Advanced Quality Systems: Guidelines for Establishing and Maintaining Construction Quality Databases

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Foreword

Construction quality databases are a key element of any construction quality assurance system. The use of construction quality databases enables highway agencies to make sound and informed decisions upon analyzing the data. This report contains guidance on how highway agencies can best establish and maintain construction quality databases for hot-mix asphalt and concrete construction. It describes an ideal database and presents illustrative examples of the types of analyses that can be performed to make sound, data-based decisions that lead to cost-effective construction.

This report should be of interest to engineers concerned with highway construction quality assurance, specifications, and management systems. Sufficient copies of this report are being distributed to provide eight copies to each FHWA Resource Center, six copies to each FHWA Division, and a minimum of ten copies to each State highway agency. Direct distribution is being made to the division offices for their forwarding to the State highway agencies. Additional copies for the public are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

Gary Henderson
Director, Office of Infrastructure
Research and Development

Notice

Quality Assurance Statement

Technical Report Documentation Page

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16. Abstract

The main objective of this study was to develop and present guidelines for State highway agencies (SHAs) in establishing and maintaining database systems geared towards construction quality issues for asphalt and concrete paving projects. To accomplish this, a literature search and review was performed on the subject matter, followed by a survey of construction quality practices at nine States and a more detailed review of practices at four of those nine States.

Information collected from the survey responses and the in-depth interviews provided insight into the multiple databases maintained by the agencies, the data categories stored, the analyses performed, links to other State databases, and the reports generated. Results indicated that the nature of information collected, the level of detail in the process, and the length over which this information is retained, differ significantly from agency to agency. In addition, the current systems differ considerably in their architecture, purpose, data collection and access procedures.

On a broad scale, it was learned that agencies are somewhat "data rich and information poor" and that agencies are "mostly focused on entering, not retrieving data." Also, because of poor linkages between construction quality and pavement performance and cost data, there is very limited ability to "close the loop" by showing how improvements in specifications and construction affect performance and life-cycle costs.

In addition to documenting these and other observations and findings, this report presents a detailed description of the features and capabilities of the ideal construction quality database. It also provides illustrative examples of how the ideal database can be used to improve the overall quality of highway pavement projects. The recommended database is a web-based system with client server architecture. It is comprised of the following four main modules, each of which are described in detail in the report:

1. Database Server Module.
2. QA Data Input Module.
3. QA Management Module.
4. Data Translation (Referencing) Module.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

State highway agencies (SHAs) have long recognized the importance of quality assurance (QA) as a means to control early failures of highway structures. Agencies have focused on developing appropriate standards and made considerable efforts in establishing and improving specifications so that high-quality construction practices are assured.

Increased testing during construction projects makes data processing more and more challenging when using traditional manual methods. Hence, database systems have come to fore in the management of construction quality data. These systems have become an integral component for construction QA processes. Effective QA systems can improve data processing efficiency, minimize errors, unify data administration, and provide data security. They also provide the data source for a variety of analyses, such as construction quality monitoring, developing pay adjustments, and performing detailed statistical analyses. Therefore, a construction quality database is essential for the effective and efficient operation of a highway construction program. A construction quality database is also essential as part of an effective management process of the highway facilities (including pavement structures) over time.

Feedback from SHAs received during the conduct of this study indicates that there are many different uses and users for construction quality databases, and the more data that are contained in a database, the more potential there is to use and analyze the data and thereby benefit from it. Potential uses are for technical, administrative, and legislative-level analyses and to generate periodic output reports. At the technical level, project-level analyses, acceptance quality characteristic (AQC) analyses (e.g., smoothness), and district- or statewide analyses can be performed.

Information assimilated in a construction quality database system may also be integrated with other databases, such as with performance information from the State pavement management system (PMS) and maintenance records. This allows the agency to perform more advanced analyses, such as those needed to develop or refine performance-related specifications (PRS), warranty specifications, innovative contracting procedures, and material/process pay factors, and those needed to check material design adequacy or validate structure design assumptions.

Clearly, a good construction quality system has more than just stand-alone benefits, as it supports other vital SHA activities. However, for such a system to be effective, the database and its attributes must be well defined and the database must be constructed in a manner that will readily permit wide use within an agency. This study aims at providing a detailed description of an ideal construction quality database.

