. QA consists of source testing (radiographic, mag particle, etc.). SHA participates in Mid-Atlantic Regional Certification Program (MAR) similar to NICET. This program provides a list of materials with good history of use backed by annual auditing.

State/ Contact Information	Interview Summary
	For field-produced material production at plant (i.e. HMA, PCC, GAB), QC staff cannot report directly to production staff. MDSHA conducts annual system-wide QA plant inspections ($250k) which are not directly charged to the projects. These QA inspections may follow a QA checklist v annual inspection **QA Cost** Construction QA plus QA lab costs are 10—15% of project for everything, and approximately 3-8% for materials QA (lab) only. For larger projects QA is a lower % and for smaller projects a higher %. For the construction phase, finance department adds the following percentages to neat cost: 15.3% - major projects 14.4% -system preservation Costs for fabricated materials can be high – SHA puts f/t inspectors in plants in some cases for double shifts. Have outsourced lab costs and use a rate schedule for material type for outsourced testing. Also use on-call inspection contracts to support lab testing. In terms of material costs, the highest $ items are generally HMA where the most dollars are spent on pavement maintenance, concrete pavements, and fabricated structural elements such as pre-stressed beams, structural steel, and sound walls. For construction QA $ of field produced materials, more testing costs are for pavements, particularly HMA compaction, etc. Contractor does ride testing (IRI) For HMA, materials testing costs are not as high as in past due to reliance on contractor test results (shifts the test cost to the contract). In general, SHA is performing less testing, more testing is outsourced, more reliance on certification, and batch (system-wide) testing for multiple projects. The industry is taking more responsibility for quality. WB account includes test costs plus a correction factor spread out over all projects.

State/ Contact Information	Interview Summary
	SHA is experimenting with new roadway compaction criteria (intelligent compaction) and proof rolling specifications. These may entail higher initial costs for QA bur result in reduced maintenance costs. **<u>Deviations from Specifications or Failure Issues</u>** Many issues have occurred related to concrete workmanship, either bad pours or bad curing of cylinders (test workmanship). Statewide materials issues included segregation of pavement due to not loading trucks properly (workmanship), premature corrosion of couplings on poles (a major manufacturer issue), and defective anchor bolts on traffic structures (this was a national safety issue related to heat treated bolts). Other singular issues included a precast supplier shorting steel in beams (did not meet design standards), and bridge seals without proper lubrication. The most concerns from a risk standpoint have been bridge decks, and anchor bolts for overhead sign structures **<u>Alternative Delivery</u>** Mega-projects modify QC and QA. Reduced number of cylinders taken for concrete' For DB, D-builder does QC, Consultant does QA, and state does verification. The MD SHA DB manual follows this process and includes quantities for testing frequencies. The SHA is moving to 20% in-house and 80% consultant staff for the normal program. For alternative delivery, consultants do the QA and are retained by SHA **<u>Thoughts on Optimization/Cost Saving</u>** • SHA is currently using a systems-based approach to IA. • Use of regional plant audits v project-based audits. • Plant certification and producer QA. • Cost-sharing among regional agencies to share the costs of QA plant inspection (e.g. many agencies use the same supplier, i.e. Valmont, for sign structures) • Greater use of national standards for certification (PCI, NTPEP)

APPENDIX F: DEMONSTRATION OF LEVEL 3 OPTIMIZATION PROCESS

Level 3 Model Overview

As shown in Figure F.1 – which provides a theoretical representation of the QA optimization for a given material – the optimal QA investment point is that which minimizes the total cost of quality.

Figure 4.1: Theoretical Optimization Model

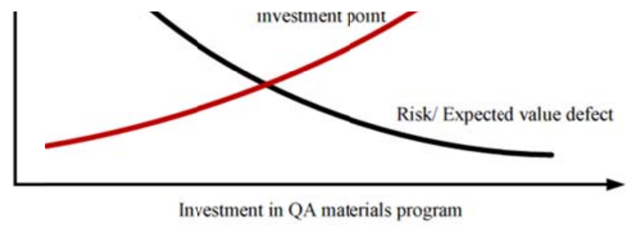

Figure F.2: Level 3 Cost-Based Optimization

The total cost of quality can be defined as the sum of the total investment in material QA and the expected value of a defect. The goal of the Level 3 optimization model is to find the minimum value of the total cost of quality based on the understanding that there is a point for any material and a given QA protocol that additional investments would yield a sub-optimal return. It is important to note that the QA investment (level of effort) and risk are interrelated and, consequently, must be evaluated as a system for each material.

With reference to Figure F.1, the required inputs for each material of interest include:

- the cost to implement different QA protocols (e.g., cost of sampling and testing vs. certification vs. inspection);
- the probability of a defect (material nonconformance) when a given QA option is implemented; and
- the expected value of potential defects (i.e., the product of the probability of a quality defect and the cost of the impact should the risk be realized)

As noted in Chapters 2 and 3 in the report, the literature review, survey, and interview efforts did not yield sufficient data related to quality costs to provide the necessary inputs to validate or test the model. Given the lack of actual, objective cost and performance data, the team convened a Delphi panel(s) of national experts on various materials of interest to arrive at a consensus estimate of material QA costs and the expected value of defective or nonconforming material. The team's Delphi approach and the results of this study are described in detail below.

Delphi Approach to Data Collection

The data required to create the cost-based optimization curves shown in Figure F.1 include: the cost of QA effort, the probability of a non-conforming material, and the impact of a non-conforming material. Given the lack of quantitative data in the existing body of knowledge related to QA costs and the probability and impacts of non-conformance, an expert-based approach was used for data collection.

We elected to use the Delphi approach to collect the quantitative data. Research shows that Delphi is useful when the judgment of individuals must be combined to address an incomplete state of knowledge (Delbecq et al. 1975; Hallowell and Gambatese 2009). As was the case in this study, Delphi is also particularly useful when the research problem does not lend itself to precise analytical techniques but can benefit from subjective judgments on a collective basis; the individuals needed to contribute to the examination of a broad or complex problem have no history of adequate communication and may represent diverse backgrounds; time and cost constraints make frequent group meetings infeasible; more individuals are needed than can effectively interact in a face-to-face meeting; and the heterogeneity of the participants must be preserved to assure the validity of the results (Linstone and Turoff 2002; Chapman 1998).

Delphi Expert Qualifications and Panel Size

The success of a Delphi study largely rests on the combined expertise of the participants who constitute the expert panel (Powell 2003) and the extent to which cognitive biases are controlled or eliminated (Hallowell and Gambatese 2009). Panels must also have a sufficient size to ensure that the results are not biased by a particular participant's experience. A recommendation for panel size is five to 20 experts with diverse knowledge (Rowe and Wright 2001), which varies according to the scope of the problem and the resources available (Delbecq et al. 1975; Hallowell and Gambatese 2009). However, the collective expertise of the panel is far more important than the number of participants.

To select our expert panel we required participants to have more than 5 years of experience in materials QA and at least 7 years of experience working for a DOT. A total of eight experts participated on the Delphi panel, with an *average* of 30 years of experience.

Number of Rounds of Data Collection

Another important aspect of the Delphi technique is the number of survey rounds included in the data collection process. The iterative nature of the procedure generates new information for panelists in each round, allowing them to modify their assessments and project them beyond their own subjective opinions. It can represent the best forecast available from a consensus of experts (Corotis et al. 1981). Typically, three rounds of surveys are sent to a pre-selected expert panel, although the decision over the number of rounds is largely pragmatic (Hallowell and Gambatese 2009). In order to reduce variance in responses and improve the precision, we conducted three survey rounds to reach consensus on questions related to materials QA.

In order to collect data from the panel, we followed the steps indicated in Figure F.2. To facilitate this effort, we developed a survey tool using Google Sheets, a web-based spreadsheet application similar to Microsoft Excel, which allowed all panelists to input their responses into the same document and thus streamline the processing of the expert opinions. With this tool, the moderator gained instant feedback on the experts' responses. Use of Google Sheets significantly reduced the overall data entry and lag time between rounds and allowed for anonymity while obtaining real-time responses.

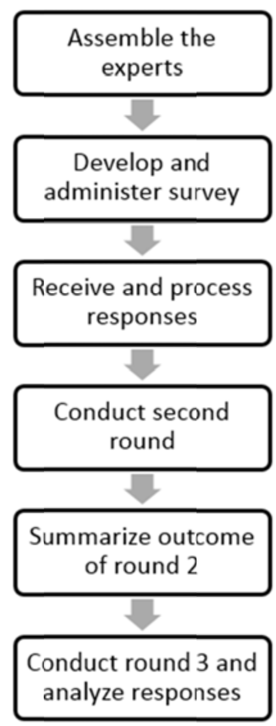

Figure F.3: Delphi Steps

Delphi Procedure and Results

Step 1: Identify materials and properties of interest

A critical step in the optimization of the QA process is the selection of materials and material properties that are representative of product performance. To test the applicability and scalability of the model, we attempted to use the Delphi panel to collect data on a wide range of materials and project conditions, as summarized in Table F.1.

Table F.1: Delphi Objectives

Material	Properties	Objective
HMA Pavement	Density Asphalt Content Gradation	Demonstrate how the model can be used to optimize the QA investment for various acceptance properties for a field-produced material. 1. For the case of HMA, the level of QA effort for three properties will first be optimized individually. 2. The results of the optimization of the QA effort for each property will then be compared against one another to illustrate how the tool can be used to determine if any of the properties are deemed to be more critical or a better indicator of performance.
Earthwork	Density	Demonstrate how the model can be used to distinguish between different applications of the same material. In the case of earthwork, two situations will be evaluated: - Embankment construction that will bear structural elements - Embankment construction where no structural elements will be placed
Precast structural concrete	Compressive Strength Location of Reinforcement	Demonstrate how the model can be used to distinguish between different applications of similar fabricated materials. In the case of precast structural concrete, two applications will be evaluated: - Precast, pre-stressed bridge members - Precast drainage structures
Traffic striping	Retro-reflectivity	Demonstrate how the model can be used to optimize the QA investment for a project-produced material that may rely more on inspection than sampling and testing
Plastic pipe	In-place Deflection	Demonstrate how the model can be used to optimize the QA investment for a standard manufactured product

The HMA optimization Delphi study yielded the most conclusive results, and will be discussed in detail in the narrative that follows. For the other scenarios and materials of interest, consensus on the estimated quality costs could not be reached – a result that highlights the difficulty of fully implementing a cost-based optimization approach without actual quantitative data. This finding further suggests that the more qualitative Level 1 and 2 analyses may be more readily implementable by most DOTs.

Step 2: Identify project factors that influence QA effort and develop representative scenarios

The results of the literature review, survey, and interviews all suggested that certain factors can influence the QA practices applied to a specific project. For example, the Florida DOT allows for reductions in the frequency of QA testing of structural concrete, excavation and embankment, and pavement by 50% when 12 or more QC tests are confirmed to be within tolerance. Such action is taken because the perceived risk is lower due to reliable contractor QC performance. Similarly, DOTs may reduce the level of inspection for fabricated structural materials (or accept by certification backed by audit) based on historic material performance, material criticality, and fabricator qualifications. The qualification of standard manufactured products (qualified products lists or national certification standards) also allows for greater use of acceptance by certification and reduced DOT product testing. The use of alternative project delivery methods, particularly for design-build and public-private-partnerships with long-term warranty or maintenance agreements, may further shift QA responsibility to the private sector and reduce the level of owner QA effort (verification testing and inspection).

To gauge the sensitivity of different factors on the optimization results, the Delphi panelists were asked to consider four different project scenarios for the case of HMA, as summarized in Table F.2.

Table F.2: Project Scenarios (for HMA Delphi Survey)

Factor	Scenarios			
	1	2	3	4
Industry Experience	High	Low	High	High
Material Quantity	High	High	Low	High
Project Delivery Method	DBB	DBB	DBB	Concession/PPP
Complexity (criticality)	High	High	Low	High

The first scenario, which served as the benchmark, assumed a highly experienced contractor/supplier, and large material quantities on a critical (e.g., high volume, urban road) design-bid-build project. The second scenario changed the industry experience variable to “low” to explore the impact of contractor/supplier reputation. The third scenario attempted to model a low risk project by holding industry experience at “high”, but changing quantities and criticality to “low.” The final scenario involved delivery by a public-private-partnership or concession. For this case, industry experience, quantities, and criticality were all assumed to be high, as would befit a project delivered using this contracting strategy.

Different materials may be more sensitive to certain project factors than others. For example, for standard manufactured products such as plastic pipe, the Delphi panelists may only be asked to consider the impact of supplier experience.

Step3: Identify levels of QA effort

The next step to build the model was to define the levels of QA effort. QA effort defines the quantity of resources that a DOT may invest to assure that the material conforms to the specifications. Generally, more rigorous controls require the DOT to commit a higher quantity of resources. The unit of analysis for QA effort would be cost (as expressed as a percentage of the material cost) that has to be committed to pay for each of the QA effort categories.

Table F.3 summarizes the levels of QA that were explored by the Delphi experts empaneled for HMA. These levels are expected to vary with different materials and properties. For example, a simple standard manufactured product may only involve the three levels of certification, with the allowance for additional inspection and testing as deemed necessary.

Table F.3: Possible Levels of DOT QA Effort

QA Level	Inspection	Certification	Sampling and Testing
Level 1	One time inspection of manufacture and field delivery/placement	Review certification and verify that certification complies with contract requirements or that materials is on the QPL	N/A
Level 2	Randomly inspect manufacture and field delivery/placement	Review certification data and back-up test data from vendor (i.e. mill test or other test attached to cert) for compliance with contract requirements	Perform random verification testing
Level 3	Intermittently inspect manufacture and placement (i.e. p/t or system-based plant inspection)	Review certification data and back-up test data from vendor (i.e. mill test or other test attached to cert) for compliance with contract requirements	Perform intermittent verification sampling and testing (or verification testing at a reduced frequency)
Level 4	Continuously inspect manufacturer and placement (i.e. system-based plant inspection and f/t field inspection)	N/A	In conjunction with use of contractor test data for acceptance, perform verification sampling and testing at a specified frequency and compares it to the contractor's results. Also responsible for IA.
Level 5	Continuously inspect (i.e. f/t plant inspection and f/t field inspection)	N/A	Performs sampling and testing and accepts materials using agency results. Also responsible for IA.

Step 4: Quantify costs of each level of QA effort

To quantify the amount of resources committed to each level of QA, empirical cost accounts or budgets would provide accurate information. Unfortunately, our research showed that DOTs generally do not track QA costs for each level, resulting in a dearth of empirical data. Therefore, we included QA cost estimates as part of the Delphi process. Costs of QA were defined as a percent of the material's total in-place cost. The Delphi panel estimated that QA costs (in terms of percentage of material cost) would be expected to increase as QA effort increases, as shown in Figure F.3.

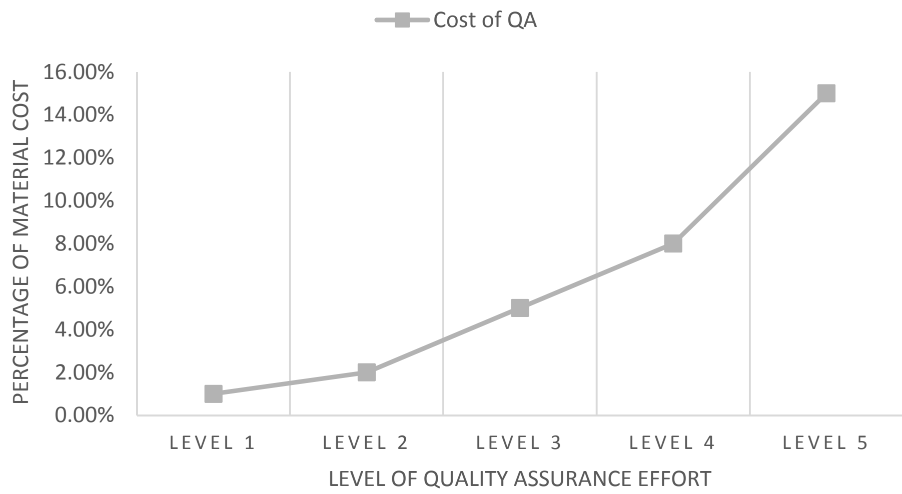

Figure F.3: Cost of QA

Step 5: Quantify the expected value of non-conforming material

The expected value of a non-conformance (i.e., cost of failure) can be quantified as the product of the probability of a defect and the cost of the expected defect, also measured as a percentage of material cost. To evaluate this cost, we asked the Delphi panel to quantify the risk reduction resulting from increases in QA effort through a two-step process.

First, Delphi participants were asked to estimate the probability that a non-conforming material would result under each scenario (from Table F.2) and each level of QA (for a total of 20 combinations). Second, the Delphi panel was asked to estimate the expected cost of a typical defect associated with each HMA property of interest. The goal of this step was to build the expected value of non-conformance for each given QA level of effort. The results are shown in Figure F.4.

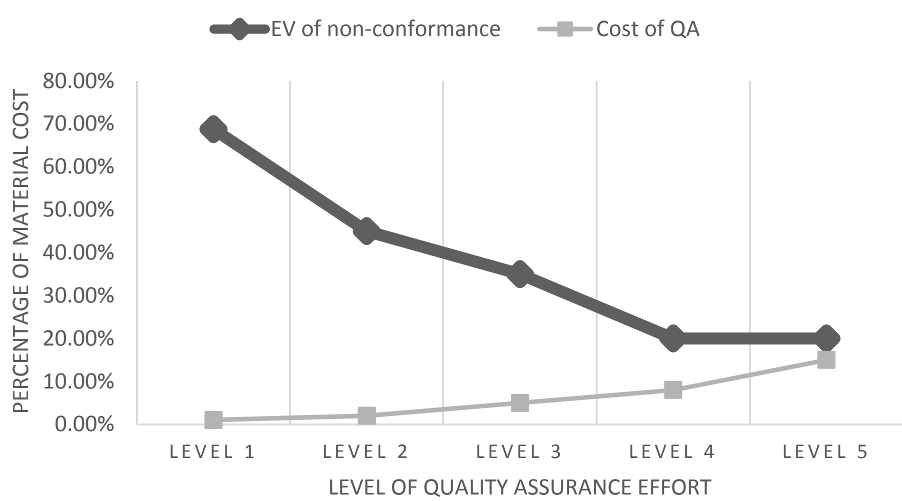

Figure F.4: Expected Value of Non-Conformance

- **Probability of a non-conforming material.** For each level of QA effort, the Delphi panel quantified the probability of material property failure and the cost of material property failure. As material QA effort increases, the logical expectation was that the probability of material property failure decreases while the cost of material property failure remains relatively constant. However, the Delphi panel was given complete flexibility in their responses.

- **Impact of a non-conforming material.** Given that some material properties might have a catastrophic impact on the project's performance and safety, there are some cases that the material's destruction, removal, and rework could be the best corrective measure. In order to maintain the same corrective measure for all scenarios and properties, we proposed remove and replace. The Delphi panel quantified (as a percentage of material cost) a scenario in which after a material was already accepted by the DOT, it is found to be non-conforming, requiring complete rework as the corrective method.

- **Expected value of non-conforming materials.** The previous steps provided the probability and cost of material property non-conformance (i.e., the constituent elements of expected value). The expected value of non-conformance was then modeled as the product of probability and cost using the equation below.

$$EV = I \times PNC$$

Where:

EV = Expected value of failure as a percentage of material cost (%)

I = Impact of rework of a material non-conforming as a percentage of material cost. (%)

PNC= Probability of non-conformance (%)

Step 6: Quantify the expected value of non-conforming material

As shown in Figure F.5, to optimize the total cost of quality (CoQ), we added the cost of QA effort and the expected value of non-conforming materials. In essence, this is the sum of the efforts taken to reduce risk and the expected value of the residual risk. This exercise was repeated for every property, every level of QA effort, and all scenarios. For each HMA property evaluated, we were able to find the minimum CoQ for a given project scenario. The level of QA effort represents the independent variable in the lifecycle CoQ optimization, which is at the discretion of the DOT.

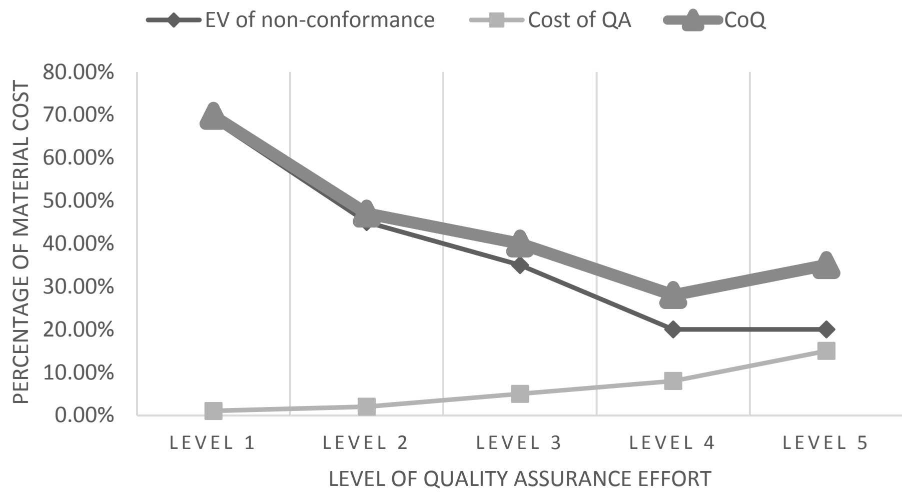

Figure F.5: CoQ curves

Delphi Results of HMA Optimization

The experts answered a total 396 questions on four different scenarios for three properties and five levels of QA effort for HMA.

The raw data for three HMA properties is shown in Table F.4. The first row shows the three properties evaluated (density, asphalt content, and gradation) followed by the four scenarios for each property (S-1, S-2, S-3, and S-4). Next, the table shows three subtitles for the three categories required to build the CoQ curve (probability of non-conforming material, cost of QA, and the impact of a non-conforming material or cost of rework) with the five levels of QA effort except for the cost of rework where it shows just one judgement per scenario and property (the assumption being that the replacement cost would be constant).

Table F.4: Delphi Results for HMA Analysis

Results for Round Three (median, 8 experts, 3 rounds)

	Density				Asphalt content				Gradation			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
	Probability of a non-conforming material											
Level 1	65%	80%	65%	63%	65%	83%	65%	65%	65%	83%	65%	65%
Level 2	48%	58%	50%	45%	50%	65%	53%	45%	50%	63%	55%	53%
Level 3	43%	50%	43%	40%	45%	55%	45%	40%	40%	50%	40%	38%
Level 4	23%	30%	23%	18%	18%	23%	20%	14%	20%	28%	20%	18%
Level 5	10%	18%	10%	10%	10%	15%	10%	9%	10%	18%	10%	10%
	Cost of QA											
Level 1	1%	1%	4%	1%	2%	1%	4%	1%	2%	2%	4%	2%
Level 2	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Level 3	2%	4%	3%	3%	2%	4%	3%	3%	2%	4%	3%	3%
Level 4	4%	5%	5%	4%	4%	5%	5%	4%	5%	5%	5%	4%
Level 5	6%	6%	7%	7%	6%	6%	7%	7%	7%	6%	7%	7%
	Impact of a non-conforming material											
Rework	118%	115%	113%	110%	125%	123%	118%	113%	110%	110%	110%	110%

S-1=Scenario 1; S-2=Scenario 2; S-3=Scenario 3; and S-4 Scenario 4

The probability of a non-conforming material was the variable with the highest variability. For example, for Scenario 4, Density's Level 2 of QA effort (visual inspection) resulted in a median of 45% but a minimum and maximum values of 5% and 90%, respectively; and a standard deviation of 23%. As shown in Figure F.6, all scenarios behaved similarly when viewed in terms of the median of the answers of the experts; outliers were more polarized in Scenario Four. The results of the impact of a non-conforming material show that removal and replacement usually costs between 110% and 125% of the original cost.

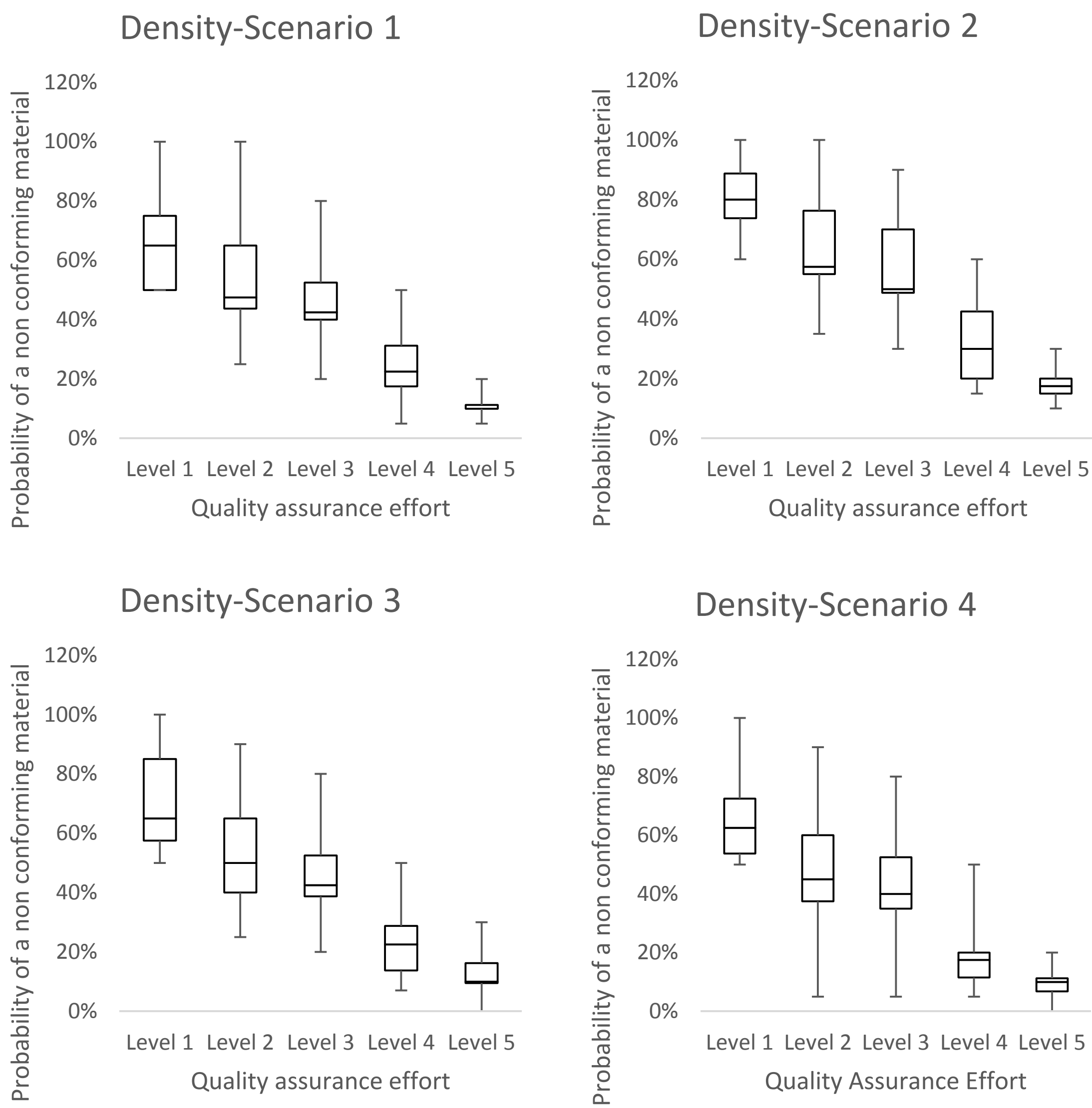

Figure F.6: Probability of a non-conforming material Delphi results for density

For Delphi rounds two and three, the experts were provided the median values from the previous rounds, comments from other panel members, and their own prior response. When providing data in subsequent rounds, participants were given the option to maintain their response from the prior round or change their response in light of the new information. In both cases, the participants were asked to explain their rationale for either changing or maintaining their estimates. Such feedback helps to reduce the tendency of conformity as it requires the panelists to reason and articulate.

Reaching Stability

Although there was strong change in estimates between rounds one and two, negligible change in participant responses occurred between rounds two and three. The Delphi process was then concluded after round three as stability was reached. Table F.5 shows that the standard deviation decreased in each round. This behavior was consistent throughout the four scenarios and the five levels of QA effort. With this information we acknowledged that experts were not changing their best estimates even if we continued with more rounds.

Table F.5: Standard deviation for three rounds

Density Standard Deviation

Scenario 1				Scenario 2				Scenario 3				Scenario 4			
Level	R-1	R-2	R-3		R-1	R-2	R-3		R-1	R-2	R-3		R-1	R-2	R-3
Probability of a non-conforming material															
1	21%	21%	18%	**1**	24%	14%	13%	**1**	27%	21%	19%	**1**	22%	19%	16%
2	28%	26%	22%	**2**	29%	20%	19%	**2**	30%	23%	20%	**2**	32%	26%	23%
3	25%	22%	16%	**3**	29%	20%	17%	**3**	24%	20%	17%	**3**	27%	23%	20%
4	16%	16%	15%	**4**	28%	15%	15%	**4**	21%	14%	14%	**4**	14%	13%	13%
5	5%	4%	4%	**5**	13%	6%	6%	**5**	7%	8%	8%	**5**	7%	5%	6%
Cost of QA															
1	4%	3%	3%	**1**	4%	3%	3%	**1**	4%	3%	3%	**1**	5%	3%	3%
2	5%	3%	3%	**2**	5%	3%	3%	**2**	5%	3%	3%	**2**	5%	3%	3%
3	5%	3%	3%	**3**	5%	3%	3%	**3**	5%	3%	3%	**3**	5%	3%	3%
4	5%	4%	4%	**4**	5%	4%	4%	**4**	5%	4%	4%	**4**	5%	4%	4%
5	6%	3%	3%	**5**	15%	8%	8%	**5**	6%	5%	5%	**5**	6%	3%	3%
Impact of a non-conforming material															
	17%	17%	16%		21%	16%	14%		15%	15%	14%		14%	14%	14%

R-1=Round 1;R-2=Round 2; and R-3=Round 3

Eighty percent of the estimates of the cost of QA and the impact of a non-conforming material were within one standard deviation of the median. In spite of this consensus-type behavior, there were two experts that maintained their extreme views regardless of the median when assessing the probability of a non-conforming material. For example, with a median of 50% and with five out of eight respondents being within 40% and 60%, we still got a minimum of 10% and a maximum of 100% chance of material non-conforming.

Optimization Curves

As previously indicated, the CoQ was computed by summing the expected value of non-conforming materials and the cost of QA. Since both values were measured as a percentage of material cost, no conversions were required. Consistent with past models (e.g., Kirkpatrick 1970), as DOTs increase QA effort the cost of QA increases and the expected value of non-conformance decreases.

Figure F.7 illustrates how the CoQ curve is built. The figure shows three lines: Cost of QA as the level of QA effort increases; the expected value of non-conformance that decreases with every increment in the level of QA effort; and the total CoQ which is the sum of the two previous curves.

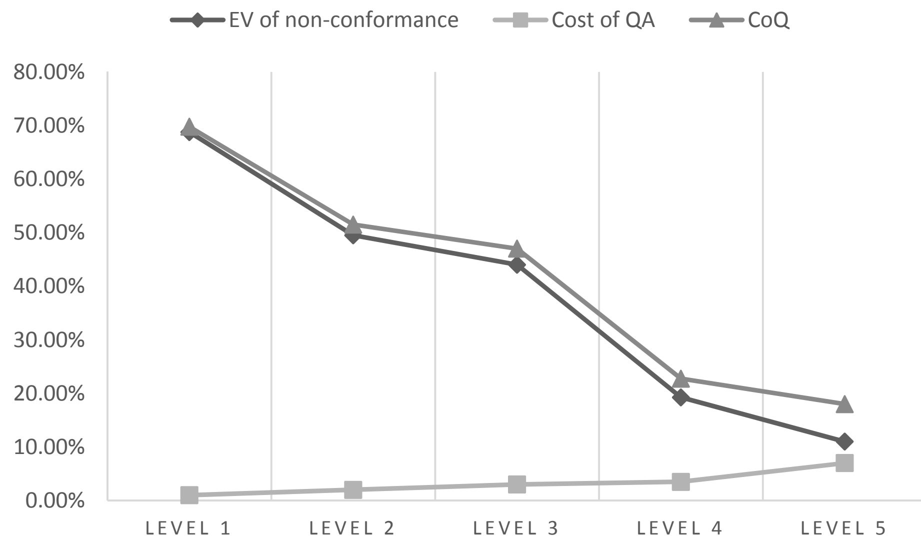

Figure F.7: Cost of Quality optimization for HMA using density in Scenario 4

All the scenarios had similar results in terms of optimization. However, a comparison of the optimization curves reveals that project factors play important roles in determining the optimal investment point. Figure F.8 shows the optimization curves for the four scenarios for each of the three properties.

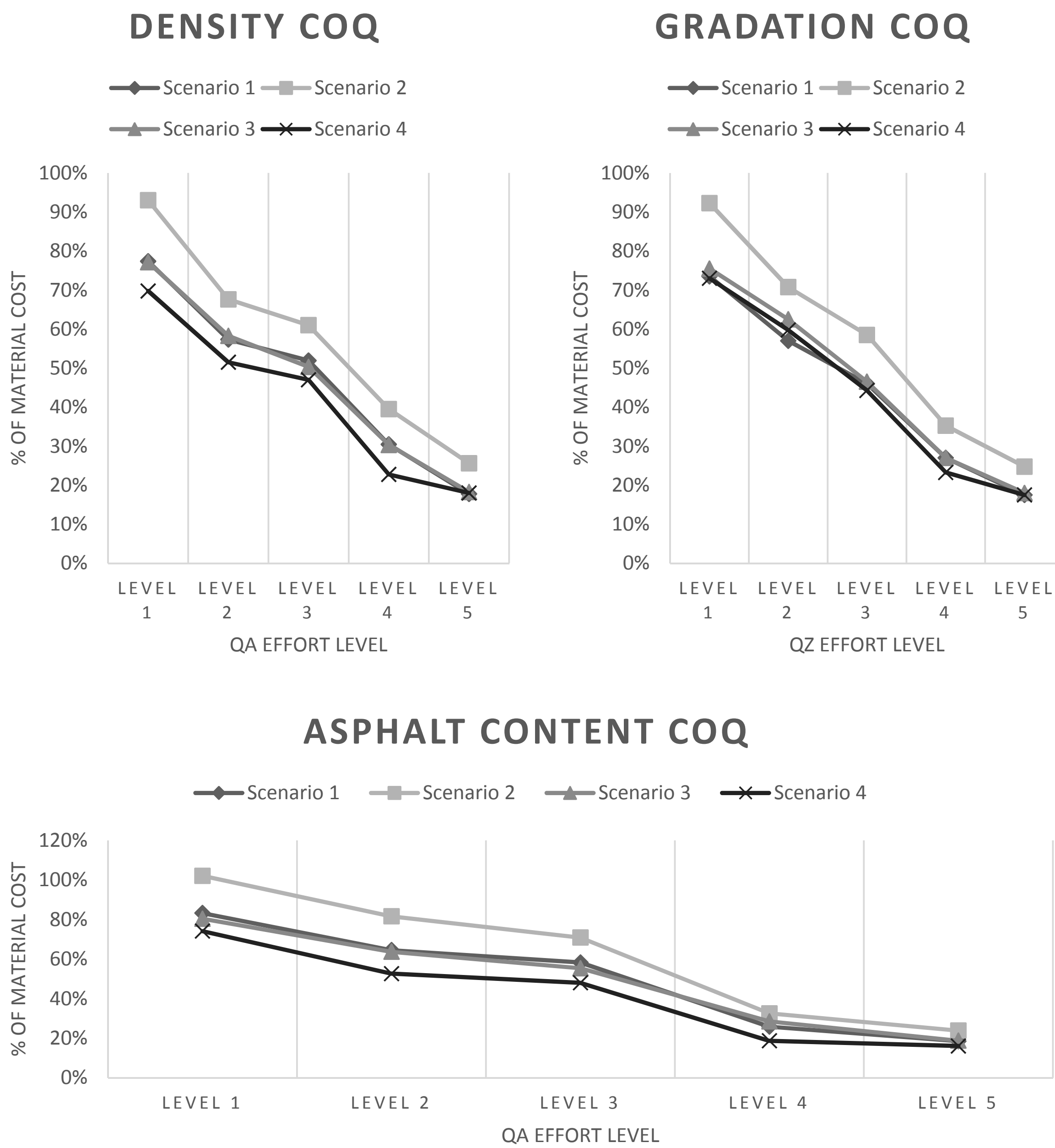

Figure F.8: Optimization Curves

Scenario 2 was consistently shown to have the highest CoQ throughout the five levels of QA effort and for all properties. The results also indicate that contractors' experience had an important impact on the probability of a material's conformance to specification. On the other hand, Scenario 4, where the contractor has long-term responsibility for the material through a concession agreement, had the lowest CoQ. Therefore, we can conclude that another way DOTs can optimize their CoQ could be by controlling some of the project factors such as delivery method or selecting contractors with previous experience.

Similar Risk Perception for Different Properties

By comparing the data gathered from the three different properties we were able to measure patterns in the optimization results. To statistically compare material property results, we ran a series of T-tests to test if the set of values followed the same distribution, variance, and magnitude. For the probability of a non-conforming material and the cost of QA we obtained high p-values that range from 0.56 to 1.00, meaning that there was no statistically significant difference in the probability or cost estimates across material properties in any of the four scenarios. This was an unexpected result as recent research has found that properties such as density and asphalt content are more related to a HMA pavement performance than gradation.

Cost of QA Stability

Interestingly, the estimated costs of QA were also stable across the various scenarios. There was no major difference in the cost estimates for scenarios one, two, and three throughout the first four levels of QA effort. However, when assessing the cost of Level 5: *Sampling and testing performed by the agency* we found a larger difference between scenarios. This means that changing the characteristics of a project would only affect significantly the Cost of QA when it is performed fully by the DOT (Level 5).

Alternatively, Scenario 4 had less alignment with the other scenarios on the levels of QA that involved some sort of sampling and testing performed by the DOT (levels 4 and 5). The t-test results comparing two scenarios of the series of values from the experts' assessments showed that none were significant at $p = 0.05$.

Perception of the Levels of Quality Assurance Effort

The expert panel was asked to provide cost estimates associated with material non-conformance resulting from a quality defect for each of the five levels of QA effort. As expected, for each scenario the data derived from the panel showed that the probability of nonconformance decreased as the QA effort increased. As shown in Figure F.9, regardless of the scenario or the properties the experts were assessing, this statement remained valid.

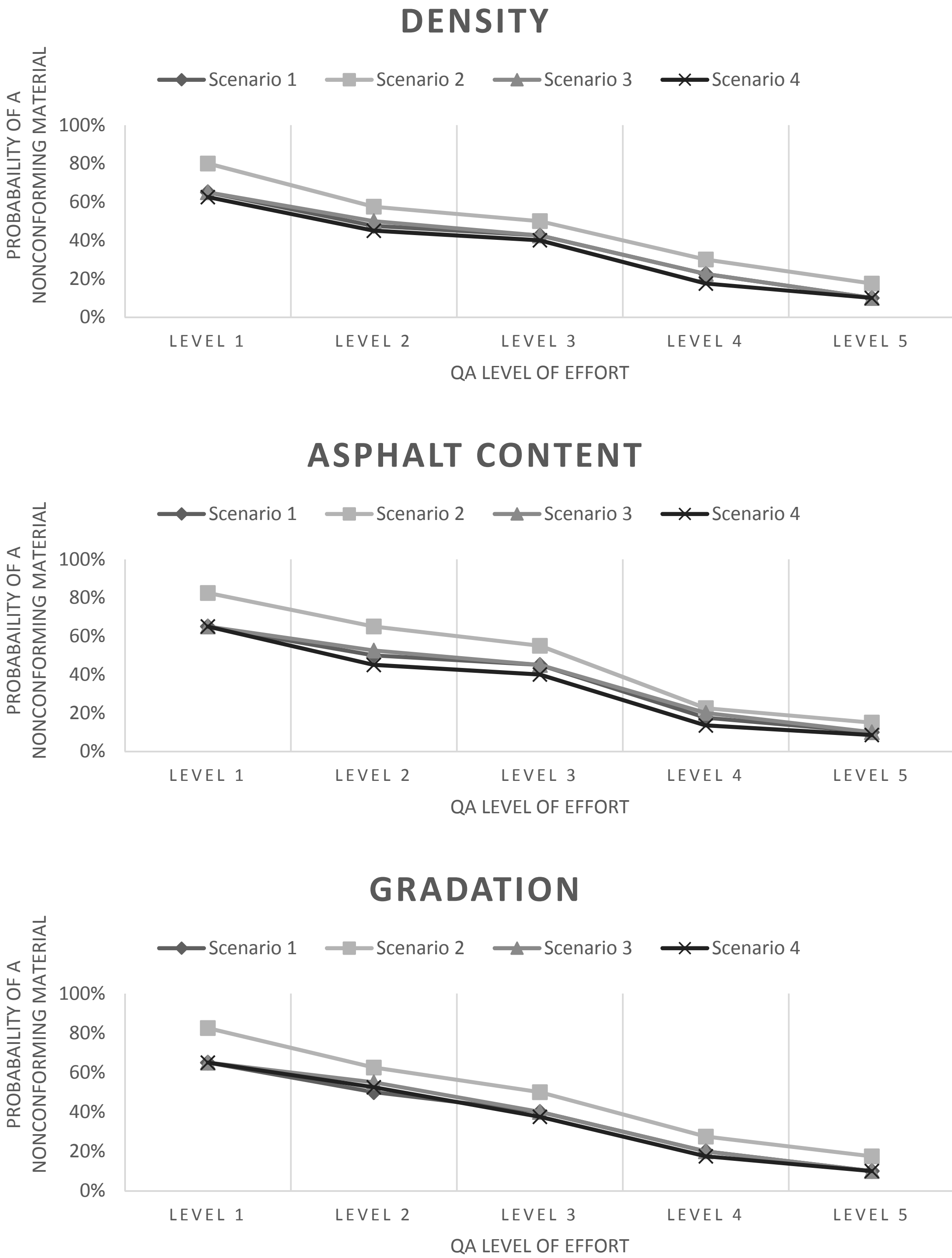

Figure F.9: Probability of Non-conformance vs. QA Level of Effort

Part 2: Guidelines

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- Linda Konrath of Hill International;
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- John D'Angelo, PhD, P.E., of D'Angelo Consulting;
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PREFACE

In response to shrinking budgets and dramatic reductions in both the numbers and experience levels of inspectors and engineers, several transportation agencies are seeking ways to improve or enhance their processes to achieve greater efficiencies in resource allocation and project and program delivery. A possible area for process improvement is materials quality assurance (QA) – a critical, though resource-intensive, component of project delivery.

The importance of materials QA is without question. Materials represent 50% of Federal-aid construction dollars (FHWA 2013). A well-designed QA program can provide confidence that the materials and workmanship incorporated into a project will be in reasonably close conformity to the approved plans and specifications. Conversely, an inadequate QA plan can increase the risk of short and long-term failures, possibly leading to reduced design life, increased maintenance costs, service interruptions, and/or safety hazards. Logically, the more comprehensive and robust the QA strategy, the less risk; however, an overly rigorous QA plan can result in unnecessary project costs.

Recognizing that current QA practices may be outdated or disproportionate to what is needed to ensure a quality product, some DOTs have begun to modify their QA plans to reflect a better balance between efficiency and risk reduction. Such modifications might entail adopting a less rigorous plan (e.g., fewer tests, use of verified contractor test data for acceptance purposes, and/or greater reliance on certification or inspection) to achieve the same result, or incorporating more advanced, performance-oriented acceptance tests – even if at a higher cost – if such practices improve durability, reduce the risk of failure, or enhance performance.

To help agencies identify such opportunities for optimization, the following guidance document has been prepared under NCHRP Project 10-92. As QA practices vary widely among DOTs, the goal of this document is not to prescribe quality management solutions but to instead provide a flexible analytical framework that can be applied to the range of materials acceptance practices in use today, as well as to any new products or practices that may emerge in the future.

The anticipated benefits of these guidelines include:

- Enhanced understanding of the cost and value of materials QA,
- More efficient allocation of QA resources, and
- Better alignment between project risk profile, delivery method, and QA practices to help agencies deliver a quality project for the lowest overall cost.

Chapter 1. Introduction

How much time and money should we devote to quality assurance?

Will the results be worth the resources invested?

In response to shrinking budgets and dramatic reductions in both the numbers and experience levels of inspectors and engineers, several state departments of transportation (DOT) are seeking ways to achieve greater efficiencies in quality management, often targeting current practices that may be either disproportionate to what is needed to ensure a quality product (e.g. does a concrete sidewalk warrant the same level of QA as a bridge deck?) or outdated given advances in testing technology (i.e., is there a more efficient or effective way to accept this material?).

The purpose of such inquiry is not to downplay the importance of QA, but to recognize that it is an inherently scalable activity driven by, among other considerations, an organization's tolerance for risk, material/product variability, and cost. As illustrated in Figure 1.1, a well-designed QA program can provide confidence that the materials and workmanship incorporated into a project will be in reasonably close conformity to the approved plans and specifications. Conversely, an inadequate QA plan can increase the risk of short and long-term failures, possibly leading to reduced design life, increased maintenance costs, service interruptions, and/or safety hazards. Logically, the more comprehensive and robust the QA strategy, the less risk of material failure or nonconformance; however, an overly rigorous QA plan can result in unnecessary project costs – an outcome that most agencies cannot afford in this time of flat or declining resources.

The following guidance document has therefore been prepared under NCHRP Project 10-92 to help DOTs identify and evaluate opportunities to optimize or enhance their materials QA practices to achieve a better balance between efficiency and risk reduction. For example, modifications or enhancements to an existing QA strategy might entail adopting a less rigorous plan (e.g., fewer tests, use of verified contractor test data for acceptance purposes, and/or greater reliance on certification or inspection) to achieve the same result, or incorporating more advanced, performance-oriented acceptance tests – even if at a higher cost – if such practices improve durability, reduce the risk of failure, or enhance performance.