1.2 OBJECTIVE AND SCOPE

The purpose of this study is to provide guidelines for SHAs in establishing and maintaining database systems geared towards construction quality issues for asphalt and concrete paving projects. This guidance includes recommendations on data types to be included, architecture of the database system, the data schema, data security, and procedures for data analyses. Another objective is to establish and make known the importance of construction quality database systems, so that SHAs are encouraged to implement new or improved databases that improve the overall quality of highway pavement projects.

1.3 METHODOLOGY AND RESEARCH APPROACH

As a first step in achieving the project objectives, current QA practices nationwide, and the associated database systems in use, were examined. Next, based on a synthesis of the state-of-the-practice in these areas, the project team developed a representation of an ideal database and recommended features that can enhance the capabilities of such a system. The following main tasks were performed to accomplish the project goals.

1.3.1 Surveys

The Federal Highway Administration (FHWA) initiated a survey in 2004 to collect information from four SHAs on their QA practices and their construction quality databases systems. The project team expanded that survey to cover other areas of interest to this project and solicited the assistance of nine additional SHAs to complete them. The surveys were distributed electronically to interested agencies. The survey results helped the project team gain insight into the functionality and implementation of construction quality database systems nationwide.

1.3.2 In-depth Interviews

Building on the initial surveys, the project team conducted in-depth interviews with representatives from six selected State Departments of Transportation (DOTs) that were proactive in maintaining and utilizing the database systems. During these interviews, the project team gained significant feedback on the potential uses and enhancements their respective construction quality database systems can undergo to make them more beneficial.

1.3.3 Program Demonstrations

The project team collected product reference manuals and literature, and received program demonstrations from selected SHAs, thereby providing insight into the functioning of all the various systems and software complexities.

1.3.4 Development of a Model Database

The project team developed a framework for an ideal database system that consists of features and capabilities that can (a) best store construction quality data and allow access by a range of users for analysis and reporting, and (b) link the data with data from other database systems in order to support other activities of the SHA.

1.4 HIGHWAY QUALITY ASSURANCE TERMS

The Transportation Research Board (TRB) released a circular (TRB, 2005) containing a glossary of highway QA terms. This document was developed to provide a uniform understanding of technical terms that have specific meanings in the highway engineering field. Definitions for these terms are cited below, to introduce and clearly distinguish among them.

- ***QA***—*All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service. QA addresses the overall problem of obtaining the quality of a service, product, or facility in the most efficient, economical, and satisfactory manner possible. Within this broad context, QA involves continued evaluation of the activities of planning, design, development of plans and specifications, advertising and awarding of contracts, construction, and maintenance, and the interactions of these activities.*

  In summary, QA is a process to ensure that the quality of the finished product meets specifications. It is the responsibility of the highway agency and is comprised of QC, inspection and acceptance, and IA.

- ***QC—****Also called process control, QC includes those QA actions and considerations necessary to assess and adjust production and construction processes so as to control the level of quality being produced in the end product.*

  QC is motivated by QA and acceptance procedures, and typically is the responsibility of the contractor and/or producer.

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

- ***Acceptance—****The process of deciding, through inspection, whether to accept or reject a product, including what pay factor to apply. Where contractor test results are used in the agency's acceptance decision, the acceptance process includes contractor testing, agency verification, and possible dispute resolution.*

- ***IA—****A management tool that requires a third party, not directly responsible for process control or acceptance, to provide an independent assessment of the product or the reliability of test results, or both, obtained from process control and acceptance. The results of IA tests are not to be used as a basis of product acceptance.*

1.5 ORGANIZATION OF THE REPORT

This report is divided into six chapters and an appendix. Chapter 1 (this chapter) provides a brief introduction to the objectives of the study and the methodology adopted to accomplish the goals of the project. Chapter 2 provides a review of literature available on construction quality database systems and discusses the standards developed by different national studies.

Chapter 3 summarizes the information collected from SHAs as part of this study. Included are the findings from surveys conducted with individual agencies and in-depth reviews carried out by the project team to learn about the features and functions of the databases the surveyed agencies manage.

Chapter 4 discusses the development of an ideal database system and recommended features for a comprehensive system. In light of the current needs of SHAs and the construction industry, this chapter describes the various modules of a comprehensive database and how they can interact with each other to provide analysis capabilities for agencies to evaluate and improve their construction and testing practices. Guidelines for an ideal construction quality database are provided.

Chapter 5 illustrates examples of analyses/reports for various levels of large and small databases. This chapter provides samples of statistical analyses that can be performed to streamline construction activities and constantly improve the quality of construction within an agency.