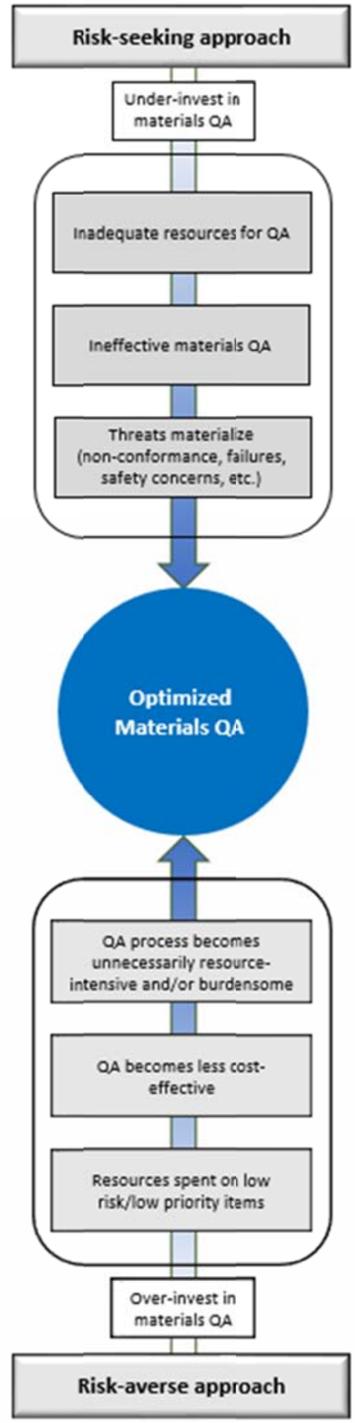


Figure 1.1: Optimized QA

1.1 Framework Overview

1.1.1 The Economics of Quality Model

Striking the optimal balance between the *cost of quality* and the *value of quality* has long been an aspirational goal of managers and engineers, particularly in the manufacturing and production industries where an effective mix of quality improvement activities can play a vital role in helping firms achieve and maintain both customer satisfaction and long-term profitability.

The conceptual foundation for analyzing the economics of quality is therefore well established in the literature. Over the years researchers have proposed and refined a theoretical model for optimizing QA based on the principle of diminishing marginal returns (e.g., Juran 1951; Kilpatrick 1970; Plunkett and Dale 1988; Hylton 1991; Morse 1993; Schiffauerova and Thomson 2006). As depicted in Figure 1.2, the *Total Cost of Quality* can be represented as a function of QA assessment/prevention costs (i.e., QA Cost) plus the cost of defective or nonconforming materials (i.e., Conformance and Correction Cost).

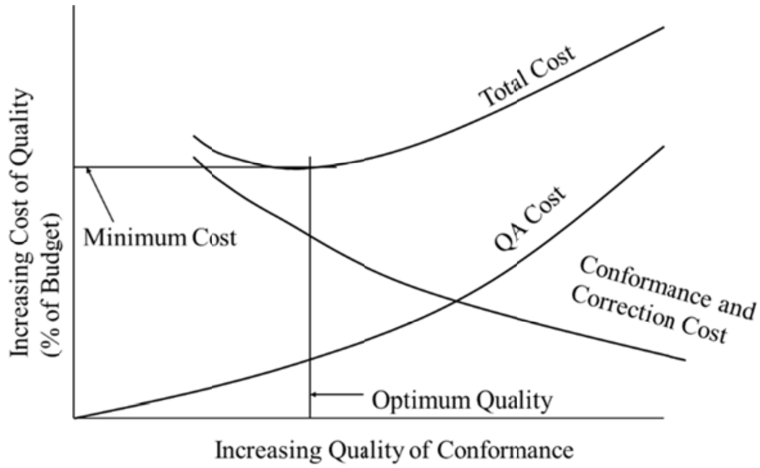


Figure 1.2: Economics of Quality of Conformance
[Adapted from Kirkpatrick 1970]

Theoretically, the cost of improving QA will continue to rise while the cost of failure continues to fall, suggesting the existence of an optimum QA investment point at which the sum of the cost of materials QA and the cost of failure are at a minimum. This would yield the lowest total cost to achieve the desired level of quality.

1.1.2 Practical Implementation of Quality Model

Although it may be conceptually elegant to frame the optimization problem as shown in Figure 1.2, practical implementation of such a model may prove difficult absent supporting cost data. For example, to fully develop the model as shown requires the following key inputs:

- Cost to implement different levels of QA (testing, inspection, certification)
- The probability of a non-conforming material for each level of QA
- The cost of repairing or replacing non-conforming materials should a defect occur

For organizations that actively track this information (e.g., through a materials management and/or asset management system), adopting such an optimization model would allow for a more explicit consideration of costs, thereby reducing the need for (or perception of) subjective decision-making.

For those that may find the required quality-related costs too difficult to capture and track, it may still be possible to develop reasonable approximations of the required inputs through expert judgment or other experimental data collection techniques (e.g., Delphi Survey).

Alternatively, if reliable cost information is too elusive to collect, taking a more qualitative approach to optimization can also provide actionable information. Engineering judgment combined with classic risk management principles can be used to prioritize materials and QA activities on the basis of the probability and consequence of material failure. What such a qualitative process may lack in academic rigor, it can make up for in accessibility and ease of use.

1.1.3 Optimization Framework

To ensure broad applicability, the framework presented in this guidebook combines the explicit cost-based optimization approach with more qualitative processes for risk ranking materials and material properties. The resulting three-level analytical framework, as summarized below and described in greater detail in subsequent chapters, is sufficiently flexible and robust to accommodate the range of materials and acceptance practices in use today as well as any new products that may emerge in the future.

The three levels of the framework can be described as follows:

- **Level 1** entails conducting a qualitative risk rating of materials and then aligning these ratings with QA methods that can provide reasonable assurance of acceptable quality. (See Chapter 3 for more details)

- **Level 2** has a narrower focus, attempting to optimize acceptance testing by emphasizing properties and test methods that are more direct indicators of performance. (See Chapter 4 for details)

- **Level 3** adds a financial dimension to the assessment by comparing the cost of different QA protocols to the cost of potential defects to arrive at the optimum QA investment point. In contrast to the other levels, this method allows for a direct approximation of costs. (See Chapter 5 for details)

As illustrated in Figure 1.3, progressing through the levels requires an increasing degree of objective information and analysis; users may choose to proceed through each level, or to stop after an answer of sufficient specificity is found or the quality of the input data does not justify the additional analytical effort associated with the subsequent steps.

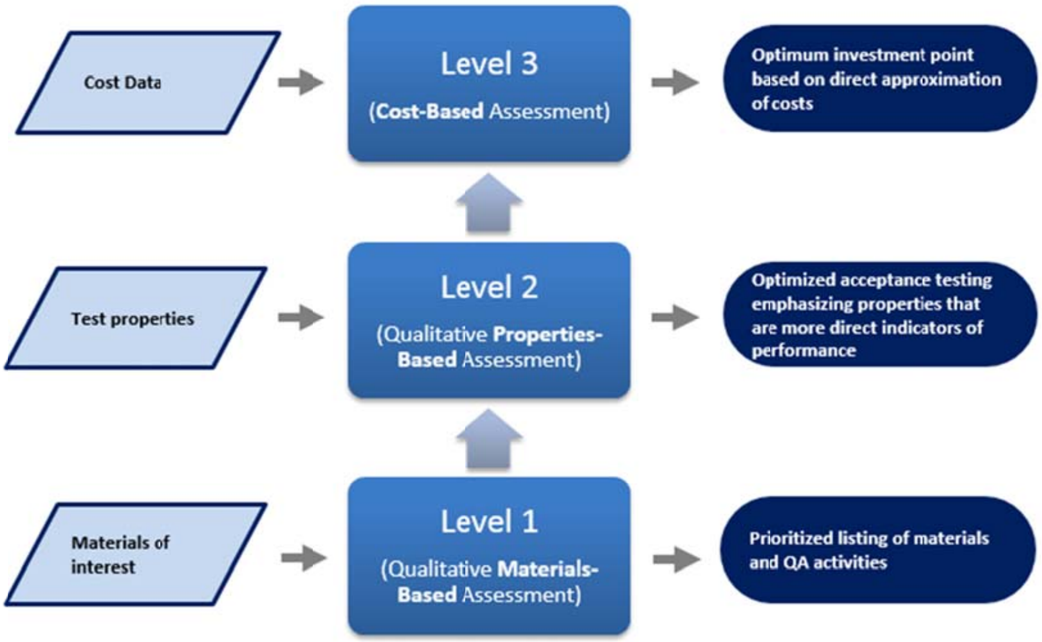


Figure 1.3: Optimization Model

The decision of which level to use will depend in part on the application (e.g., programmatic vs. project-level assessment), the availability and quality of the input data, and the desired level of analytical rigor. As summarized in Table 1.1, each level has unique objectives, benefits, and challenges, which should be considered when selecting the appropriate approach to use for a particular program, project, or project element.

Table 1.1: Comparison of Optimization Levels

	Level 1	Level 2	Level 3
Objective	Adjust QA effort (e.g., greater reliance on certification and inspection) based on qualitative assessment of the risk of material failure	Adjust owner QA **testing** effort based on material property importance and risk	Obtain the optimal QA investment point based on an explicit consideration of the cost of QA vs. the cost of nonconformance
Inputs	• Materials of interest • Standard acceptance plans • Expert judgement regarding material risk	• Standard acceptance plans • Primary and secondary properties and test methods • Traditional and advanced properties and test methods • Expert judgement regarding material risk	• Cost to implement different levels of QA (testing, inspection, certification) • The probability and cost of potential defects
Output	Prioritized listing of materials and QA activities	Optimized acceptance testing emphasizing properties that are more direct indicators of performance	Optimum QA investment point

	Level 1	Level 2	Level 3
Benefit	Ease of use	Enhanced focus on materials properties	Direct approximation of QA and non-conformance costs
Challenges	Subjectivity of qualitative ratings, which can be difficult to defend	Subjectivity of relative contribution of properties to material performance	Difficulty of obtaining actual cost data (or reasonable approximations thereof)

1.2 Overview and Organization of Manual

As an outgrowth of the NCHRP Project 10-92 research effort, the following guidance document has been prepared to help DOTs identify opportunities to optimize their existing materials acceptance practices. Given the variability in QA practices across the DOTs, the optimization methodology presented herein is not intended to replace the steps and procedures that a DOT would normally follow in developing a materials acceptance plan; it instead provides a supplementary risk-based decision process that can serve to optimize or enhance existing practices.

Understanding current QA practices therefore provides an essential starting point for developing an optimization model that can be adapted to programs and projects of varying types, sizes, and complexity. To this end, **Chapter 2** describes the current state of practice among the DOT community for materials QA, placing particular emphasis on any existing optimization strategies being used to align acceptance practices to what is needed to ensure a quality product.

Subsequent chapters then present a detailed discussion of the framework methodology itself:

- **Chapter 3** describes a "Level 1" materials-based optimization approach, which uses a qualitative risk-based rating process to prioritize materials and QA activities on the basis of the probability and impact of material failure or non-conformance;
- **Chapter 4** describes a "Level 2" optimization of material properties (e.g., strength, density) for materials subject to sampling and testing; and
- **Chapter 5** describes a "Level 3" cost-based optimization process that balances the cost of different QA protocols against the cost of potential material defects to determine an optimal QA investment point.

Finally, **Chapter 6** presents strategies and tools that can facilitate the implementation of the optimization framework.

Chapter 2. Materials QA State of the Practice

To provide context for the optimization processes presented later in this manual, this chapter describes the current state of materials QA in the highway construction industry.

A general summary of standard methods used by DOTs to assure materials quality is presented first, followed by a discussion of some existing optimization strategies being used by DOTs to achieve better efficiencies in quality management.

2.1 Background

2.1.1 Categories of Materials

To understand the current state of materials QA, it is important to first recognize that materials used in transportation construction can be broadly assigned to one of three categories based on their source and method of production. As described in AASHTO R 38 and summarized in Table 2.1 below, these materials categories are as follows: project-produced, fabricated structural materials, and standard manufactured materials.

Table 2.1: Material Classification based on Production Mode

	Project Produced	Fabricated	Standard Manufactured
Description	Items that are produced directly for a specific project, often at the project site	Materials custom-made for a specific project under what are generally controlled conditions	Items that are mass produced for routine use under highly controlled conditions
Material Variability	Subsequent mixing, placing, compacting, finishing, curing, or other operations can substantively impact quality and material variability	Properties are highly stable, assuming proper handling, transporting, and storage practices	Properties are highly stable, assuming proper handling, transporting, and storage practices
Examples	Earthwork, subbase and base courses, and pavement	Structural steel and precast/prestressed concrete structural elements	Binders, paints and coatings, geosynthetics, landscaping items, piping, and traffic control devices

To a large extent, materials falling within the same category will generally exhibit similar characteristics regarding level of production control and stability of properties, and will thus likely require a similar level of QA to assure product acceptability. For example, for field-produced materials, a high level of testing and inspection is often required or anticipated to control variability and assure performance.

2.1.2 QA Methods

Despite differences in the specific details according to which DOTs manage the acceptance of construction materials, current programs all generally include some combination of prequalification, sampling and testing, certification, and inspection processes to assure that the materials, products, and workmanship incorporated into a project are in reasonably close conformance to the approved plans and specifications. Descriptions and objectives of several QA practices in standard use today are summarized in Appendix A.

2.2 Examples of Existing Optimization Strategies

Materials QA has historically been a critical though resource-intensive component of project delivery for DOTs. Driven by budget and resource constraints, DOTs have begun to investigate ways to more efficiently balance the risk of poor quality against the cost of materials QA. Greater use of alternative project delivery methods that shift more responsibility to industry for managing quality, increased understanding of materials behavior, and innovations in non-destructive testing and related technologies are providing additional motivation for DOTs to revisit their existing QA practices.

Examples of strategies DOTs are implementing to optimize materials QA are discussed in the following subsections.

2.2.1 Use of Contractor Test Results

Contractors have been assuming more sampling and testing responsibility in recent years in connection with increasing use of statistically-based QA specifications and alternative contracting methods that place more performance risk on industry. Including contractor quality control (QC) data in the acceptance decision allows for some optimization of DOT resources (even if, on the whole, the overall testing effort is not reduced).

In recognition of the increasing role played by industry in assuring materials quality, FHWA's sampling and testing regulation, "QA Practices for Construction" published at Title 23, Code of Federal Regulations, Part 637 (23 CFR 637) was revised in 1995 to expressly allow use of contractor QC test results in an DOT's acceptance decision provided that:

- The sampling and testing is performed by qualified laboratories, using qualified sampling personnel.
- The DOT, or its designated agent (i.e., consultant under direct contract with the DOT), validates the contractor's test results by performing some level of independent verification sampling and testing. (Use of a third-party testing and inspection firm hired by the contractor does not relieve the agency of its responsibility for verification. Likewise, splits of contractor-obtained samples cannot be used for verification purposes.)
- The QC sampling and testing is evaluated under an independent assurance (IA) program.
- The DOT has a dispute resolution system in place to resolve possible discrepancies between the contractor's QC and the agency's verification data.

The DOTs are expected to perform enough verification sampling and testing to be able to identify statistically valid differences between its results and those of the contractor. [The F-test (comparison of variances) and t-test (comparison of means) are commonly used together to validate contractor test data.] While there is no universally accepted standard, a minimum rate of 10% of the contractor's testing rate has been suggested as a rule of thumb. The FHWA Tech Brief *Construction Quality Assurance for Design-Build Highway Projects* (FHWA-HRT-12-039) does acknowledge that rates of verification may differ based on the risks involved, and offers as an example that structural concrete would likely require more verification testing than embankment materials (FHWA 2012).

> For additional information related to the use and validation of contractor test results refer to:
>
> - FHWA Technical Advisory T6120.3 (*Use of Contractor Test Results in the Acceptance Decision, Recommended Quality Measures, and the Identification of Contractor/Department Risks*) issued on August 9, 2004
> - FHWA Tech Brief *Construction Quality Assurance for Design-Build Highway* Projects (FHWA-HRT-12-039) issued in April 2012

2.2.2 Small Quantity Acceptance

Several DOTs allow sampling and testing requirements to be waived or adjusted for small quantities of materials. For example, Washington State DOT (WSDOT) in Chapter 9 of its Construction Manual, provides project engineers with substantial latitude to judiciously adjust testing frequencies based on established guidelines (WSDOT 2013).

In accordance with the WSDOT Construction Manual, project engineers may choose to accept small quantities of materials without meeting the minimum sampling and testing frequencies (e.g., by visual acceptance, certification, or other methods) if the proposed quantity for that material is less than the minimum required testing frequency. Other considerations that WSDOT project engineers may factor into their decision to use small quantity acceptance include whether or not:

- The material has been previously approved;
- The material is certified;
- A mix design or reference mix design is available;
- The material has been recently tested with satisfactory results; or
- The material is not structurally significant.

WSDOT also allows use of small quantity acceptance for *any* quantity of the following:

- Curbs and sidewalks;
- Driveways and road approaches;
- Paved ditches and slopes; and
- Packaged concrete meeting ASTM C387 used for jobsite mixing.

2.2.3 Large Quantities under Control

DOTs will generally allow project engineers some discretion to reduce the frequency of sampling for high volume materials once initial testing has verified that the materials supply is relatively uniform or statistically under control and within specification limits. (However, such DOTs typically reserve the right to focus and increase QA testing if the situation suggests that the process is somehow changing and is not consistently under control.)

For projects with large quantities or volumes of materials, WSDOT's policy is that it may choose to reduce sampling frequency and/or eliminate selected test properties after ten consecutive samples taken at the standard testing frequency are shown to be well within the specification limits. If there are any failing tests, the sampling and testing frequency will revert back to the normal schedule. The authority to approve deviations to testing frequencies is as shown in Table 2.2.

Table 2.2: WSDOT Adjustments in Testing Frequency

Role	Authority Level
Project Engineer	May initiate and approve up to 10% deviations from the testing frequency schedule, with the exception of the following materials: hot mix asphalt, warm mix asphalt, structural concrete, and cement concrete pavement
Region Materials Engineers	May approve requests from Project Engineers for: • An additional 10% deviation, with the exception of the following materials: hot mix asphalt, warm mix asphalt, structural concrete, and cement concrete pavement • Elimination of fracture and/or SE from a Quarry Site
State Materials Engineer or Assistant State Materials Engineer	May approve requests: • To eliminate any other testing not expressly delegated to Project Engineers or Region Materials Engineers • For sampling frequency deviations exceeding the authority of Project Engineers and Region Materials Engineers • For sampling frequency deviations for hot mix asphalt, warm mix asphalt, structural concrete, and cement concrete pavement

[Source: WSDOT Construction Manual M 41-01.15, August 2013]

2.2.4 Criticality of Materials or Activities

Some DOTs use or are investigating use of tiered or risk-based processes to qualitatively evaluate and assign materials to different levels of QA based on their perceived criticality from the perspective of difficulty to repair or replace, safety, maintenance cost, or cost of rework. Examples of such strategies include the following:

- The **California DOT (Caltrans)** Construction Quality Assurance Program Manual assigns materials to one of four different tiers based on their consequence of failure. As summarized in Table 2.4, Tier 1 items are considered to have the greatest consequence of failure, while Tier 4 items have the least consequence (Caltrans 2015).

Table 2.3: Caltrans Tier Levels Based on Consequence of Failure

Tier	Failure Category	Consequence of Failure	Example Items
1	Catastrophic	Failure is likely to cause loss of life or serious injury	Structural steel, precast girders, pre-stressing
2	Safety	Failure creates a safety hazard for employees or the public	Delineation, safety barriers, lighting, signal controllers
3	Interrupt Service	Failure or repair may cause an interruption in service, or environmental impact	Pavements, bases, embankment, storm water pollution prevention plan-best management practice devices

Tier	Failure Category	Consequence of Failure	Example Items
4	Monetary	Monetary loss only	Grass seed, drainage and irrigation products, fencing

[Source: Caltrans Construction Quality Assurance Program (CQAP) Manual, August 1, 2015]

- **WSDOT's** Construction Manual provides project engineers with latitude to adjust normal acceptance procedures for minor or non-critical items as follows (WSDOT 2013):
  - *Project Engineer Discretionary Materials Acceptance*: The project engineer may choose to modify the normal acceptance procedures for minor, noncritical work items occurring outside the traveled way. Acceptance in such cases typically entails verifying dimensional conformance to the plans and making a visual determination that the materials are suitable.
  - *Optional Approval/Acceptance for Materials*: WSDOT's Construction Manual includes a list of materials that the project engineer may accept by visual inspection. If the quality or ability of the material to perform as intended is in question, the project engineer must determine if visual acceptance is appropriate or if additional acceptance testing or certification is necessary. The materials included on the list include items such as erosion control materials and miscellaneous fittings and hardware.
- **South Dakota DOT** (SDDOT), as described in its manual of Required Samples, Test, and Certificates, implemented a 3-tiered process for certification of materials ranging from critical to non-critical on basis of safety considerations or replacement costs (SDDOT 2013). The certification requirements vary from certificates of compliance supported with test results to umbrella certificates for component products of a system or assembly. Verification methods for certification range from sampling and testing to documented inspection, random audits, or annual inspections of suppliers.
- The **Indiana DOT** (INDOT) sponsored a research project performed by Purdue University to develop a tiered prioritization system for inspection resources. As described in a report prepared by Mostafavi and Abraham (2012), the objectives of this project were to evaluate the current inspection practices of INDOT and develop a risk-based inspection protocol to facilitate the efficient allocation of limited inspection resources to activities with higher risk consequences.

  The Purdue researchers conducted a risk analysis, using information obtained from 101 experts, representing INDOT, other DOTs, and consultants, to prioritize construction activities based on the perceived risk impacts due to reduced inspection. The results of this analysis are summarized in Table 2.4. Based on this prioritization, a protocol for various inspection activities was developed that could be used to assist with the allocation of inspection resources when multiple activities are proceeding concurrently and available resources are not sufficient to fully inspect all ongoing activities. For example, site clearing, which was rated as a low priority activity, would require only random inspection. In contrast, the higher priority activities of base course and embankment construction would require frequent to constant inspection based on the specific inspection item in question (e.g., embankment lift height would require *frequent* inspection whereas density would require *constant* inspection).

Table 2.4: List of Prioritized Construction Activities for Inspection

High Priority	Medium- High Priority	Medium Priority	Medium- Low Priority	Low Priority
Aggregate base courses Asphalt paving Bolting structural connections Concrete paving Driven piles Embankment Placement of concrete in structures Post- tensioning (pre-stressed structures) Reinforcement steel in structures Retaining walls Structure rehabilitation (repair concrete deck)	Beam erection Pipe placement Sub- grade treatment Drilled shafts Guardrail Overhead sign structure Painting steel Traffic marking	Barrier curb Blasting Concrete forms (structures) Drainage Excavation Handling/removal of regulated waste Highway Lighting Installing soil erosion/sediment control items Sound wall panel placement Sound wall post placement Traffic control- set up Traffic signals	Cofferdam Electrical conduit and wiring Fence ITS- fiber optic conduit and cable Landscape plantings Milling Placement of lighting features Seal coating Sheet piles Sidewalk	Clearing site Clearing site- bridge Stripping

[Source: Mostafavi and Abraham 2012]

2.3 Summary

Several DOTs currently optimize their materials QA practices to some extent based on what is required for each material or product to assure the quality of the end product. The rationale for selecting a particular acceptance method (ranging from continuous or statistically-based sampling and testing to certification and inspection) is often not well-defined but may be based on factors such as material criticality, quantities, type/size of project, and project delivery method.

In general, existing optimization efforts appear to be largely qualitative and informal in practice, with much discretion left to project engineers to modify rates or protocols based on engineering judgment. However, regardless of the level of rigor applied to current QA decision-making, the use of such optimization strategies suggests that a strong foundation and knowledge base exists for developing and implementing a more rational and in-depth process for optimizing the costs and risks of materials QA. Subsequent chapters of this guide thus focus on describing a flexible framework that DOTs may apply to determine how to efficiently allocate their QA resources.

Chapter 3. Level 1 Materials-Based Optimization

As introduced in Chapter 1, this guidebook presents a three-level analytical framework to help DOTs identify the QA acceptance plan necessary to meet specification requirements within an acceptable level of risk. Briefly, these levels can be described as follows:

- **Level 1** entails conducting a qualitative risk rating of materials and then aligning these ratings with QA methods that can provide reasonable assurance of acceptable quality.

- **Level 2** focuses on optimizing acceptance testing by emphasizing properties and test methods that are more direct indicators of performance.

- **Level 3** compares the cost of different QA protocols to the cost of potential defects to arrive at an optimum QA investment point.

The focus of this chapter is on describing the Level 1 assessment process; Chapters 4 and 5 proceed to address Levels 2 and 3, respectively. Although this guidebook presents these three levels as a linear progression, the framework may be applied either in whole or in part, and in any order. The selection of which level(s) to use will depend in part on the application (e.g., programmatic or project-level assessment), quality of input data, and the desired level of analytical rigor.

3.1 Conceptual Framework

The Level 1 assessment framework, as illustrated in Figure 3.1, provides a structured, risk-based decision process for prioritizing materials and QA activities on the basis of the probability and consequence of material failure or nonconformance.

This knowledge is then used to effectively allocate QA resources to different project items on the basis of their perceived risk of failure. For example, high risk materials are aligned with acceptance methods designed to provide maximum confidence in the quality of the materials provided, whereas less resource-intensive methods are considered for lower risk materials.

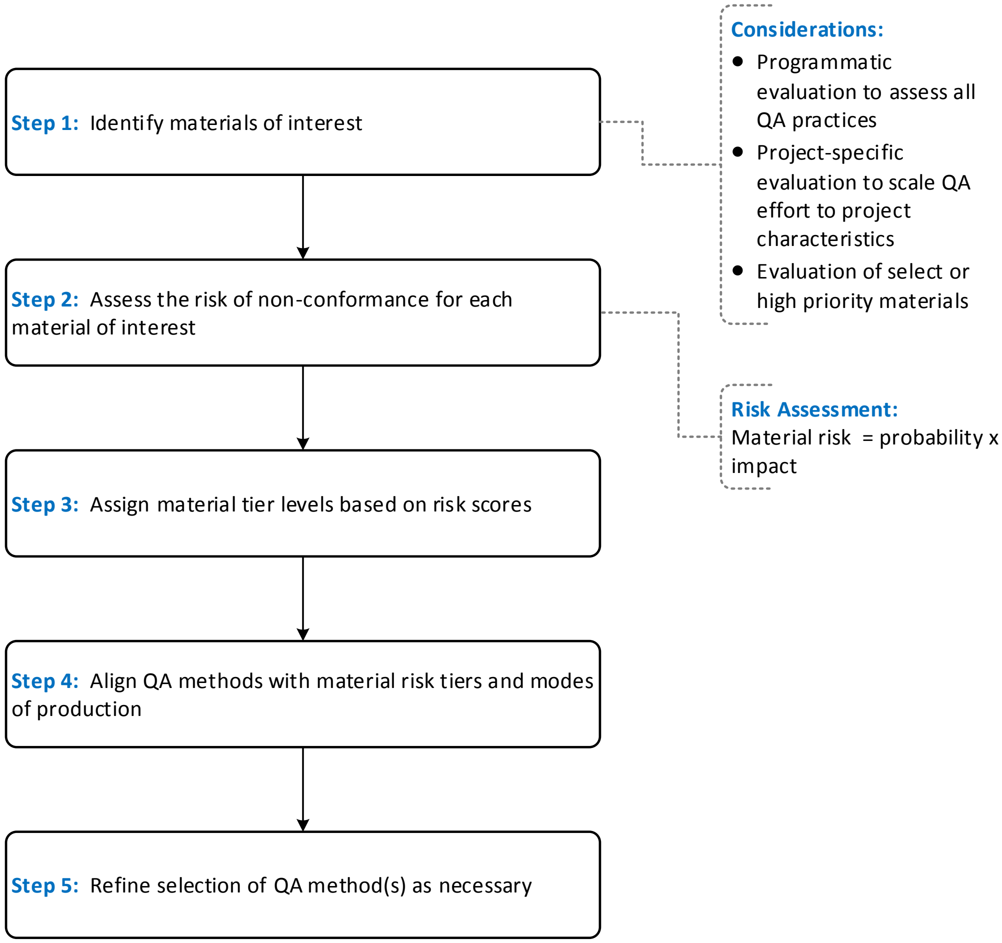


Figure 3.1: Level 1 Assessment

3.2 Framework Steps

This section systematically leads users through each step of the Level 1 qualitative risk-based decision process. The initial step largely entails a planning effort to help users define and structure the specific QA problem or opportunity that they wish to address. Subsequent steps then entail use of classic risk management principles to align materials to an appropriate level of QA.

Step 1 – Identify material(s) of interest

As QA protocols and risks are material-specific, it is important to first identify the specific materials or project elements that will evaluated.

Given unlimited time and resources, DOTs would likely benefit from reviewing and optimizing the QA protocol for all materials included in their Standard Specifications. If, however, such an overarching study is not practical, smaller subsets of materials could be explored on a programmatic basis (e.g., safety-critical materials, fabricated items, project or field-produced materials).

Similarly, if operating on a project-level rather than a programmatic basis, one would have to decide whether to optimize the QA processes for all pay items or, for example, only a few select or high priority items.

Step 2 – Assess the risk of non-conformance for each material of interest

Qualitative risk management principles can be used to prioritize the materials of interest on the basis of their relative risk of failure (or nonconformance). Once materials have been prioritized in this manner, QA resources can be allocated accordingly (i.e., the higher the risk of failure for a given material, the greater the amount of resources that should be dedicated to its QA).

As described in greater detail below, to determine a given material's *risk* of failure requires assessing:

- The *probability* (or likelihood) of receiving non-conforming material.
- The *impact* (or consequence) of the material failing to meet specification. For example, possible impacts could range from low (e.g., acceptance at reduced pay or increased maintenance), to high (e.g., early failure of a safety critical material or product).

The *risk* of failure can then be determined as the product of the probability and impact ratings:

$$\textit{Risk} = \textit{Probability} \times \textit{Impact} \qquad \textit{(Eq. 3.1)}$$

a. Assess probability of nonconformance. For each material of interest, the likelihood or probability of that material failing to meet specifications must be determined. The likelihood of non-conformance will be driven in part by the material's inherent variability. For example, one would expect standard manufactured items produced under highly controlled conditions to have more stable properties (and thus be more likely to conform to specifications) than project-produced materials that are subject to subsequent mixing, compacting, finishing, curing, or other operations at the jobsite that could substantively impact quality and material variability.

Although a single person could make this determination, typically a group of experts and interested stakeholders will systematically arrive at this assessment in a workshop setting. As individuals initially may hold differing attitudes and tolerance towards risk, all participants must come to share a common understanding of the probability of occurrence (e.g., "high" probability should mean the same thing to all participants) for such a process to be effective.

A key initial task is to therefore define the probability scales that will be used to assess risk. Establishing this range upfront lends structure to the analysis exercise and ensures that all participants are viewing probability in a consistent manner. Table 3.1 provides an example of possible risk probability definitions. As shown, either numerical (1, 2, 3) or adjectival (low, medium, high) rating scales may be used.

Table 3.1: Example Risk Probability Definitions

Numerical Rating	Adjectival Description	Definition
1	Nonconformance is *unlikely*	<15%
2	Nonconformance is *somewhat likely*	≥ 15% to <45%
3	Nonconformance is *likely*	≥ 45% to <75%
4	Nonconformance is *highly likely*	≥ 75% to <95%

b. Assess impact of nonconformance. For each material of interest, the project team must also determine the potential impact associated with nonconformance. For example, the assessment could range from no impact on performance or safety to a potential catastrophic impact requiring complete removal and replacement of a safety critical item.

Similar to estimating probabilities, all participants must share a common understanding of "impact" for the process to be effective. Possible perspectives from which to consider impacts include safety, difficulty to repair or replace, maintenance costs, and cost of work. Before conducting the assessment, the evaluators should reach agreement on the impact definitions that will be used.

The tables below provide examples of possible ways to define the impact of material nonconformance, with Table 3.2 focusing on performance issues and Table 3.3 on safety criticality.

Table 3.2: Example Risk Impact Definitions

Numerical Rating	Adjectival Description	Definition
1	Minimal Impact	Little if any impact to service life
2	Some Impact	Earlier than planned maintenance needed
3	Significant Impact	Earlier than planned major rehabilitation needed
4	Catastrophic Impact	Immediate intervention needed

Table 3.3: Alternative Example of Risk Impact Definitions
(adapted from Caltrans)

Numerical Rating	Adjectival Description	Definition
1	Monetary Impact	Monetary loss only
2	Service Interruption	Failure or corrective action may cause an interruption in service, or an environmental impact
3	Safety Impact	Failure creates a safety hazard for employees or the public
4	Catastrophic Impact	Failure is likely to cause loss of life or serious injury

c. Determine the risk score. Once probability and impact ratings are determined, they can then be combined (by multiplying the probability and impact ratings, or by using a probability-impact (PI) matrix similar to that shown in Figure 3.2) to arrive at a "score" for each material of interest. This score reflects the combined effect of a material's probability of nonconformance and the estimated severity of any unmitigated consequences associated with that nonconformance.

Figure 3.1 provides an example PI matrix, which incorporates the probability and impact rating scales previously shown in Tables 3.1 and 3.2.

Probability			Impact 1 *Minimal*	Impact 2 *Some*	Impact 3 *Significant*	Impact 4 *Catastrophic*
	4	*Highly Likely*	4	8	12	16
	3	*Likely*	3	6	9	12
	2	*Somewhat Likely*	2	4	6	8
	1	*Unlikely*	1	2	3	4

Figure 3.2: Example Probability-Impact Matrix

In the example matrix shown in Figure 3.2, the probability rating is multiplied by the impact rating to arrive at an overall risk score. This score will then be used in the following steps to prioritize materials for the purpose of efficiently allocating QA resources on the basis of material criticality.

Step 3 – Assign material tier levels based on risk scores

The risk scores established in Step 2 can then be used to assign materials to different tiers of material criticality using a scale similar to that shown in Table 3.4, which translates the risk score (probability x impact) to different materials tiers (low, moderate, and high risk) based on the risk of material non-conformance.

Table 3.4: Example Material Tiers

Risk Score	Material Tier	Description
Risk Score ≥ 8	Tier 1	Materials having the greatest risk of failure
2 ≤ Risk Score < 8	Tier 2	Moderate risk materials
Risk Score ≤ 2	Tier 3	Low risk materials

Note that the risk scores included in Table 3.4, along with the other risk-related definitions and criteria included throughout this manual, are intended to be illustrative only. Users should tailor these rating scales based on their own agency's overall tolerance or appetite for risk.

It is also important to bear in mind that risk tolerance (as reflected in the probability and impact definitions, PI matrix, and risk scoring cutoffs) may change over time. Changing circumstances (e.g., heightened public, political, or regulatory scrutiny) may trigger a reevaluation of what constitutes an acceptable level of risk for the agency.

Step 4 – Align QA methods with material tiers and modes of production

The previous risk assessment step focused on evaluating material nonconformance risk. In this step, the focus shifts to identifying an appropriate level of QA given this material risk.

Risks related to materials quality are generally managed using some combination of prevention and appraisal techniques:

- **Prevention** techniques refer to those measures taken to avoid poor quality. This could include prequalification (e.g., of materials, sources of supply, contractors, fabricators), submittal reviews, preconstruction meetings, etc.

- **Appraisal** techniques refer to methods, such as inspection and sampling and testing, which are used to determine the degree of material conformance to specifications.

For the purpose of this step, the distinction between prevention and appraisal is not as important as the idea that assuring quality often requires use of multiple methods that vary in cost and effectiveness. A key step in the optimization process therefore entails first identifying the full spectrum of QA options available and then aligning these methods to the risk-based material tiers established in Step 3.

a. Identify all possible QA methods. As illustrated in Figure 3.3 and defined in greater detail in Appendix A, DOTs currently use a variety of methods to assure project and/or material quality, including but not limited to the following practices:

Figure 3.3: Example QA Methods

- **Prevention Methods:**
  - Materials Prequalification
    - Qualified (or Authorized) Products List
    - Manufactured to National Quality Standard
    - Pre-approved Sources of Supply
  - Qualification Requirements for Facilities, Contractors, and Personnel
    - Prefabrication Audit
    - Authorized Facility List
    - Authorized Plant
    - Contractor Qualifications
    - Qualifications for Personnel
  - Submittals
    - Review of Working Drawings
    - Review of Mix Designs
    - Review of Quality Management Plans

- **Appraisal Methods:**
  - Contractor Quality Control sampling and testing
  - Certificates of Compliance
    - Certificate of Compliance from a Producer
    - Certificate of Compliance from a producer with test results
  - Sampling and Testing
    - Source and field
    - Contractor and agency
  - Inspection
    - Benchmark, intermittent, or continuous
  - Warranties

Similar to most quality systems, the methods listed above represent a mix of measures used to both prevent and appraise material quality. Although it is possible that under certain circumstances one method alone could be used to assure a material's desired level of quality and performance (e.g., requiring use of materials selected from a Qualified Products List), the use of multiple methods in series or in combination is more typical of most construction materials.

For example, to assure the quality of HMA, DOTs will often require use of prequalified constituent materials, submission of mix designs for DOT review, contractor QC, and DOT acceptance sampling and testing. Then, even if produced correctly, proper placement and final processing are still necessary to ensure an HMA pavement's final in-place quality. Improper handling and placement can cause segregation of the aggregate components of the product thereby negatively impacting final uniformity, porosity, or ride quality. To ensure quality, inspection is therefore also a critical element of a QA program even when significant sampling and testing is being performed.

b. Align possible QA methods to material tiers and production modes. The risk-based materials tiers established in Step 3 can be used to determine the type and level of QA needed for a particular item; the higher the risk (likelihood and impact) of failure for a given material, the greater the level of resources that should be allocated to its QA. For example, certification and intermittent inspection may be sufficient for low risk Tier 3 materials, whereas more frequent inspection and sampling and testing may be necessary for Tier 1 and 2 materials.

Focusing first just on an owner's materials *acceptance* practices, one can apply this risk-based philosophy of QA resource allocation to align the material tiers established in Step 3 to acceptance methods that would provide an appropriate degree of confidence in the quality of the material provided. Table 3.5 provides an example of how acceptance methods could vary based on material tiers.

In addition to the material tiers, it is also important to recognize, as reflected in Table 3.5, that the mode of material production (i.e., project-produced, fabricated, and standard manufactured item) will also influence the selection of an appropriate materials acceptance strategy. As discussed previously in Chapter 2, materials produced in a similar manner will generally exhibit similar characteristics regarding variability and stability of properties, and will thus likely require comparable levels and types of QA to assure product acceptability.

Table 3.5: Alignment of Primary Acceptance Methods to Material Tiers and Production Modes

Material Tier	QA Strategy	Primary Acceptance Methods		
		Project-Produced	Fabricated	Manufactured
1	QA methods designed to provide **maximum** confidence in the quality of the materials provided.	DOT Acceptance Sampling and Testing, or DOT Verification Sampling and Testing (if using Contractor QC data)	Continuous DOT fabrication inspection combined with a requirement for a Fabricator Quality Management System Plan	Certificates of Compliance backed by periodic sampling and testing by manufacturer and random DOT verification testing
2	QA methods designed to provide a **high** level of confidence in the quality of the materials provided.	Same as above	Intermittent DOT inspection combined with certificates of Compliance	Certificates of Compliance backed by random or programmatic sampling and testing by manufacturer
3	QA methods designed to ensure that the specified material has been supplied	Random or programmatic sampling and testing	Random or programmatic assessment of fabricator combined with certificates of compliance	Certificates of Compliance or Catalogue Cuts

Additional examples of risk-based materials acceptance methods are provided in case studies from the Washington State DOT and Caltrans (see boxes 3.1 and 3.2, respectively).

Looking beyond an owner's materials acceptance practices, a comprehensive materials QA program, as noted above, would likely entail use of multiple QA methods (including both prevention and appraisal techniques), some of which may be the responsibility of the owner, while others are performed by industry.

Table 3.6 therefore expands on the acceptance methods presented in Table 3.5 to provide a broader summary of the various QA techniques that are used to assure material quality (and thus contribute to a material's total cost of quality). The table is by no means exhaustive in its identification of possible QA methods, nor is it meant to suggest that DOTs should incorporate all of the identified methods into their QA program. For example, some QA methods, such as performance warranties on jobsite-produced materials, may be challenging to implement. Users should tailor the table to the various QA methods employed by their own agencies.

Furthermore, the suggested QA solutions in the table (as denoted by the "x" in the matrix) are not intended to be definitive. A method to further refine these selections is provided in Step 5.

Table 3.6: Alignment of QA Methods to Material Tiers and Production Modes

Quality Assurance Methods	Production Mode			Material Risk Tier		
	Project Produced	Fabricated	Manufactured	Tier 1	Tier 2	Tier 3
Materials Prequalification						
Qualified (or Authorized) Products List [(1)]	x	x	x	x	x	x
Tested Stock		x		x	x	
Manufactured to National Quality Standard (i.e. NTPEP)			x	x	x	x
Commercial Quality			x			x
Pre-approved Source	x			x	x	x
Qualification Requirements for Facilities, Contractors, and Personnel						
Prefabrication Audit		x		x		
Authorized Facility List		x		x	x	
Authorized Laboratory	x	x		x	x	x
Approved Manufacturer			x	x	x	x
Contractor Qualifications	x			x	x	x
Qualification Requirements for Sampling/Testing Personnel	x	x		x	x	x
Qualification Requirements for Installer/Fabricator Personnel		x		x	x	x
Submittals						
Agency Review of Contractor Working Drawings		x		x	x	x
Agency Review of Contractor Mix Designs	x	x		x	x	x
Agency Review of Quality Management Plan	x	x		x	x	
Sampling and Testing by Contractor						
Quality Control Sampling and Testing (Source)		x	x	x	x	x
Quality Control Sampling and Testing (Jobsite)	x			x	x	x
Quality Control Sampling and Testing for Acceptance	x			x	x	

Quality Assurance Methods	Production Mode			Material Risk Tier		
	Project Produced	Fabricated	Manufactured	Tier 1	Tier 2	Tier 3
Sampling and Testing by Agency						
Verification Sampling and Testing	x			x	x	
Programmatic QA Inspection and Testing (Jobsite)	x					x
Acceptance Sampling and Testing	x	x		x	x	
Independent Assurance Testing (Project Basis)	x			x	x	
Independent Assurance Testing (System Basis)	x	x		x	x	
Sampling and Testing by Agency						
Certificate of Compliance [(1)]	x		x	x	x	x
Certificate of Compliance with Test Results		x		x	x	x
Inspection						
Quality Control Inspection	x	x	x	x	x	x
Continuous Inspection of Work In Progress	x	x		x		
Intermittent Inspection of Work In Progress	x	x			x	
Benchmark Inspection	x	x				x
Warranties						
Material and Workmanship Warranty	x			x	x	x
Performance Warranty	x			x		
Manufacturer's Guarantee			x	x	x	x

[(1)] For project produced materials, this method could be applied to constituent materials

x = compatible; blank cell = incompatible

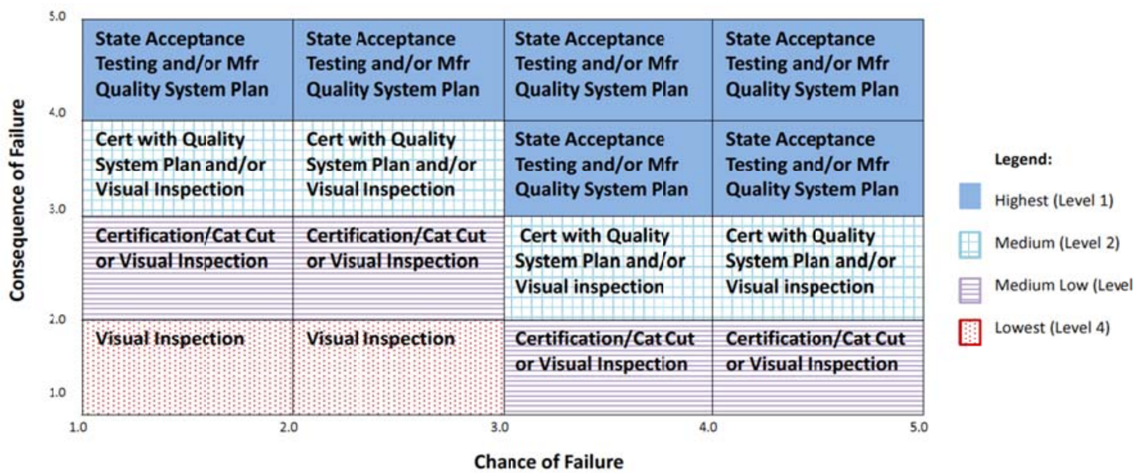
Box 3.1: WSDOT Risk Rating of Materials

Washington State DOT (WSDOT) performed an internal programmatic materials risk analysis between 2002 and 2005 to develop a system to more formally evaluate the risk of materials and to determine the level of assurance needed to accept each construction material based on that perceived risk.

As documented in the WSDOT Research Report entitled *Materials Risk Analysis* (Baker et al. 2010), WSDOT first developed a conceptual internal ranking of QA acceptance practices, ranging from the most intensive level of scrutiny to the least intensive as follows:

- **Level 1:** Highest level - WSDOT acceptance testing, or a combination of fabrication inspection coupled with a requirement for a manufacturer's quality system plan (e.g., structural steel)
- **Level 2:** Second highest level - Requires a manufacturer's certification of compliance coupled with a quality systems plan (e.g., soil nails, structural earth walls, ground anchors, and guardrail)
- **Level 3:** Intermediate level - Either a certification from the contractor that the supplied material meets contract requirements or a catalog cut stating the qualities of the material being used (e.g., fencing, compost, soil amendments, and other non-structural items that do not require testing or certification)
- **Level 4:** Lowest level - Visual inspection in the field to verify the correct product is used

WSDOT then plotted these QA acceptance levels on a five-by-five risk rating matrix, as shown below, to align QA levels with risk ratings.



State Acceptance Testing = DOT testing & Inspection and/or Fab insp with Mfr QSP

Once this framework was established, WSDOT followed a Delphi process to assign risk ratings for all the materials in its program. Material risk ratings were determined by considering each material's chance (or probability) of failure and the consequences of this failure.