Chapter 6 summarizes the entire work effort and presents important conclusions from this project. Appendix A contains a bibliography of the literature collected and reviewed for potential use in the study.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

As the first step in the research, a comprehensive literature search and review was performed to obtain information on construction quality database systems used nationwide. The search included national (Transportation Research Information Service [TRIS], Research in Progress [RIP], FHWA, TRB) and state agency databases. Many published documents on construction/materials quality measures, processes, specifications, and systems were identified and retrieved for in-depth review. Appendix A contains a bibliography of all the literature collected and examined in the study.

This chapter presents a summary of the information deemed most pertinent to this study. While a considerable amount of good information has been written in recent years regarding the development and use of QA practices and programs (i.e., QC, acceptance, IA, PRS), the focus of this search/review was on quality database systems. Of particular interest was information on data items, database schema and architecture, data entry and security, data querying and analysis tools, and integration with other databases.

2.2 LITERATURE REVIEW FINDINGS

Construction quality databases can be defined as computerized databases containing a variety of pavement construction-related data that characterize the quality of materials and workmanship used to construct the pavement. The primary purpose of a construction quality database is to facilitate the assessment of quality of materials production and placement, including the establishment of pay factors, as defined by specifications. A secondary purpose is to enable detailed research analyses of quality, performance, and cost data that can help guide future improvements to current standards and specifications (e.g., materials, techniques, and design strategies to use; quality characteristics and levels to use in acceptance; incentive/disincentive plan).

While most SHAs have established and maintained construction-related databases for many years, it is only within the last 5 to 10 years that they have realized the need for more detailed systems to accommodate the requirements of new QA programs (developed in response to Title 23, Part 637, Code of Federal Regulations [FHWA, 1995]). The exact number of construction quality databases currently in existence at the State level could not be ascertained through the literature review. However, based on the results of a recent National Cooperative Highway Research Program (NCHRP) survey on State construction QA programs (Hughes, 2005), it is believed that several States have some form of a quality database in use, particularly as it relates to hot-mix asphalt (HMA) and portland cement concrete (PCC) paving materials. This survey, which among other things focused on QA programs for soils and embankments, aggregate base and subbase, HMA paving, PCC paving, and PCC structures, indicated that all of the 45 responding agencies (43 States, the District of Columbia, and the FHWA Federal Lands Division) have a QA program in place for HMA paving, while about two-thirds have such a program for PCC paving.

Presented below are discussions of works undertaken in recent years having special focus on the various attributes of construction quality databases. Information gleaned from the following documents was instrumental in the development of the concepts and best practices reported herein:

- *NCHRP Synthesis 346*, "State Construction Quality Assurance Programs" (Hughes, 2005).
- FHWA Manual, "Optimal Procedures for Quality Assurance Specifications" (Burati et al., 2003).
- FHWA Report Evaluation of Procedures for Quality Assurance Specifications (Burati et al., 2004).
- *Transportation Research Circular Number E-C074*, "Glossary of Highway Quality Assurance Terms" (TRB, 2005).

2.2.1 Construction Quality Data Items

Results of the aforementioned NCHRP survey (Hughes, 2005) showed a variety of attributes being used for QC and acceptance of HMA and PCC paving materials. Table 1 shows gradation, asphalt content, volumetric properties, and compaction as the most frequently used QC attributes for HMA. These same characteristics and ride quality are also most common for acceptance of HMA. For PCC paving, table 2 shows gradation, air content, and slump as the most common QC attributes, and thickness, air content, cylinder strength, slump, and gradation as the most common acceptance characteristics.

Table 1. Attributes used for QC and acceptance of HMA paving (Hughes, 2005).

Attribute	Number of responses	
	QC	Acceptance
Asphalt content	40	40
Gradation	43	33
Compaction	28	44
Ride quality	16	39
Voids total mix	20	26
Voids in mineral aggregate	26	23
Aggregate fractured faces	25	23
Thickness	13	22
Voids filled with asphalt	19	13

Note: 44 total responses

Table 2. Attributes used for QC and acceptance of PCC paving (Hughes, 2005).

Attribute	Number of responses	
	QC	Acceptance
Air content	25	38
Thickness	14	36
Slump	24	33
Cylinder strength	18	31
Gradation	25	26
Beam strength	14	18
Water-cement ratio	12	16
Ride quality	1	15
Aggregate fractured faces	7	6
Sand equivalence	0	3
Permeability	0	3
Core strength	0	2

Note: 44 total responses

A review of State specifications by Burati et al. (2004) indicated similar findings with regard to quality characteristics used in the QA program. This review also showed gradation, asphalt content, air voids, in-place density, and smoothness as the quality characteristics used in determining pay factors for HMA, and thickness, air content, smoothness, and flexural or compressive strength as the quality characteristics for determining PCC pay factors.