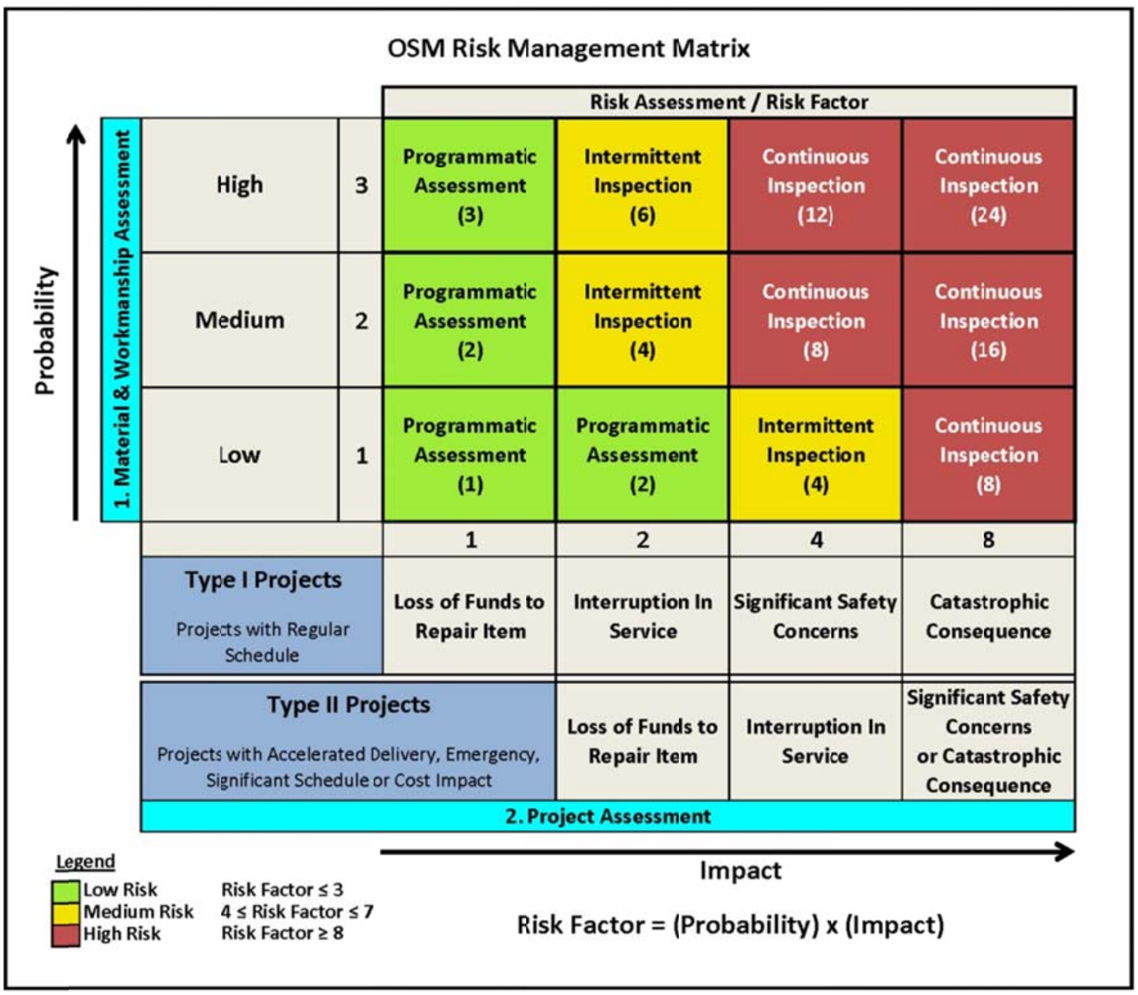
As a result of this analysis, WSDOT was able to adjust or optimize the level of QA for some materials that previously were subject to more rigorous QA. The number of materials requiring the highest level of examination (i.e., acceptance testing and/or manufacturer's quality system plan) decreased from 98 to 88. Similarly, materials in the second level of acceptance also decreased, while the number of materials that could be accepted based on visual inspection or certification increased accordingly.

Box 3.2: Caltrans Risk Rating of Fabricated Materials

The Caltrans Office of Structural Materials (OSM) has initiated a qualitative risk-based decision framework for acceptance of fabricated materials. The Material Plant Quality Program (MPQP) certification is used for plant produced materials. The program assures that the QA effort is scaled correctly by deploying inspectors through a risk-based decision process that determines the level of inspection (i.e., from programmatic to intermittent to continuous).

High priority/high risk items are inspected or tested at higher inspection levels. Project type is also considered in the evaluation, with higher profile or higher risk projects subjected to more rigorous QA.

As shown in the figure below, the qualitative risk process involves a material and workmanship probability assessment (low-medium-high) and an impact assessment scaled according to material failure and project types. The risk assessment determines the level of plant inspection (QA effort) required, ranging from low (programmatic) to high (continuous inspection). A low or programmatic level might not entail a shop inspection whereas higher levels would entail intermittent shop inspections or a full/time plant inspector. Caltrans distinguishes between projects with a regular production schedule and those with accelerated or higher impact production schedules, which tend to increase the level of QA required.



Step 5 – Refine selection of QA methods

Step 4, and more specifically Table 3.6, provides a *starting* point for identifying QA methods that *may* be appropriate for materials falling within a given tier. To help further refine the selection of appropriate QA methods, Table 3.7 below summarizes some additional project-related considerations that can influence the QA strategy for a given material and/or project.

Table 3.7: Factors that can Influence Selection of QA Methods

Factor	Considerations	Possible Optimization Strategies
Contractor/supplier qualifications and experience	• Does the contractor, fabricator or supplier (as applicable) have a history of consistently acceptable performance (i.e., compliance with specifications or with national or regional quality standards, such NTPEP)? • Are the materials being provided from a pre-approved source, Qualified Products List, or similar? • Does the contractor/supplier have a Quality Management Plan?	If the DOT has confidence in the reliability of the contractor or supplier, consider the following options: • Reduce sampling and testing and/or inspection frequency • Consider programmatic, system-wide or regional testing or certification • Accept by certification backed by desktop audit of certification documentation and visual inspection
Small material quantities	• Is the planned quantity less than the minimum required test lot? • Has the material been previously approved or certified? • Has the material been recently tested with satisfactory results? • Is the material structurally significant?	• Reduce sampling and testing frequency • Accept based on visual inspection or certification
Large quantities	• Has initial testing verified the material supply is relatively uniform or statistically under control?	• Reduce sampling and testing frequency • Eliminate selected test properties (e.g., focus on end-result testing)
Project criticality or complexity	• Does the project have a low risk profile based on size, location or complexity? • Is the work item in question located outside the traveled way? • Is the item non-structural?	For a low risk project (e.g., low volume rural roadway or culvert reconstruction), consider: • Acceptance based on visual inspection • Acceptance based on certification backed by random or periodic tests

Factor	Considerations	Possible Optimization Strategies
Project delivery method	• Is the project being delivered using an alternative delivery method (e.g., design-build) that places that places more responsibility for performance on industry? • Is the contractor required to submit and implement a detailed, project-specific Quality Management Plan? • Will the material be covered under a warranty or post-construction maintenance provision?	• Use contractor QC test data, that has been independently verified by the DOT or its agent, in the acceptance decision • Use more performance-oriented or end-result tests

To further optimize the QA strategy for a given material requires taking a closer look at its failure scenarios to identify:

- The different threats that could lead to material nonconformance,
- The consequences associated with these failure modes,
- QA measures that could be used to manage (i.e., prevent or detect) the specific threats identified, and
- Possible response or recovery measures that could be used to mitigate the identified consequences.

This step provides a structured framework for analyzing such causal relationships to identify fit-for-purpose QA strategies that will help ensure ongoing minimization and management of risks related to material quality. Unlike prior steps, the focus here is not on assessing the level of risk, but on demonstrating effective *control* of these risks.

a. Identify the threats and consequences. To design an effective and efficient QA program for a given material requires first identifying the specific threats that could lead to the material's nonconformance, as well as the potential consequences that could result from its failure. In essence, this entails providing a response to the following questions:

What can cause the material to fail? How can control be lost?

What consequences are associated with these different failure modes?

For example, possible threats could include limited owner QA resources, contractor inexperience, and material-specific issues (e.g., poor constituent materials in mix design, or unsuitable local material sources). Consequences could include service interruptions, reduced design life, and safety issues.

b. Identify control measures to minimize threats. Once a comprehensive set of threats and consequences have been identified, the next step is to evaluate what controls (i.e., QA methods) could be used to prevent or otherwise monitor each individual threat.

For example, to help prevent the threat of unsuitable local material sources, one could require the contractor to supply materials from agency pre-approved suppliers/sources or require higher levels of source testing.

From the perspective of QA optimization, tailoring a QA protocol to address the specific issues or events that could lead to a material's failure can help minimize the implementation of unduly burdensome QA practices and unnecessary procedures that are disproportionate to the actual threats posed.

c. **Identify recovery measures to minimize consequences.** Despite the implementation of controls, a material nonconformance may still occur. As part of the overall QA strategy, it is therefore important to also consider what recovery methods could be used to minimize the consequences associated with material nonconformance. For example, if materials are non-compliant, the agency could then either accept the non-conforming material at reduced payment or require removal and replacement of the smaller production lot or element.

A structured approach used across industries to facilitate the above analysis, particularly when performed in a workshop setting, is known as the Risk Bowtie Method. As discussed further in Box 3.3, Bowties are a useful technique for analyzing and communicating the interactions between risk causes, effects, and controls.

If the selected QA strategy ultimately involves sampling and testing, additional refinement can be achieved by performing a Level 2 assessment. As described in Chapter 4, the Level 2 analysis optimizes acceptance testing by emphasizing properties and test methods that are more direct indicators of performance and by establishing a risk-based approach to determine the appropriate level of owner verification testing (if contractor test data is being used).

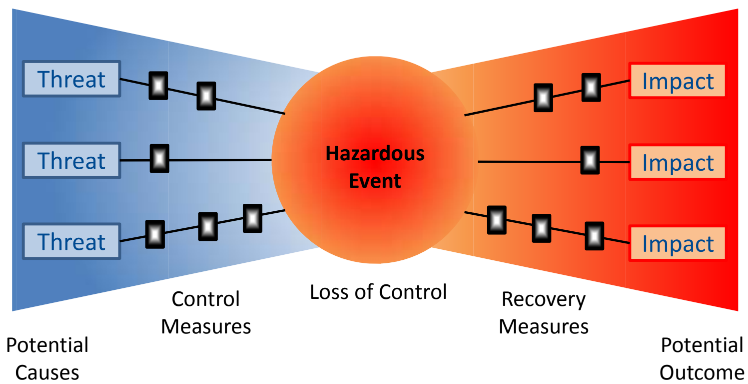
If the agency has access to cost data (or reasonable approximations thereof), a Level 3 assessment, as described in Chapter 5, can be performed to quantitatively arrive at an optimum QA investment point by comparing the cost of different QA strategies to the cost of potential defects.

Box 3.3: Using Risk Bowties to Refine QA Strategy

The Bowtie method is a structured risk evaluation technique that can be used to qualitatively assess and demonstrate effective control of risks. Popularized by Royal Dutch/Shell Group, the Bowtie method is now used by many organizations, particularly in the chemical, oil and gas, and airline industries, to:

- Evaluate risk scenarios (threats and impacts) that could exist around a certain hazardous event (typically involving safety or quality), and
- Identify the measures that will be used to control these risks

The Bowtie combines elements of fault tree (causes) and event tree (consequences) analyses to arrive at a single diagram, resembling a bowtie, which can be used to analyze and communicate the interactions between risk causes, effects, and controls.



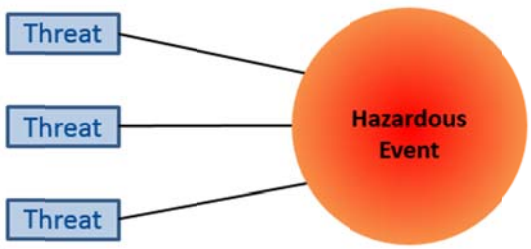
The method, which is typically applied in a workshop setting, is built out piece-by-piece by having knowledgeable people talk through the different elements of a risk scenario (causes, impacts, controls, and recovery measures), as well as the linkages between these elements.

The steps to this process include the following:

1. **Identify the <u>hazard</u> of concern.** Place the undesired or hazardous event (e.g., material non-conformance or material hazard) in the center of the model.

Box 3.3: Using Risk Bowties to Refine QA Strategy (con't)

2. **Assess the specific __threats__ could cause that hazard.** Identify the potential threats that could cause the hazard to occur. In the case of material nonconformance, this could include:
    - Inexperienced Contractor/Fabricator/Producer
    - Owner constraints related to QA resources (limited testing/inspection staff)
    - Material-specific issues (e.g., for HMA this could include segregation, rutting, cracking, etc.)



3. **Assess the __impacts__ of each threat.** Identify the potential impacts if the undesired event were to occur. In the case of material nonconformance, this could include:
    - Premature failure (or reduced design life)
    - Service interruption
    - Safety concerns
    - Aesthetic issues

Box 3.3: Using Risk Bowties to Refine QA Strategy (con't)

4. Identify <u>controls</u> (i.e., QA methods) that could be used to minimize the possibility that threats will materialize. For example:

- Use of prequalified materials
- Contractor qualifications
- Sampling and testing
- Inspection

5. Identify <u>recovery measures</u> that can be used to mitigate the potential impacts of the threat should it occur. For example:

- Accept at reduced pay
- Remove and replace
- Require warranty

Chapter 4. Level 2 Property-Based Optimization

The Level 1 optimization process discussed previously in Chapter 3 provides a framework for identifying suitable method(s) for assuring a given material will be in reasonably close conformance to the approved specifications.

For materials that are to be accepted by *sampling and testing*, the optimization process presented in this chapter provides a systematic approach for further evaluating:

- properties and test methods that are more direct indicators of performance
- the appropriate level of owner verification testing (if contractor test data is being used in the acceptance decision)

4.1 Conceptual Framework

The Level 2 assessment framework, as illustrated in Figure 4.1, provides a structured decision process for prioritizing material sampling and testing activities on the basis of the risk (i.e. likelihood and consequences) of nonconformance of key material properties.

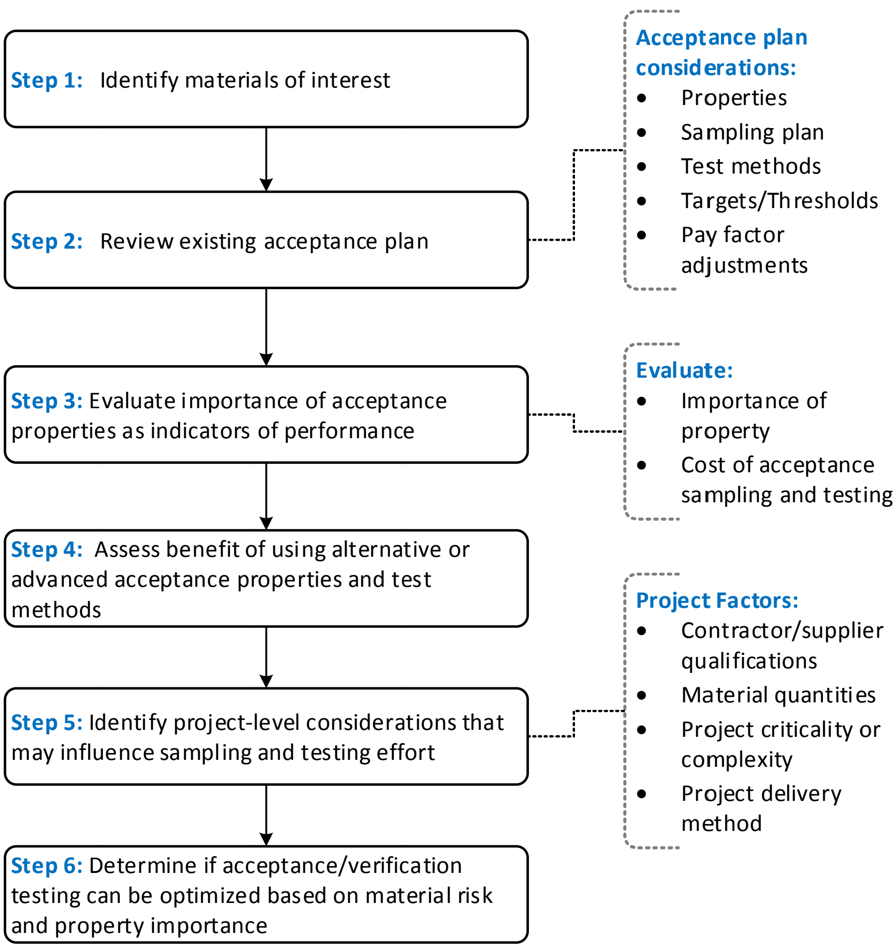


Figure 4.1: Level 2 Assessment

4.2 Framework Steps

The framework shown in Figure 4.1 includes a six-step process to determine the extent to which acceptance testing can be optimized or reduced based on performance risk.

Step 1 – Identify materials of interest

The Level 2 optimization process applies to materials that are accepted on the basis of sampling and testing, a resource-intensive method that is primarily used for higher risk or more critical materials.

Similar to the Level 1 assessment, a key first step to fully defining the optimization problem entails identifying the specific materials of interest. One may wish to assess all material items requiring sampling and testing, or focus simply on specific items having the greatest potential for optimization.

Step 2 – Review existing acceptance plans for materials of interest

For each material of interest, the DOT's current sampling and testing plan should be reviewed, bearing in mind that although such QA practices are likely based on methods that have historically produced satisfactory quality, they may fail to take advantage of possible efficiencies to be gained from:

- recent developments in the understanding of materials behavior,
- advances in non-destructive testing technology, and
- increasing use of performance specifications and alternative delivery methods that shift more responsibility for quality management to industry.

Step 3 – Evaluate the importance of acceptance properties

Most if not all tested properties routinely used for acceptance have some relationship to product performance. However, DOT acceptance testing of less important properties can result in inefficient allocation of an agency's QA resources and unnecessary project costs.

The resources allocated to the sampling and testing effort for a particular material property should be consistent with:

- criticality of the contract item (see Level 1 process described in Chapter 3), and the
- ability of the individual property to act as an indicator of performance.

When reviewing the existing QA strategy for a given material (or alternatively, when selecting acceptance properties for a new pay item), consider the following questions to help determine the relative importance of a property as an indicator of performance:

- Is the property more strongly or less strongly associated with distresses?
- What is the likelihood that property non-conformance would result in reduced or impaired performance?
- Are any properties more suited for the contractor's quality control function (e.g., gradation for HMA) than for agency acceptance testing?

- Does the property provide a measure of fundamental material characteristics (e.g., stiffness, fatigue)?
- Is the acceptance property used to determine a payment adjustment or to support a remove-and-replace decision?

From the perspective of optimization, additional questions to consider may include:

- Is the standard frequency of sampling and testing for certain properties relatively higher than others? What test(s) require the most resources?
- What test(s) can only be performed in the state laboratory?
- What test(s) require special equipment or expertise?
- What properties require destructive testing?

Answering such questions requires a thorough understanding and evaluation of each property being considered for inclusion in the QA plan. Historical data obtained from the agency's project quality management records or asset management system may provide a reliable source of information to support the decision process.

Based on such an analysis, any given material property can be characterized as being a primary, secondary, or observational indicator of performance, as described in Table 4.1. If analysis indicates that a property is strongly associated with common failure modes, then the property could be considered a primary indicator of performance. It is also important to remember that, as a general rule, properties tested in the end product are more closely related to end-product performance than when tested during production. Thus, testing of the in-place (in-situ) product (or at the point of placement), while not currently practical for some materials, is a desirable goal.

Table 4.1: Assignment of Material Property Tiers based on Property Importance

Property Tier	Description	Suggested Level of QA
Primary	Property has strong relationship to performance and/or has the highest risk related to non-compliance	QA methods designed to provide maximum confidence in the quality of the materials provided
Secondary	Property has a moderate or less direct relationship to performance; risk related to non-compliance is moderate	QA methods designed to provide an adequate level of confidence in the quality of the materials provided. For optimization purposes, consider: • Reducing the level of acceptance testing after start-up for material properties demonstrated to be under control, or • Using alternative non-destructive sampling and testing strategies to expedite testing, and increase the sample size

Property Tier	Description	Suggested Level of QA
Observational	Property has an indirect relationship to performance and risk related to non-compliance is low	QA methods entailing observational verification of contractor/producer tests combined with intermittent to random inspection, sampling, and testing of in-progress work

Step 4 – Assess benefit of using alternative or advanced acceptance properties

Current sampling and testing protocols for material acceptance often rely on destructive testing of the in-place product. Although such testing generally provides more accurate and reliable results, it tends to be costly and time intensive. For example, obtaining core samples for HMA can be considerably more resource intensive than non-destructive test (NTD) methods. NDT methods, though often less precise, yield a higher volume of samples (or continuous sampling), which can offset this disadvantage. Examples include Ground Penetrating Radar (GPR) as a measure of durability (in-place air voids, thickness), and Intelligent Compaction to more rapidly characterize material quality and variability.

For less critical material items or as a secondary measure of QA (e.g., as a QC tool for screening purposes), the use of rapid NDT methods may provide a cost effective alternative to standard tests.

Use of advanced performance tests (i.e. performance-based mixture design of mechanistic properties) may also be appropriate for acceptance purposes if they can potentially provide stronger indicators of performance for high risk projects or they correlate well with specific performance objectives (e.g., durability, fatigue, or rutting resistance).

Step 5 – Identify project-level considerations that may influence sampling and testing

Consideration of project-related factors, such as those discussed previously in Table 3.7, can also help with the selection of effective sampling and testing strategies. In effect, a DOT can use a lower frequency of sampling and testing when a material item is supplied by an extremely reliable, qualified supplier, and/or the material is for a low volume or less critical/complex project.

Step 6 – Determine the extent to which acceptance testing can be reduced or optimized based on material risk and property importance

The last step in the Level 2 property-based optimization entails deciding the extent to which acceptance testing can be reduced or optimized for a given material based on material risk and property significance. As described in the Level 1 assessment, materials can be generally characterized as high (Tier 1), moderate (Tier 2), and low risk (Tier 3) items. The QA sampling frequency of tested properties can be reduced for less critical materials and less important properties.

DOT-Performed Acceptance Testing

Table 4.2 provides an example of how a sampling and testing acceptance plan could be optimized based on material risk and property importance when the DOT performs all acceptance testing (i.e., contractor test data is not used in the acceptance decision).

In general, the DOT may choose to modify the normal inspection or testing procedures for lower risk projects or project elements. For primary properties, sampling frequency may be reduced for tests that are under control (e.g., after ten consecutive samples taken at the normal testing frequency indicate full conformance with the specifications). The sampling and testing frequency should revert back to the default frequency if there are failing tests.

Table 4.2: Example Property-Based Optimization (DOT Performing Acceptance Testing)

Property Importance	Material Risk			Example Properties
	High Risk (e.g., structural or safety critical elements, high user impacts, large quantities)	**Moderate Risk** (e.g., structural elements with moderate safety or user impacts)	**Low Risk** (e.g., non-structural elements, small quantities)	
Primary indicator	• Use default frequencies • If process is determined to be under control, reduce to 75% of default frequency	• Use 90% of default frequency after process is determined to be under control	• Use 50% of default frequency (double lot size) after production start-up • Waive acceptance testing at Engineer's discretion	• Concrete Strength • Concrete air content • HMA In-place air voids • Key mixture properties (e.g. AC) • Performance tests*
Secondary indicator	• Use 90% of default frequency after process is determined to be under control	• Use 50% of default frequency (double lot size) after production start-up	• Observational verification of QC tests with audits of certifications and random verification tests	• Slump • Gradation • Secondary mixture properties • NDT*
Observational indicator	• Observational verification of QC tests with audits of certifications and random verification tests	• Observational verification of QC tests with audits of certifications	• Random verification of QC records for compliance with specifications	• Segregation profile • Temperature • Workmanship indicators • NDT*

* Note: Testing of more advanced material properties (i.e. stiffness, dynamic modulus, permeability) or advanced rapid NDT test methods can provide cost-effective strategies to reduce risk or to meet specific performance goals (e.g., durability or long life) when used at lower frequencies or a once-per-project basis correlated with standard tests

Contractor QC Test Results Used in Acceptance Decision

For the case where contractor quality control (QC) test results are used in the DOT's acceptance decision, the DOT must still perform independent verification sampling and testing in accordance with 23 CFR Part 637. The optimal verification sampling and testing plan would be driven by material criticality and the ability of the property to act as an indicator of performance.

A case study example is provided at the end of this chapter describing how Texas DOT has implemented a risk-based protocol that assigns higher levels of QA analysis to properties that have been historically shown to have greater residual risks related to long-term performance. A general summary of such a risk-based process follows below.

a. Primary Properties. For primary properties, verification testing frequency is typically a minimum of 10-25% percent of the QA testing frequency. F- and t- tests are performed on these key material properties on a continuous basis with the addition of each verification test result. The p-values (from the F- and t- tests) are reported for each analysis and tracked over time compared to a specified *level of significance* for the material (e.g. $\alpha = 0.025$ for structural concrete and 0.01 for non-structural concrete).

The levels of significance refer to the probability of rejecting the null hypothesis assumption that the DOT and contractor populations are equal. AASHTO R 9 provides suggested values of $\alpha_{critical}$ used in the highway construction industry. An example of material categories and $\alpha_{critical}$ used for statistical analyses is shown in Table 4.3.

Table 4.3: Example Level of Significance Applied to Materials

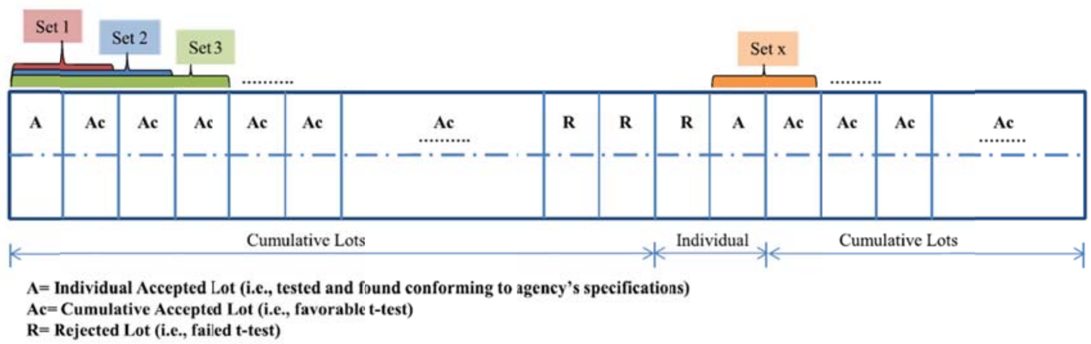
Material Category	Level of Significance ($\alpha_{critical}$)
Embankment, Subgrades, Backfill, and Base Courses	0.01
Asphalt Stabilized Base (Plant Mix)	0.01
Hydraulic Cement Concrete – Structural	0.025
Hydraulic Cement Concrete – Non Structural	0.01
Hydraulic Cement Concrete Pavements	0.025
Asphalt Concrete Pavement	0.025

This approach enables the DOT to monitor the validation status of each property daily and allows for corrective action to address non-validating test results.

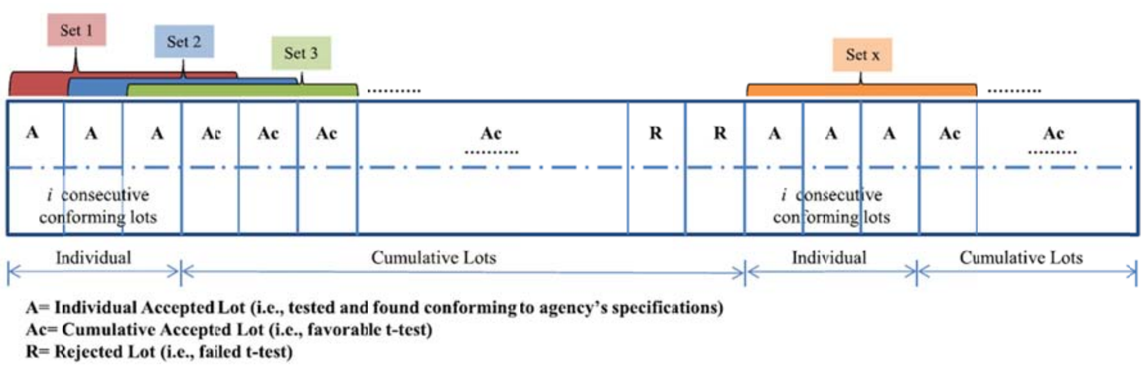
For a sampling and testing process determined to be under control, a continuous-cumulative lot or a chain lot strategy, as described in Box 4.1, has been used to increase the sample size for the F-test and t-test where contractor test results are used in the acceptance decision.

Box 4.1: Continuous-Cumulative and Chain Lot Methods

The continuous-cumulative method shown in the figure below consists of accumulating incrementally test results from sequential lots (i.e., results from lots 1 and 2; results from lots 1, 2, and 3; results from lots 1, 2, 3, and 4). Lot accumulation starts once one lot is found to be conforming (i.e., favorable t-test or other DOT application). Then, as long as the accumulated lots yield a favorable t-test, the accumulation of lots continues until a failing t-test occurs for consecutive sets of lots.



Similarly, in the chain-lot method shown below, a fixed number of lots (e.g., 2 ≤ i ≤ 5) are individually tested. After a specified number of lots i are found conforming, the accumulation of lot results begins. The chain-lot method considers a constant set size of i + 1 lots for assessing the acceptance properties (Arambula and Gharaibeh 2014).



b. **Secondary Property.** A secondary property provides independent verification for those materials and test methods that are secondary indicators of performance. An example is a slump or gradation test for hydraulic cement concrete. For such low risk materials and properties, the DOT verification testing frequency could be scaled back and not involve statistical validation (i.e. F and t- testing).

c. **Observational Property.** An observational property can entail observation verification for those materials that require only a few QA tests for compliance with the standard guide schedule or materials having a low risk of failure that will not affect long-term performance. Under the observational approach, the DOT does not directly perform tests but instead observes the contractor's QC testing for equipment and procedural compliance with the test standard.

Table 4.4 provides an example of how a sampling and testing acceptance plan could be optimized based on material risk and property importance when the DOT uses contractor QC data for acceptance purposes.

Table 4.4: Example Property-Based Optimization (Contractor QC Data Used in Acceptance Decision)

Property Importance	Material Risk			Example Properties
	High Risk (e.g., structural or safety critical elements, high user impacts, large quantities)	**Moderate Risk** (e.g., structural elements with moderate safety or user impacts)	**Low Risk** (e.g., non-structural elements, small quantities)	
Primary indicator	• Verification testing at 25% QC frequency with continuous F & t analysis • If process under control, use chain lot or cumulative sampling	• Verification at 25% QC frequency • If process is under control, reduce verification by 50% and use chain lot or cumulative sampling	• Acceptance tests at 50% of default frequencies • Verification at once per quarter w/ no statistical validation	• Concrete Strength • Concrete air content • Cover depth • HMA in-place air voids • Primary mix properties (e.g. AC) • Performance tests*
Secondary indicator	• Verification at 25% of QC frequency • If process under control, reduce verification by 50% and use chain lot or cumulative sampling	• Acceptance tests at 50% of default frequencies after start-up • Verification at once per quarter w/ no statistical validation	• Observational verification of QC tests with audits of certifications	• Slump • Gradation • Secondary mix properties • NDT*
Observational indicator	• Observational verification of QC tests with audits of certifications and random verification tests	• Observational verification of QC tests with audits of certifications	• Random verification of QC records and compliance with specifications	• Segregation profile • Cracking • Joint consolidation • Workmanship indicators • NDT*

* Note: Testing of more advanced material properties (i.e. stiffness, dynamic modulus, permeability) or advanced rapid NDT test methods can provide cost-effective strategies to reduce risk or to meet specific performance goals (e.g., durability or long life) when used at lower frequencies or a once-per-project basis correlated with standard tests

Box 4.2: TXDOT Risk-Based Approach to Verification Testing

Texas DOT (TXDOT), in its *Design Build Quality Assurance Program (QAP) Implementation Guide,* evaluated the ability of individual material properties to act as indicators of performance. This analysis of material properties was then used as a basis for determining how much owner verification testing should be performed to validate contractor test results used in the acceptance decision (TXDOT 2011).

For design-build projects with 15-year capital maintenance agreements, TXDOT's guide applies three-tiers of owner verification (OV) testing to specific materials and properties, which are based on the TxDOT's perceived residual risk after the contractor has completed construction and fulfilled its maintenance obligations. As explained in the guide, these levels are as follows:

- **Level 1** provides continuous analysis for those analysis categories that are strong indicators of performance. Examples include compressive strength for hydraulic cement concrete, percent soil compaction for embankment, and percent asphalt content for hot-mix asphalt concrete. The QA testing frequency is in compliance with the Guide Schedule, and the OV testing frequency should be a minimum of 10 percent of the QA testing frequency. F- and t- tests are performed on these material categories on a continuous basis with the addition of each OV test result.
- **Level 2** provides independent verification for those materials that are secondary indicators of performance. An example is the slump test for hydraulic cement concrete. The QA testing frequency is required to be in compliance with the Guide Schedule and the OV testing frequency should be a minimum of once per quarter.
- **Level 3** provides observation verification for those materials that only require very few QA tests for compliance with the Guide Schedule or tests on materials whose risk of failure does not affect the long-term performance of the facility past the contractual maintenance obligations. An example is the entrained air test (Tex-416-A) for non-structural (miscellaneous) concrete riprap where risk of failure does not affect the long-term performance of the facility past the contractual maintenance obligations. Under the Level 3 approach, OV does not perform tests but observes the QA test performance for equipment and procedural compliance with the test procedure.

The figure below provides an example of how TXDOT's guide applies these analysis categories to specific materials and properties.

Levels for Analysis	Level 1	Level 2	Level 3

EMBANKMENTS, SUBGRADES, BACKFILL, AND BASE COURSES

MATERIAL OR PRODUCT	TEST FOR	TEST NO.	TXDOT RECOMMENDED
EMBANKMENT (CUTS & FILLS)	Liquid Limit	Tex-104-E	2
	Plasticity Index	Tex-106-E	1
	Linear Shrinkage	Tex-107-E	2
	Gradation	Tex-110-E	2
	Moisture/Density	Tex-114-E	3
	In-Place Density	Tex-115-E	1
RETAINING WALL (NON-SELECT BACKFILL)	Liquid Limit	Tex-104-E	2
	Plasticity Index	Tex-106-E	1
	Linear Shrinkage	Tex-107-E	2
	Gradation	Tex-110-E	2
	Moisture/Density	Tex-114-E	3
	In-Place Density	Tex-115-E	1
RETAINING WALL (SELECT BACKFILL)	Gradation	Tex-110-E	2
	Resistivity	Tex-129-E	2
	pH	Tex-128-E	2
	Soundness	Tex-411-A	3
	In-Place Density	Tex-115-E	1
UNTREATED BASE COURSES	Liquid Limit	Tex-104-E	2
	Plasticity Index	Tex-106-E	1
	Linear Shrinkage	Tex-107-E	2
	Gradation	Tex-110-E	2
	Moisture/Density	Tex-113-E	3
	Wet Ball Mill	Tex-116-E	2
	Triaxial	Tex-117-E	2
	In-Place Density	Tex-115-E	1
	Moisture Content	Tex-103-E	2
	Thickness	Tex-140-E	1

Chapter 5. Level 3 Cost-Based Optimization

In contrast to the Level 1 and 2 analyses presented in Chapters 3 and 4, respectively, the Level 3 optimization process described below explicitly compares the direct costs of different QA protocols to the associated cost of material failure to arrive at the optimum QA investment point.

5.1 Conceptual Framework

5.1.1 Cost of Quality

To apply the Level 3 optimization process, it is important to first understand what is meant by the *cost of quality*.

Quality-related materials costs can generally be assigned to the two broad categories defined in Table 5.1.

Table 5.1: Cost of Quality

Category	Description	Example Components
Cost of Conformance (Prevention + Detection)		
Prevention Costs	Costs related to assuring the product or project meets requirements	• Design analysis and reviews • Constructability reviews • Quality management systems
Appraisal Costs	Costs related to determining the degree of product or project conformance	• Inspection • Sampling and testing
Cost of Non-Conformance (Defects or Failure)		
Cost of Defects or Failures	Costs associated with non-conforming materials	• Repair/rework • Schedule delays • Road user impacts • Reduced life

5.1.2 Conceptual Model

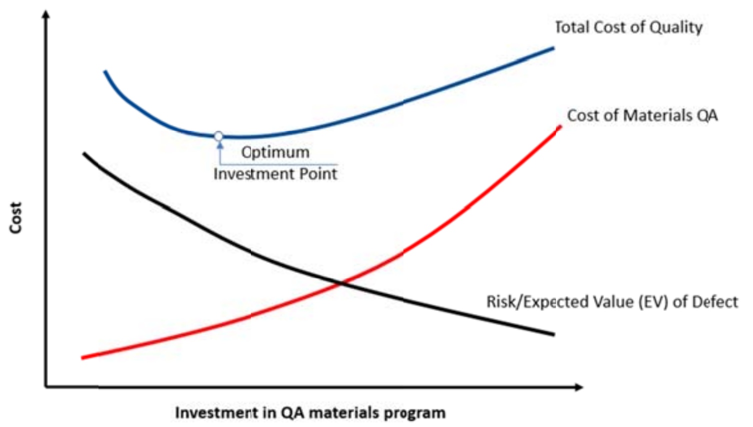
While providing more and/or better QA measures should result in higher quality products, it also tends to entail higher costs of *conformance*. In turn, higher quality products display fewer defects and require less rework, and thus generally have lower costs of *non-conformance*.

These relationships, which can displayed graphically as represented in Figure 5.1, suggest there is an optimum level of QA investment corresponding to the minimum point on the total cost of quality curve, where the total cost of quality can be calculated as:

Total Cost of Quality = Cost of Conformance + Cost of Non-Conformance *(Eq. 5.1)*

Or, stated differently,

Total Cost of Quality = Cost of Materials QA + Cost (or Expected Value) of a Defect *(Eq. 5.2)*

<table>
<tr><th>Model</th><th>Key Definitions</th></tr>
<tr><td>
</td>
<td>Total Cost of Quality =
Cost of QA + Expected Value of a Defect

Where:
Cost of Materials QA refers to the costs to implement different QA protocols (e.g., cost of sampling and testing vs. certification vs. inspection)
Risk/Expected Value (EV) of Defect can be calculated as a function of the probability of receiving non-conforming material and the cost impact of the non-conformance should it occur (e.g., cost of repairing or replacing the non-conforming material):
EV = Probability x Impact</td></tr>
</table>

Figure 5.1: Level 3 Optimization Framework

The goal of the Level 3 optimization process is to therefore find the minimum value of the total cost of quality, based on the understanding that, for any given material and QA protocol, a point exists where additional investment in QA would yield a sub-optimal return. The level of QA associated with this investment point would represent the optimum balance between the *cost* of quality and the *value* (or benefit) of quality.

The steps in the Level 3 process are summarized in Figure 5.2 and described in detail in Section 5.2. Section 5.3 then proceeds to introduce an Excel-based tool, included in Appendix B, which may be used to facilitate the analysis.

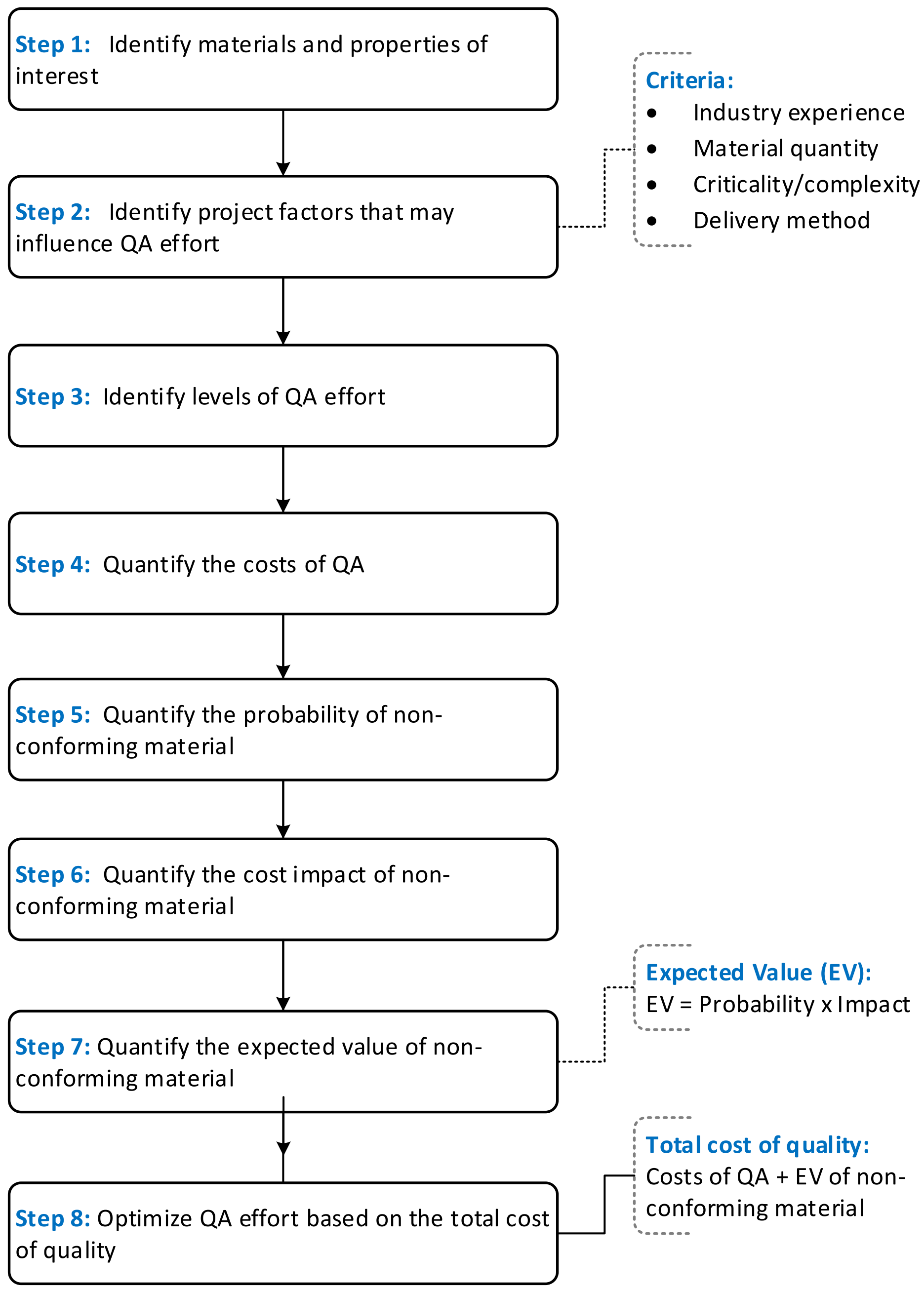


Figure 5.2: Level 3 Optimization

5.2 Framework Steps

The Level 3 optimization framework, as conceptually described below, entails a structured decision process that explicitly considers the following variables to determine the optimum QA investment point:

- the specific material and properties of interest,
- project characteristics,

- possible incremental levels of QA that could be used to assure material quality,
- the costs associated with each of these QA levels, and
- the risk reduction (e.g., reduced cost of failure) associated with each of these QA levels.

Step 1 – Identify the materials and properties of interest

As QA protocols, costs, and risks are material and property-specific, the first step when attempting to optimize the costs and risks of QA – whether on a programmatic or project-level basis – is to identify the materials and properties of interest.

For example, recognizing that obtaining the data needed to support the Level 3 model may entail a significant effort, one could choose to focus only on those materials that account for a significant proportion of project cost, QA effort, and/or risk-related cost if non-conformances were to occur.

Step 2 – Consider project factors that could influence QA effort

As previously summarized in Table 3.7, one should consider if any project-related factors (e.g., project complexity, delivery method, etc.) could influence the QA practices applied to a specific project.

Step 3 – Identify levels of QA effort

The next step to build the cost-of-quality model is to define the possible levels of QA effort. QA effort quantifies the amount of resources that a DOT may invest to assure that the material conforms to the specifications. Generally, to apply more rigorous QA measures, a DOT will have to commit more resources. The unit of analysis for QA effort would be cost (as expressed as a percentage of the material cost) that has to be committed to pay for each of the QA effort categories.

Table 5.2 provides an example of possible levels of QA effort performed by the DOT, ranging from visual inspection up to continuous inspection and/or sampling and testing.

Table 5.2: Example Levels of DOT Acceptance Practices

Level of Effort		Description of Owner Acceptance Method
Level 1	Visual Inspection	Visual inspection of the work to assure compliance with the contract and prevailing industry standards
Level 2	Certification	Verification that certified material complies with specification requirements or is on the current Qualified Products List
Level 3	Certification with back-up data	Certificates of Compliance backed by random or programmatic sampling and testing by manufacturer
Level 4	Verification sampling and testing	Owner verification testing at a reduced frequency and statistical comparison with contractor's results.
Level 5	Full owner sampling and testing	Agency acceptance sample and testing

As the levels increase, the QA effort may be compounded to some extent. For example, even if significant sampling and testing is conducted, inspection must still be performed to ensure that any handling and placement activities do not affect the final in-place quality or performance of the material.

Although not explicitly addressed in the model, it is also important to bear in mind that the cost of an effective owner's acceptance program will be driven in part by the quality control efforts applied.

Step 4 – Determine the cost of QA

The next step entails quantifying the cost of each level of QA effort. DOTs typically account for the costs of various QA activities as a percentage of a program budget (lab tests and plant inspections) or as a percentage of project cost (field inspection and testing). This cost is specific to each material and property of interest. With the progressive increase in QA cost, expressed as a percentage of the budget for the material of interest, this information should yield a curve similar to that shown in Figure 5.3, assuming a compounding effect exists between the level of effort and QA costs required.

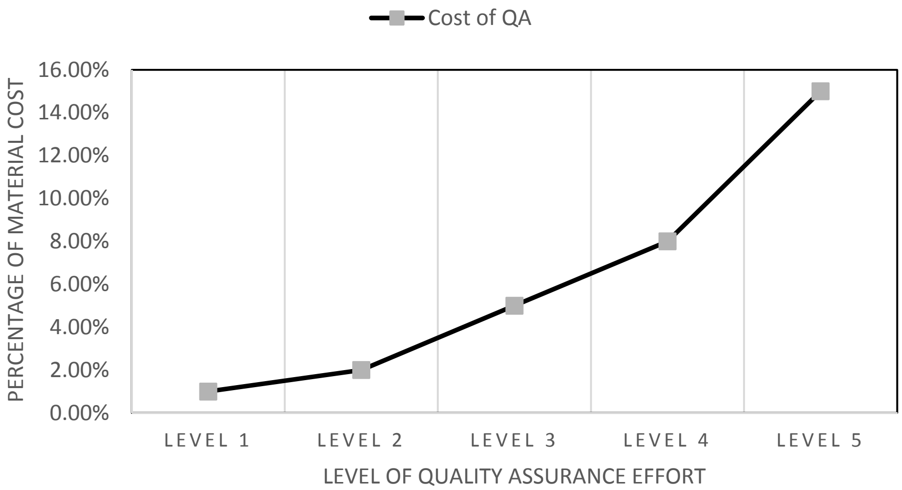


Figure 5.3: Estimated Cost of QA Effort

As QA effort continues to increase, the expectation is that the risk of material non-conformance will ultimately decrease to a point where the risk-related cost of material non-conformance remains relatively constant. In other words, the additional QA effort would not significantly reduce the risk of non-conformance.

To determine this risk of non-conformance requires first evaluating the probability of the material failing to meet specifications (as described below in Step 5) and then the related impact of this nonconformance (as described in Step 6). Once probabilities and impacts are determined, they can be combined, as described in Step 7, to arrive at the expected value of a non-conforming material.

Step 5 – Quantify the probability of non-conforming material

Step 5 entails evaluating the probability that the material of interest (or material property if performing a property-based assessment) will be non-conforming for each QA level. Conceptually, the probability is expected to decline with increasing levels of QA.

The probability of non-conformance can be estimated based on historic QA non-conformance data. Absent such data, subject matter experts could be gathered to estimate probability in a workshop setting.

Step 6 – Quantify the cost of non-conforming material

The impact of non-conforming material can be evaluated as the cost of any assumed remedial work, reductions in service life, or some other cost impact related to the specific non-conforming material (or property). While historic data may be available, direct estimates by subject matter experts may be more practical.

Specifications typically include options to address non-conforming materials, which may range from acceptance as is, acceptance at reduced payment, or removal and replacement of the lot or unit of production. Accepting non-conforming material in an "as is" condition assumes that it is in reasonably close conformance to the requirements, and the non-conformance will have minimal impact on performance or longevity. Accepting at a reduced price recognizes the possibility of some service life reduction, and the reduction in payment may be representative of future costs. Removal and replacement is intended to restore the specified quality and intended service life.

Step 7 – Quantify the expected value of a non-conforming material

Based on the probability of a non-conforming material (Step 5) and the cost of rework (Step 6), the expected value of non-conformance can be calculated as:

$$EV = PNC \times I \qquad \text{(Eq. 5.3)}$$

Where:

EV=expected value of non-conformance expressed as a percentage of material cost (%)
PNC=Probability of non-conformance
I=Impact of non-conforming material as a percentage of material cost

With increasing levels of QA effort, the expected value of non-conformance (as a percentage of material cost) is expected to decrease, as illustrated in Figure 5.4.

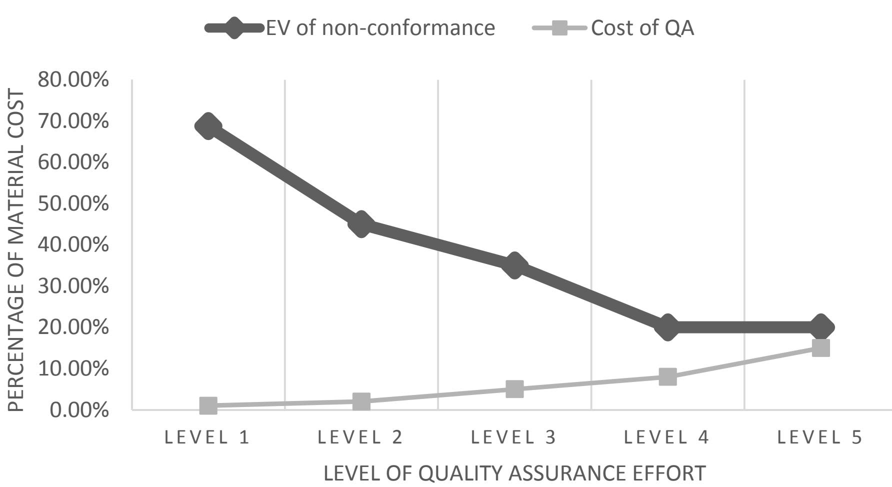


Figure 5.4: Expected Value of Non-Conformance

Step 8 – Optimize QA based on the total cost of quality (CoQ)

To optimize the cost of QA, the curves associated with the QA effort and the expected value of non-conforming materials can be added together to determine the total cost of quality (CoQ), and plotted as shown conceptually in Figure 5. In this case, the optimal investment point (i.e. QA level) is that corresponding to the level 4 QA effort, the minimum point on the CoQ curve.

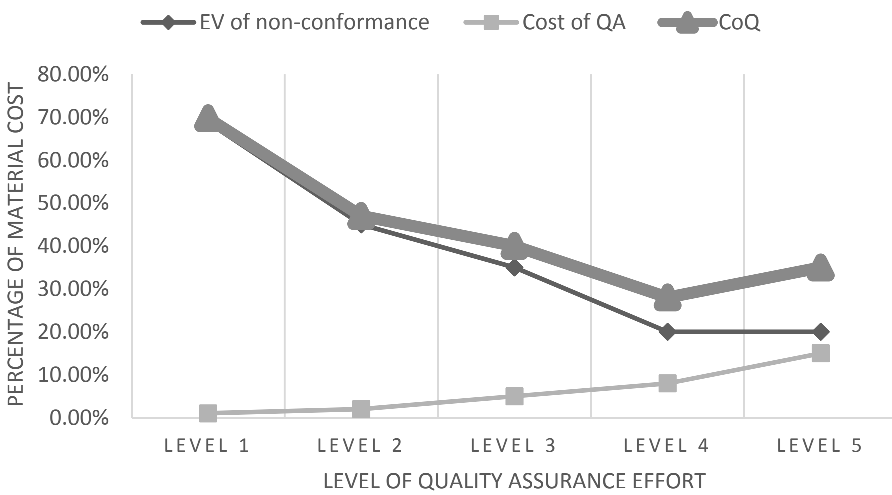


Figure 5.5: Total Cost of Quality (CoQ)

5.3 Optimization Tool

The Level 3 model is designed to use actual or estimated QA costs and potential cost impacts related to material non-conformance to optimize materials QA. Appendix B includes an Excel-based spreadsheet tool that automates the development of the optimization curves discussed above. The data required for a comprehensive QA risk-based optimization include: (1) the cost of each level of QA effort; (2) the probability of a non-conforming material at each QA level; and (3) the impact of a non-conforming material. The Excel-based tool contains separate work sheets for each of these inputs. Detailed instructions on using the tool are included in Appendix B.

When historic data on QA costs and risk-related impacts (e.g., increased cost of maintenance, repair, or replacement of non-conforming materials) are available, the user can directly input these cost elements into the model. However, the effort for collecting these historic data can be significant, and even impractical in some cases. If historic data are not available, experts can be used to estimate QA costs, the likelihood of non-conformance, and costs of non-conformance. Collection of expert data can take the form of judgements of a subject matter expert or, more frequently, judgements of a group of experts using a workshop, survey or Delphi data collection technique.

5.4 Applications of the Optimization Tool

The optimization framework can be applied as a planning tool to determine the optimal approach to QA for different project scenarios. It can also be used to assess the relative importance of material properties for a specific material item on a project.

Chapter 6. Implementation

This chapter provides a high level recap of the optimization process, a discussion of potential implementation strategies, and lastly examples to illustrate the application of the QA optimization framework.

6.1 Recap of Optimization Process

This guidebook applies a three-level analytical framework to help DOTs identify the QA acceptance plan necessary to meet specification requirements within an acceptable level of risk. Briefly, these levels can be described as follows:

- **Level 1** entails conducting a qualitative risk rating of materials and then aligning these ratings with QA methods that can provide reasonable assurance of acceptable quality.

- **Level 2** focuses on optimizing acceptance testing by emphasizing properties and test methods that are more direct indicators of performance.

- **Level 3** compares the cost of different QA protocols to the cost of potential defects to arrive at an optimum QA investment point.

Each level is based on the principle that materials QA is an inherently scalable activity, and the approach and resource commitment invested by DOTs to assure quality should be commensurate with:

- Material variability and the level of control required for materials to meet specifications, as well as

- Material criticality from the perspective of:

    - Difficulty to repair or replace
    - Safety
    - Maintenance cost, and/or
    - Cost of rework.

6.2 Applying the Framework

To successfully apply the framework requires careful implementation planning and data collection efforts, as described below.

6.2.1 Implementation Planning

Current DOT QA programs are largely based on methods and protocols that have historically produced satisfactory results. Given the institutional knowledge and existing infrastructure (e.g., specifications, manuals, test equipment, etc.) associated with these traditional practices, some resistance may be encountered when attempting to implement a QA strategy that is new or different.

To help achieve staff buy-in, it is important to therefore establish and communicate the rationale as to why optimization is necessary or would be beneficial. For example,

- Is the agency facing budget or staffing constraints?

- Is the agency increasing its use of alternative delivery methods that shift more responsibility for quality to industry?
- Is the agency interested in exploring new or emerging test methods?
- Do the resources needed to implement traditional QA protocols in some cases exceed the value received (i.e., the risk of non-compliance does not justify the level of QA applied)?

Such awareness of agency goals and constraints related to materials QA will help establish a foundation for subsequent discussions on what is and is not an appropriate or implementable optimization strategy for a particular material or project. For example, an agency contending with limited field or source inspection staff may be open to different optimization strategies (e.g., contractor QC testing in acceptance decision, industry standards for self-certification of materials, etc.) than one facing constraints related to industry inexperience.

Understanding what is driving the need for optimization will also help users frame or define the specific scope of the optimization effort. For example, based on the agency's needs or objectives, possible applications of the process could include:

- Conducting a programmatic evaluation of all materials and their associated QA practices to optimize a standard sampling and testing schedule or materials manual.
- Conducting a project-specific evaluation to scale the QA effort to a given set of project characteristics
- Evaluating the cost/benefit of new or emerging QA methods against traditional methods

6.2.2 Framework Application

The framework can be applied at the programmatic or project levels. A Level 1 materials-based assessment can be applied as a programmatic assessment of all material/product items for incorporation into the DOT's materials management system, standard specifications, and the state-wide construction and materials manual(s). Similarly, a Level 2 properties-based assessment could be applied at the program or project level for project-produced or fabricated materials requiring acceptance sampling and testing.

If the DOT is interested in shifting more responsibility for quality management to industry, a Level 2 properties-based assessment can be applied in particular to projects involving alternative delivery (e.g., Design-Build or Design-Build-Operate-Maintain) where industry assumes the risk for quality management, and contractor test results are used in the acceptance decision.

A Level 3 cost-based risk assessment can be used when costs of QA and costs of non-conformance can be evaluated to determine the optimal QA investment point for a given project scenario and material.

6.2.3 Data Collection and Analysis Techniques

The optimization process is dependent upon the availability of reliable input data for QA costs and risk (or reasonable approximations thereof). Although a single person could collect and evaluate such information, it is generally advisable to instead assemble a multi-disciplined team to provide for a more balanced and accurate evaluation. Sufficient discussion should take place among the experts to allow a consensus to be reached on the data input values. Members of this team should include internal DOT subject matter experts on materials and products, and construction and maintenance personnel. It may also be useful to consult with representatives from local materials suppliers and contractors, and national organizations that certify materials and products for highway construction to obtain their perspective on materials QA.

The techniques used to assess material risks could range from an informal brainstorming exercise to a more structured and facilitated work session in which project team members and independent subject matter experts are asked to evaluate material risks, QA costs, and impacts related to material non-conformance. In addition to brainstorming activities, other common techniques for assessing the risk and costs of materials QA are described below. These techniques may be used alone or in combination, depending on the optimization approach, the time and resource constraints, and the information available. For a given project, the approach taken to assess material risks should represent a balance between the objectives for the optimization effort and the available resources and skills of the team.

Brainstorming Workshops. One approach, commonly used in project risk assessment processes, is to conduct a brainstorming workshop(s) to assess the likelihood of material non-conformance and the potential impacts of material defects. Brainstorming can assume many forms, but it generally works as follows:

1. A facilitator organizes a workshop with a panel of multidisciplinary experts (materials, construction, maintenance, etc.), and may invite other stakeholders as appropriate. Experts who are the most knowledgeable with DOT QA practices and materials and construction management, and who are regularly confronted with the impacts of material quality failures, would be the most desirable candidates. Effective brainstorming workshops generally entail some or all of the following practices:

    - Under the guidance of the facilitator, participants should establish the agenda and scope of the optimization effort.

    - Relevant documents should be provided to the participants (preferably in advance to allow for some preparation). These may include programmatic materials (e.g. standard specifications, materials and construction manual) or project-specific specifications and material schedules with default materials QA plans.

    - Participants should review or have knowledge of existing DOT testing and evaluation procedures, policies, and practices. It may be necessary to document certain information regarding the QA effort. For example,

        - Resource capabilities (staffing, laboratory facilities, equipment)

        - Time, effort, and cost to perform inspection or a particular test

        - Inspection and testing data management

    - For more complex programmatic assessments, it may be desirable to hold multiple workshops, each focused on a specific material category based on specification categories (e.g. earthwork, base courses, pavements, structures, etc.) with key subject matter experts participating.

    - A note-taker should be appointed to capture the ideas that are being discussed.

2. Panel members share their experience and opinions, which provides the opportunity to build on each other's ideas. (A more structured brainstorming session, where each group member presents ideas in turn, may be used to ensure feedback is obtained from all group members.)

3. For each of the materials of interest, the facilitator will structure the discussion to assess inherent material (or property) risks, project or other factors that may affect material (property) risks, the likelihood and cost impact of material non-conformance, and optimal levels of QA required to manage or mitigate these risks. The facilitator will attempt to reach group consensus through polling, survey, or other methods.

4. After participants have identified the perceived optimum levels of QA necessary for materials management for the given scope and materials of interest, the facilitator will then compile and present the optimized materials QA plan for final discussion and validation by the expert panel.

Retrospective Analysis. Material non-conformance issues can impact multiple projects, unless something is done differently to avoid or mitigate the problem. Historic cost data from remediation work related to non-conformance or unplanned maintenance work, lessons learned, and project postmortems can provide a rich source of data for assessing the cost of material non-conformance. A retrospective analysis of projects performed either on its own or in conjunction with a brainstorming workshop can serve as a useful tool to quantify costs, as well as to identify optimal QA efforts required to minimize the risk of failure.

Delphi Technique. The Delphi method is a technique used to obtain the judgment of a panel of experts on a complex issue or topic such as material risk. It provides a systematic method of data collection that can minimize bias and the influence any one person can have on the outcome. Conducting a Delphi analysis to evaluate materials QA risks could entail the following steps:

1. A facilitator develops and distributes a questionnaire to solicit ideas regarding perceived material non-conformance risks (likelihood and impact) and costs of QA.

2. Participants work independently and report data anonymously.

3. The facilitator receives and aggregates the data.

4. The aggregated data from this first round are then circulated back to the experts for further comment and refinement.

5. The process is repeated until consensus is achieved. Typically this requires 2 or 3 more survey rounds.

6. The aggregated data is circulated back to the experts for re-consideration.

The iterative nature of this process has been found to yield more reliable results than a single survey round. Applying administrative controls, such as keeping responses anonymous and randomly ordering questions within a survey, has been shown to further improve the reliability and validity of the resulting data.

Interviews. Material risks and costs can also be validated by interviewing experienced project managers and/or independent subject matter experts. After being briefed on the material QA optimization process, the interviewees can be asked to identify QA costs and material non-conformance risks and costs based on their experience and knowledge. Interview results can be used to validate the results of earlier brainstorming or other information gathering techniques or as an input to these other methods.

6.2.4 Examples of the Optimization Process

Appendix C presents examples that demonstrate the use of the optimization framework.

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Appendix A: Current State of Materials QA

While not an exhaustive list, the following table summarizes several QA practices in standard use today. Although it is possible that under certain circumstances one method alone could be used to assure a material's desired level of quality and performance (e.g., requiring use of materials selected from a Qualified Products List), the use of multiple methods in series or in combination is more typical of most construction materials.

QA Method Description	QA Strategy/Objectives
Materials Prequalification	
Qualified (or Authorized) Products List: List of products that have been tested and/or otherwise evaluated by the DOT and found to meet specification requirements. Once prequalified, the listed materials typically undergo periodic testing and field performance evaluations at a prescribed frequency to ensure continued receipt of material of the specified quality	• Minimize project-specific inspection and testing needs, particularly for o Materials that cannot be evaluated or tested within a typical construction project timeframes o Materials that require extensive prequalification testing not practical to repeat for every job • Ensure objective and consistent process for evaluating *new* products for use in construction
Tested Stock: A defined quantity (batch, heat, lot, tank, etc.) of the manufacturer's or supplier's inventory that has been sampled and tested by the agency and has been set aside for use on agency projects. Approved material(s) may then be shipped to any project until the approved quantity is depleted.	• Minimize project-specific inspection and testing needs
Manufactured to National Quality Standard: Items produced to meet the specifications of industry-wide trade associations, professional societies, standards-writing organizations etc. (e.g., AASHTO, ASTM, the American Wood-Preservers' Association, the American Institute of Steel Construction (AISC), among others)	• Referencing national standards of quality provides a cost-effective alternative to the process of developing agency-specific contract item specifications and test methods for manufactured items • Minimize project-specific inspection and testing needs
Commercial Quality: "Off-the-shelf items" readily available for purchase at local supply houses.	• Eliminate need to develop agency-specific specification • Minimize project-specific inspection and testing needs for low risk, generic items
Pre-approved Source: Source designated as being an approved and/or certified supplier (typically for a specific periodic of time) on the basis of acceptable testing and evaluation periodically performed by the agency.	• Streamline quality management and material acceptance by reducing the need for testing at the project site (if proper documentation accompanies the material delivered from the pre-approved source)
Qualification Requirements for Facilities, Contractors, and Personnel	
Prefabrication Audit: Agency-performed audit to evaluate if a fabricator has the processes and the resources to fabricate project-specific products to the quality indicated in the specifications.	• Obtain a measure of assurance that a producer has the capability to perform by conducting an onsite facility audit

QA Method Description	QA Strategy/Objectives
Authorized Facility List: List of facilities that are audited on a system-based approach to ensure the fabricator is adhering to its quality control plan.	• Audit process ensures that the fabricator has and is adhering to its quality control processes • The prospect of periodic audits should help keep fabricators cognizant of their responsibility for quality control
Authorized Laboratory: Laboratories recognized by the agency (or a formal accrediting body) such as AASHTO Accreditation Program (AAP) as meeting quality system requirements.	• Ensure testing is performed by laboratories having demonstrated competence to perform standard test procedures
Approved Manufacturer: A manufacturer who has submitted quality control documentation and/or material samples, and has been given approval status to certify specific material(s).	• Streamline quality management at the project site by allowing for acceptance of certain products on the basis of certifications
Contractor Qualifications: Specification of minimum requirements for contractors.	• Ensure construction is performed by qualified contractors having the requisite experience
Qualification Requirements for Sampling/Testing Personnel: Requirement that sampling, testing, and inspection personnel are certified to a recognized standard or certification program (e.g. ACI).	• Ensure contractor, vendor, and agency sampling, testing, and inspection data used in the acceptance decision is performed by qualified personnel
Qualification Requirements for Installer/Fabricator Personnel: Requirement that certification production personnel are certified to a recognized standard (e.g., AWS).	• Ensure work is performed by qualified personnel
Submittals	
Agency Review of Contractor Working Drawings: Review of contractor's working drawing submittals.	• Assure construction and fabrication details conform with design requirements prior to the start of construction or fabrication
Agency Review of Contractor Mix Designs: Review of contractor's mix design submittals.	• Assure contractor's planned mix proportions will meet performance requirements prior to the start of construction or fabrication
Agency Review of Quality Management Plan: Review of contractor's planned quality control procedures describing how it intends to perform and control the work to meet the specifications.	• Assure the contractor performs, as a minimum, the quality inspections and testing identified in its plan. • Assure the contractor understands how its own actions (e.g., in the scheduling, ordering, handling, placing, finishing, curing etc.) will impact in-place material properties and performance of the work, and that the contractor has planned the work and allocated its resources accordingly
Sampling and Testing by Contractor	
Quality Control Sampling and Testing (Source): Required testing performed by the contractor during the production process.	• Measure quality characteristics that affect the production at a time when corrective action can be taken to prevent appreciable nonconforming material from being incorporated in the project

QA Method Description	QA Strategy/Objectives
Quality Control Sampling and Testing (Jobsite): Required testing performed by the contractor during the production process.	• Measure quality characteristics that affect the production at a time when corrective action can be taken to prevent appreciable nonconforming material from being incorporated in the project
Quality Control Sampling and Testing for Acceptance: Agency's use of contractor test results in the acceptance decision for select quality characteristics (as validated by the agency's verification and independent assurance testing).	• Use verified contractor test results to minimize the duplication of agency and contractor testing and reduce agency's testing burden
Sampling and Testing by Agency	
Verification Sampling and Testing: Agency performed testing to validate contractor test results used in the acceptance decision.	• Use verified contractor test results to minimize the duplication of agency and contractor testing and reduce agency's testing burden. Verification testing at 10-25% of frequency of QA testing
Programmatic QA Inspection and Testing (Jobsite): Periodic inspection and testing performed by the agency on random "check" samples of manufactured products at the jobsite.	• Confirm that a manufacturer continues to provide products meeting the desired standard of quality • Determine the reliability of the manufacturer's quality control process • Provide data to support continued acceptance of a particular product on all agency projects via use of a certificate of compliance
System-Based Acceptance: Agency monitoring and management of material quality on a statewide basis (would likely require implementation of a materials management system).	• More efficient use of testing and sampling resources • Streamline project-level quality management and material acceptance
Acceptance Sampling and Testing: Sampling and testing to determine the degree of compliance with specifications.	• Measure the degree to which materials comply with specification requirements
Independent Assurance Testing (Project Basis): Unbiased and independent project-level evaluation of all the sampling and testing procedures used in the acceptance program (frequency of IA testing based on testing frequency on a particular project, e.g., 10% of verification/acceptance testing).	• Assure sampling and testing activities are being performed by qualified personnel using proper procedures and properly functioning and calibrated equipment • Promote confidence in test results used for acceptance purposes
Independent Assurance Testing (System Basis): Centralized independent assurance testing, the frequency of which is generally based on a time basis for all testers and equipment. (Note this would likely require implementation of a materials management system).	• Improve efficiency of IA testing by focusing on the testers not project quantities (ensures that most testers are reviewed over the period of a year as opposed to continually reviewing the same testers) • Incorporate IA program results as part of technician qualification programs

QA Method Description	QA Strategy/Objectives
Certificate of Compliance	
Certificate of Compliance from a Producer: Written and signed statement from a producer, submitted before the material is incorporated into the work, for each batch or lot of the material stating that the material provided complies with the contract. (All materials and products accepted by certificate of compliance require periodic programmatic quality assurance testing of random "check" samples with results that support the reliability of the certificate provider.)	• Receive confirmation that the contractor has accepted the material and is confident that the material complies with the specifications • Eliminates need for agency sampling and testing at the jobsite
Certificate of Compliance from a Producer with Test Results: A written statement from a producer accompanied by test data (e.g., mill test reports for steel, pressure treating reports for timber) that affirms a product meets the specifications.	• Obtain field or laboratory test data verifying the suitability of material representative of the same lot of material as the material to be incorporated in the work • Eliminates need for agency sampling and testing at the jobsite
Inspection	
Quality Control Inspection: Required inspection performed by the contractor during the production process to ensure that a material or product meets the contract requirements.	• Visual inspection of quality and workmanship during production or installation to ensure that a material or product meets contract requirements
Acceptance Inspection: Inspection performed by the agency or designated agent to ensure that a product is acceptable in terms of the specifications for a specific project.	• Validate the quality of the product to ensure the proper combination of materials and details of construction
Continuous Inspection of Work In Progress: Agency monitoring of the contractor's construction processes on a continuous basis to ensure that the construction quality and workmanship are in compliance with the plans and specifications.	• Provide the highest degree of confidence in the quality of workmanship and fitness for purpose (e.g., Inspect 80–100% of the time work is in progress with assistant(s) assigned only to one operation)
Intermittent Inspection of Work In Progress: Agency monitoring of the contractor's construction processes on an intermittent basis to ensure that the construction quality and workmanship are in compliance with the plans and specifications.	• Provide a reasonable degree of confidence in the quality of workmanship and fitness for purpose (e.g., Inspect 30–80% of the time work is in progress with assistant(s) assigned to two or three operations simultaneously)
Benchmark Inspection: Agency inspection up to 30% of the time work is in progress, allowing construction operations to proceed until a predetermined critical activity or hold point has been reached.	• Provide some confidence in the quality of workmanship while minimizing disruption of construction operations
Warranties	
Material and Workmanship Warranty	• Requires the contractor to correct early defects in products caused by elements within the contractor's control
Performance Warranty	• Shift some post-construction performance risk to industry • Monitor and evaluate Contractor performance over time

Appendix B: Optimization Tool

Description of Tool

The Level 3 model is designed to use actual or estimated QA costs and the potential cost impacts related to material non-conformance to optimize materials quality assurance (QA). Appendix B introduces an Excel-based spreadsheet tool that automates the optimization process and which is available at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3403. The data required for a QA risk-based optimization are: (1) the cost of each level of QA effort; (2) the probability of a non-conforming material at each QA level; and (3) the impact of a non-conforming material. The Excel tool has separate worksheets for these inputs.

Input Materials of Interest, Properties, QA Levels of Effort, and Factors

Select the material of interest or material property(s) for evaluation of material QA. The user could select a material of interest (material item), or material properties used for acceptance as part of the agency's standard acceptance plan. The model may be used to think through the use of advanced material properties and test methods (i.e. stiffness) to assess their cost benefit.

To complete the input sheet for Step 1 as shown in Figure B.1 below, users should input the material of interest and a subcategory within the material in the yellow color coded cells for the "Specification/property." The tool is able to perform optimizations from one to six properties. The user should input the ones that are most important for optimization purposes.

Material	
Material	
Specification/property	
1	Property 1
2	Property 2
3	Property 3
-	
-	
-	

Figure B.1: Material/Property Inputs

For analysis of QA level of effort and costs, the Excel template tool defines five levels of QA effort performed by the DOT based on the primary mode of acceptance, ranging from visual inspection up to sampling and testing as shown in Table 5.4. The definitions worksheet includes definitions for QA levels of effort. The user can modify (add or delete) levels of QA as appropriate.

QA Levels of Effort	
1	Visual inspection
2	Certification
3	Certification w/data
4	Verification sampling and testing
5	Full sampling and testing
-	
-	
-	

Figure B.2: QA Levels of Effort

If applicable, input factors that have an obvious impact on the QA approach (i.e. industry experience, project complexity, delivery method). The more factors, the greater the complexity. The model allows input of up to four factors. For certain material items (i.e. standard manufactured products such as plastic pipe), the impact of supplier experience may be the only important factor affecting the level of QA.

Factors that affect QA approach		Definition	**Scenarios**	
1	Industry Experience	The confidence or reliability an owner has on the contractor and/or supplier.	High	Low
2	Criticality/Complexity	Project size, location, criticality (urban/rural)	High	Low
3	Delivery Method	The delivery system used by the owner for design, construction, operation, and maintenance services for project	DBB	DB
-				

Figure B.3: Factors Affecting QA Approach

The tool can handle up to four factors. If a material requires more than four factors, then the user should look for which of those factors have a strong correlation and group them together. This proposed QA optimization methodology may be used in an iterative manner so the user could initially run the process with the four factors and rerun the process with different factors to determine factors that have a highest impact on the outcomes.

A two-option dichotomous rating (i.e. low-high) is used in the tool for the characterization of factors for generating scenarios. A score of low or high is assigned. For delivery strategy Design Bid Build (DBB) or Design-Build (DB) is selected. Although this is not a comprehensive manner of characterizing all potential scenarios, it is adequate for demonstrating the data collection for use of the optimization model. For example, Figure B.3 illustrates three factors that were used to develop project scenarios. The factors may change depending on the material type and use.

The tool will auto-generate scenarios based on the number of factors selected as shown in Figure B.4. To gauge the sensitivity of different factors on the optimization results, the user can select different scenarios in the Definitions worksheet (select ON to activate a scenario), and analyze them in an iterative manner.

Scenarios\Factors	Industry Experience	Criticality/Complexity	Delivery Method	On/Off
1	High	High	DBB	ON
2	Low	Low	DBB	ON
3	Low	High	DBB	ON
4	High	Low	DBB	ON

Figure B.4: Scenarios for Selected Factors

The user could initially run the process with selected factors and rerun the process for different scenarios (i.e. small v. large) to determine how they will affect the level of QA. This may be useful in the project planning and development stages to determine the optimal level of QA effort for different project scenarios.

If the model is used for a project-specific assessment, the user would input the factors for the one specific pre-defined project (i.e. high level of industry experience, large quantity of material, large complex project, and design-build delivery method). The user could then analyze materials of interest for the single project scenario to determine the optimal QA level of effort for the project.

Input Cost of QA

Input the cost of QA as a percentage of cost as shown in Table B.1 for each QA level. DOTs typically account for the costs of various QA activities as a percentage of a program budget (lab tests and plant inspections) or as a percentage of material cost (field inspection and testing) specific to each material item. A user can also input historic QA cost data as a percentage of item cost for each level of QA or input data based on subject matter experts. It is expected that the cost of QA would generally increase with each level of QA and may vary somewhat based on the levels of industry experience, material quantities, criticality, and chosen project delivery method.

Table B.1: Estimated cost of QA

	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	0%	0%	0%	0%
2	Certification	0%	0%	0%	0%
3	Certification w/data	0%	0%	0%	0%
4	Verification sampling and testing	0%	0%	0%	0%
5	Full sampling and testing	0%	0%	0%	0%

Input Probability of Non-conforming Material

Input the probability that the material or material property will be non-conforming (i.e. the probability of a defect) considering each QA level as shown in Table B.3. Here, the probability is again expressed as a percentage (i.e. 0-100%).

Table B.2: Probability of Non-conformance Worksheet

	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	0%	0%	0%	0%
2	Certification	0%	0%	0%	0%
3	Certification w/data	0%	0%	0%	0%
4	Verification sampling and testing	0%	0%	0%	0%
5	Full sampling and testing	0%	0%	0%	0%

It is expected that the probability of non-conformance will be lower with increasing levels of QA across all project scenarios.

Input Cost of Non-conforming Material

Input the cost of a non-conforming property as shown in in Table B.3. The user can assign expected values based on the perceived impact of the material non-conformance considering the range of options previously discussed.

Table B.3: Impact of Non-conformance

Spec\Property		Scenarios 1	2	3	4
1	Property 1	0%	0%	0%	0%
2	Property 2	0%	0%	0%	0%
3	Property 3	0%	0%	0%	0%

Outputs: Expected value of a non-conforming material and Total cost of Quality

The tool will calculate the expected value of non-conformance and the Total Cost of Quality (CoQ) outputs. The CoQ output is presented as a heat map in Table B.4 to illustrate the optimal investment point for the material item. The cells colored in red are the ones with the highest expected cost of quality and the ones in green have the lowest cost of quality. For this example, the assessment indicates that, Level 5, full agency sampling and testing, is the optimal QA investment for the example material across all scenarios.

Table B.4: Total Cost of Quality (CoQ)

	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	78%	93%	77%	70%
2	Certification	59%	69%	59%	52%
3	Certification w/data	53%	62%	52%	47%
4	Verification sampling and testing	31%	40%	31%	24%
5	Full sampling and testing	18%	27%	18%	18%

The user can optimize QA effort as planning or decision tool to choose among different project scenarios. It can also be used to assess the relative importance of material properties for a specific material item on a project.

Appendix C: Case Study Examples of Optimization Process

Example 1: Level 2 QA Optimization for HMA pavement reconstruction

This example illustrates the use of the Level 2 property-based optimization for HMA pavement. HMA is categorized as a project-produced material. Items are typically produced for a specific project, and mixing, placing, compacting, and other field operations can substantively impact quality and material variability. Because of these characteristics, QA processes for acceptance of HMA pavements typically include QA sampling and testing of material properties. The remainder of this example describes the steps that a DOT would follow to optimize QA.

Step 1: Identify project description, objectives and material(s) of interest

Level 2 Property-based Optimization Assessment Worksheet	
Project Name	Project ID: Asphalt Pavement Reconstruction/Widening
Date of Review	MM/DD/YY

Project Description:	Reconstruction of a rural interstate highway to add capacity.
Objectives:	• Improve capacity • Speed of construction • Pavement durability
Material(s) of interest	• Dense-graded Hot-Mix Asphalt (QC/QA), Item xxx, high volume roadway mix • Project-produced • Material quantities: ≥50,000T

Step 2: Review existing acceptance plan for Materials of Interest

The Standard Minimum Sampling and Testing Guide for HMA is shown in Table C.1. The guide schedule establishes the minimum required frequencies for sampling and testing for specific material properties. The worksheet can be used to determine the optimal QA frequency for acceptance testing of material properties.

Table C.1: Sampling and Testing Guide for HMA

Dense-Graded HMA Pavement (Source: TXDOT Item 341 2014)				
Material/ Product	Test For:	Analysis:	Location/Timing	Std. Acceptance Frequency
Complete Mixture	Asphalt Content (%)	AC content of JMF	Truck sample	Minimum 1 per Lot
	Voids in Mineral Aggregates (VMA)	Bulk specific gravity of lab molded JMF	Truck Sample	1 per Sublot
	Gradation	Dry gradation sieve analysis	Engineer Truck Sample	1 per 12 Sublots
	Boil Test	Lab specimen	Truck Sample	1 per project
	Moisture Content	Oven drying	Engineer Truck Sample	1 per project
	Lab Molded Density	Density of production material	Truck Sample	1 per Sublot
	Hamburg Wheel	Lab molded JMF	Truck Sample	1 per project
Roadway	In-Place Air Voids	Core for density of in-place material	Roadway	2 cores per Sublot
	Joint Density	Density gauge	Roadway	1 per project
	Segregation profile	Density gauge	Roadway	1 per project
	Ride Quality	Inertial Profiler (IRI)	Travel Lanes	As per Specification

Step 3: Evaluate importance of acceptance properties

Consider the following in rating the importance of the property:

- *Consequences of non-conformance (i.e. pay adjustment system or remove and replace unit of production)*
- *Sampling frequency in the standard guide schedule*
- *Location and test method (i.e. in-place destructive v. production test)*

- *Relationship of property to pavement distresses*
- *Relationship to fundamental material characteristics*

Table C.2 illustrates the ratings for acceptance property importance for the HMA material item

Table C.2: Assessment of Acceptance Property Importance

Acceptance Properties for HMA Pavement			
Test For:	**Location/Timing**	**Std. Acceptance Frequency**	**Importance**
Lab Molded Density	Truck Sample	1 per Sublot	Primary
In-Place Air Voids	Roadway	2 cores per Sublot	Primary
Asphalt Content (%)	Truck sample	Minimum 1 per Lot	Primary
Hamburg Wheel	Truck Sample	1 per project	Primary
Voids in Mineral Aggregates (VMA)	Truck Sample	1 per Sublot	Secondary
Gradation	Engineer Truck Sample	1 per 12 Sublots	Secondary
Boil Test	Truck Sample	1 per project unless waived	Low
Moisture Content	Engineer Truck Sample	1 per project	Low
Joint Density	Roadway	1 per project	Low
Segregation profile	Roadway	1 per project	Low
Ride Quality	Travel Lanes	Per Specification	N/A

For this material specification, in-place air voids and lab molded density are payment adjustment properties. In-place air voids requires destructive core tests. Thus, the key material properties for acceptance are in-place air voids, lab molded density, and asphalt content. VMA is measured frequently, but is not part of the payment adjustment system. Gradation is tested for acceptance less frequently (1 per 12 sub-lots). Ride quality is a pay adjustment performance property. The remaining properties are tested less infrequently, or can be waived by the Engineer.

Step 4: Assess benefit of using alternative or advanced testing properties

As noted in the acceptance plan, this acceptance plan includes Hamburg Wheel Tracking, a performance test for rutting resistance. The frequency is one test per project, usually done at the start of or early during production as a measure of mixture performance, particularly if recycled material is used in the mix. It is an important test in that production can be suspended until mix design is adjusted if the test results to not meet the performance standard for Hamburg rutting. Other possible performance measures that might be considered as supplemental measures include mixture fatigue tests (Beam Fatigue), Intelligent Compaction monitoring of the in-place material as a rapid QC measure to control compaction variability, or Ground Penetrating Radar (GPR) to non-destructively check density and layer thickness.

Step 5: Identify project-level considerations

To refine the selection of appropriate QA methods, Table C.3 below summarizes some additional project-related considerations that can influence the QA strategy for a given material and/or project.

Table C.3: Project Factors that Influence QA Strategy

Contractor Qualifications:	*Contractor has a satisfactory performance history, and is experienced with quality management and with Design-Build.*
Project Delivery Method:	*Design-Build*
Acceptance Method:	*Contractor test results used in acceptance decision*
Material Quantities:	*Large Quantities*
Project Criticality/Complexity	*Moderate – Rural Interstate*

Step 6: Determine the extent that acceptance testing can be reduced or optimized based on material risk and property importance

For this Design-Build project, contractor quality control (QC) test results are used in the DOT's acceptance decision, but the DOT must still perform independent verification sampling and testing in accordance with 23 CFR Part 637. The optimal verification sampling and testing plan would be driven by material criticality and the ability of the property to act as an indicator of performance. Using the Level 2 guidelines, the optimal level of verification QA (testing or observational verification) is shown in Table C.4 below. In this example, the material item risks characterized as moderate based on the material application.

Table C.4: Property-based Optimization of HMA Pavement

Dense-graded Hot-Mix Asphalt (QC/QA), Item xxx, high volume roadway mix				
Test For	Location	Std. Acceptance Frequency	Property Importance	Optimal Verification QA:
Asphalt Content (%)	Truck sample	1 per Lot	Primary	• Verification testing at 25% of QC frequency • Reduce to 50% if process under control & use cumulative/chain lot sampling
Gradation	Engineer Truck Sample	1 per 12 Sublots	Secondary	• Acceptance at 50% of default frequency after start-up • No statistical validation
Voids in Mineral Aggregates (VMA)	Truck Sample Plant Produced	1 per Sublot	Secondary	• Reduce to 50% of std. frequency • No statistical validation

Dense-graded Hot-Mix Asphalt (QC/QA), Item xxx, high volume roadway mix				
Test For	Location	Std. Acceptance Frequency	Property Importance	Optimal Verification QA:
Boil Test	Truck Sample	1 per project	Observational	• Observational verification of QC with audits
Moisture Content	Engineer Truck Sample	1 per project	Observational	• Observational verification with audits
Lab Molded Density	Truck Sample	1 per Sublot	Primary	• Verification testing at 25% of QC frequency • Reduce to 50% for process under control & use cumulative/chain lot sampling
Hamburg Wheel Tracker	Engineer Truck Sample	1 per project	Primary	• 1 per project after start-up (for high RAP mixes)
In-Place Air Voids (density)	Roadway	2 cores per Sublot	Primary	• Verification testing at 25% of QC frequency • Reduce to 50% for process under control & use cumulative/chain lot sampling
Joint Density	Roadway	1 per project	Observational	• Observational verification of QC with audits
Segregation profile	Roadway	1 per project	Observational	• Observational verification of QC with audits

Example 2: QA Optimization for Precast Structural Concrete

This example illustrates the use of the Level 3 cost-based optimization tool to optimize DOT's QA program for different precast concrete applications. Precast concrete can be used for structural or non-structural applications. The remainder of this example describes the steps that a DOT would follow to use the optimization tool.

Step 1: Define Material(s) and Properties (Categories) of Interest

In this example precast concrete was selected for analysis. Materials have a large variety of applications but some of them are of greater interest because of cost, criticality, safety or other reasons. Structural bridge elements and drainage structures commonly use precast concrete. However, these two applications differ significantly in terms of QA cost and the risks of non-conformance.

Level 3 Cost-based Optimization Assessment Worksheet	
Programmatic	QA program for precast concrete
Date of Review	MM/DD/YY
Material(s) of interest	Precast concrete

	Bridge element	**Drainage Structure**
Description	Precast bridge deck	System of precast inlets and drains (precast pipe) to collect and draw off water from structures, pavements.
Category	Critical Structure	Non-critical structure

Figure C.1: Input for Precast Concrete Example

Precast concrete is the material of interest in this example. Bridge members and drainage structures are sub categories within the material. There are many applications or uses for precast concrete but the user should select only those of interest for a specific optimization strategy.

Step 2: Identify project factors

Input Factors that affect QA approach	Definition	Scenarios	
Industry Experience	The experience and reliability of the contractor and/or supplier.	High	Low
Material Quantity	The planned quantity or volume of material.	Large	Small
Criticality/complexity	Project size, location, criticality (urban/rural)	High	Low
Delivery method	The delivery system used by the owner for design, construction, operation, and maintenance services for project	DBB	DBOM

Figure C.2: Project Factors

Use factors that have a greater impact on the way the agency approaches QA. Industry experience, material quantity, criticality or complexity, and project delivery method; all can influence the QA procedures or the risks that the agency is managing. As noted in Figure C.2 above, all the scenarios represent extremes. The project complexity is either high or low. The delivery method is either traditional design-bid-build (DBB) or design-build-operate-maintain (DBOM). The 4 project scenarios selected for this example are shown in Table C.5 as follows:

Table C.5: Project Scenarios

Factors	**Scenarios**			
	1	**2**	**3**	**4**
Industry Experience	High	Low	High	High
Material Quantity	Large	Large	Small	Large
Project delivery method	DBB	DBB	DBB	DBOM
Criticality/ Complexity	High	High	Low	High

Step 3: Identify levels of QA effort

Table C.6 provides the assumed levels of effort with a range of options for what the DOT's QA approach could be with concise definitions for the levels of QA effort and factors previously identified.

Table C.6: Levels of QA

	Levels of Effort	Description of QA Effort
Level 1	**Visual inspection**	Visual inspection of the work to assure compliance with the contract and prevailing industry standards
Level 2	**Certification**	Verify that certified material complies with contract or is on the current QPL
Level 3	**Certification w/data**	Review certification for compliance with specifications supported by test data
Level 4	**Verification sampling and testing**	Agency verification testing at a reduced frequency and statistical comparison with contractor's results. Also responsible for IA
Level 5	**Full sampling and testing**	Agency performs acceptance sampling and testing. Also responsible for IA.

Step 4: Quantify cost of QA (% of material cost)

Input the cost of QA by quantifying the cost to perform each level of QA for the different scenarios. The cost QA, is expressed as a % of material element cost for each scenario as shown in Figure C.3.

	Bridge Deck				
	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	2%	1%	1%	1%
2	Certification	3%	2%	2%	2%
3	Certification w/data	8%	5%	3%	3%
4	Verification sampling and testing	9%	8%	6%	9%
5	Full sampling and testing	12%	12%	10%	10%

	Drainage Structure				
	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	1%	2%	1%	1%
2	Certification	2%	3%	2%	2%
3	Certification w/data	2%	0%	3%	3%
4	Verification sampling and testing	6%	7%	4%	8%
5	Full sampling and testing	9%	10%	6%	10%

Figure C.3: QA effort for each scenario

Step 5: Quantify the probability of non-conforming material

Estimate the likelihood or probability of a non-conforming material properties is shown in Figure C.4 for each level of QA effort and each scenario. The probability is expressed as a percentage (0-100%)

	Bridge Deck				
	QA Effort\Scenarios	**1**	**2**	**3**	**4**
1	Visual inspection	50%	60%	40%	20%
2	Certification	30%	40%	35%	15%
3	Certification w/data	11%	20%	5%	8%
4	Verification sampling and testing	10%	11%	5%	5%
5	Full sampling and testing	6%	9%	4%	3%

	Drainage Structure				
	QA Effort\Scenarios	**1**	**2**	**3**	**4**
1	Visual inspection	45%	50%	40%	25%
2	Certification	25%	30%	25%	15%
3	Certification w/data	10%	18%	5%	6%
4	Verification sampling and testing	7%	12%	5%	3%
5	Full sampling and testing	5%	7%	5%	3%

Figure C.4: Probability of Non-conforming material

Step 6: Quantify the cost of non-conforming material

Estimate the cost of non-conforming material. If a key property (i.e. strength, air content) is not in conformance with the specifications, and it is determined that the degree of non-compliance requires replacement, the cost of replacement of precast bridge deck element (lot) is estimated at 115% (i.e. the initial cost of the replacement element 100% plus the cost of removal 15%) as shown in Figure C.5. The cost of the drainage structure segment similarly includes an estimated cost of replacement 100% plus the cost of removal 15%.

	Spec\Scenario	1	2	3	4
1	Bridge Deck	115%	115%	115%	115%
2	Drainage Structure	115%	115%	115%	115%

Figure C.5: Estimated impact of non-conforming element

Step 7: Quantify the expected value of non-conforming material

The expected value (EV) of nonconforming material is expressed as the product of the probability of non-conformance (PN) and the cost impact (I) of rework expressed as a percentage of the installed material cost.

EV = PN x I

If the estimated impact of the non-conforming bridge element and drainage structure is multiplied by the probability of nonconformance, the EV of nonconformance for each level of QA effort and scenario is calculated in Figure C.6 below.

	Bridge Deck				
	QA Effort\Scenarios	**1**	**2**	**3**	**4**
1	Visual inspection	58%	69%	46%	23%
2	Certification	35%	46%	40%	17%
3	Certification w/data	13%	23%	6%	9%
4	Verification sampling and testing	12%	13%	6%	6%
5	Full sampling and testing	7%	10%	5%	3%

	Drainage Structure				
	QA Effort\Scenarios	**1**	**2**	**3**	**4**
1	Visual inspection	52%	58%	46%	29%
2	Certification	29%	35%	29%	17%
3	Certification w/data	12%	21%	6%	7%
4	Verification sampling and testing	8%	14%	6%	3%
5	Full sampling and testing	6%	8%	6%	3%

Figure C.6: EV of non-conformance

Step 8: Optimize the QA effort based on total cost of quality

Table C.7 is a heat map that compares the cost of quality in two dimensions; the QA levels of effort on the vertical scale and scenarios on the horizontal scale. The percentage signifies the expected total CoQ of the material. The green color coding represents the lowest cost of QA and the red coding represents the highest cost of QA. The color coding from green to red is specific to each heat map.

In scenario one the overall expected cost of quality for the bridge element is 59% (orange) for visual inspection compared to 16% (green) for agency would perform verification sampling and testing. In scenario four, the lowest overall expected cost of quality (11% green) is for the agency performing verification sampling and testing. It also shows that scenario two has a higher expected cost of quality at all QA levels.

Table C.7: Optimal level of QA effort based on total cost of quality

Bridge Deck

	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	59%	70%	47%	24%
2	Certification	37%	48%	42%	19%
3	Certification w/data	21%	28%	9%	12%
4	Verification sampling and testing	20%	21%	12%	15%
5	Full sampling and testing	19%	22%	15%	13%

Drainage Structure

	QA Effort\Scenarios	1	2	3	4
1	Visual inspection	53%	59%	47%	30%
2	Certification	31%	37%	31%	19%
3	Certification w/data	13%	21%	9%	10%
4	Verification sampling and testing	14%	21%	10%	11%
5	Full sampling and testing	15%	18%	12%	13%

Comparing the bridge deck CoQ with the drainage structure example, the optimal QA level for the bridge deck entails sampling and testing for scenarios 1 and 2 and certification with supporting test data for lower risk scenarios 3 and 4. The optimal QA level for the drainage structure entails certification with supporting test data for all scenarios.