2.2.2 Web-Based Quality Systems

The following is a review of two Web-based quality systems, *HMA View* and *ELVIS*.

HMA View

The development of a Web-based HMA database system, *HMA View,* by the University of Washington, and its use was the focus of a recent paper by White et al. (2002). The motivation for developing the system was the desire to (a) link all phases of a project life-cycle—mix design, construction, usage/maintenance, and performance—to allow for the evaluation of Superpave mixes and (b) bring current computing technology and HMA construction together to create real-time (or near real-time) construction tools.

A schematic of the Web-based, server/client-type database system is provided in figure 1. The system can open different avenues of data entry to each of the users and allows a variety of users from various locations access to a large-scale data warehouse in real time. It supports a wide variety of data types, including test results, digital and infrared images, inspection videos, instrument readings, and audio clips, and each type of media can be referenced to a specific location using global positioning system (GPS) technology.

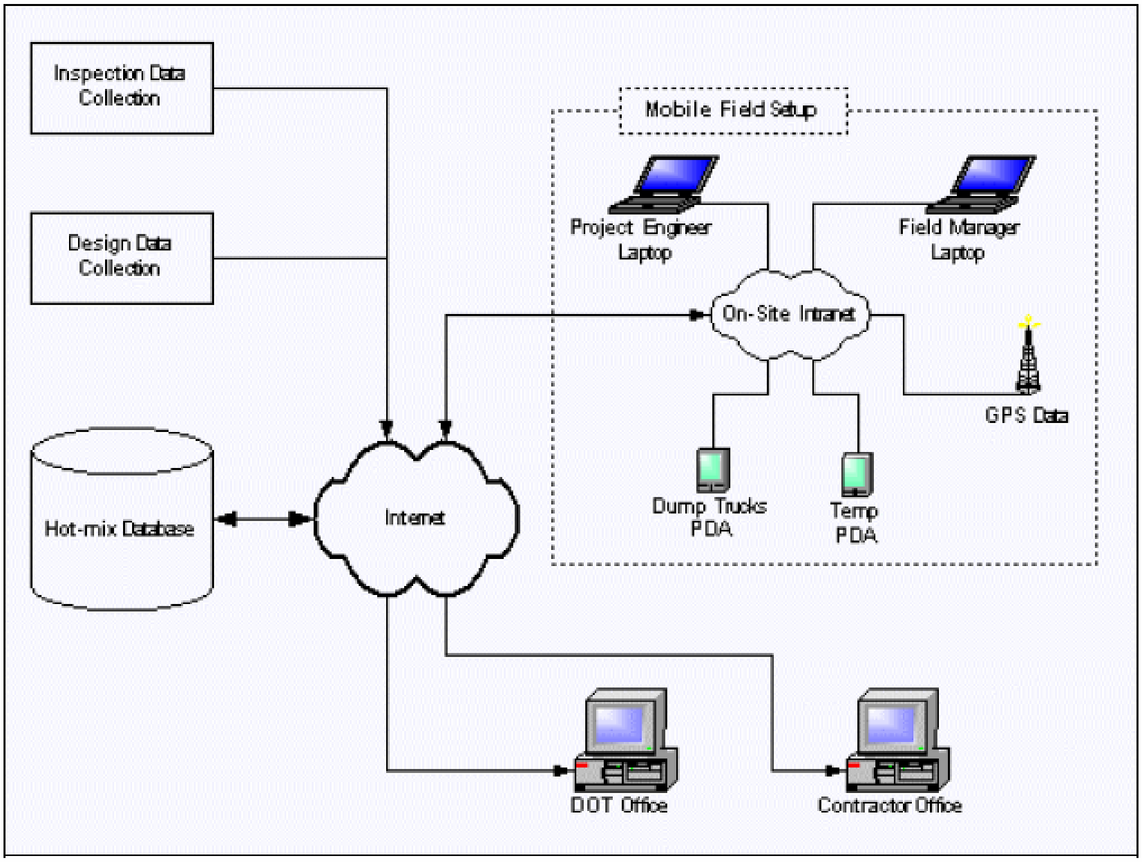


Figure 1. Schematic of *HMA View* system (White et al., 2002).

Brief descriptions of the system's features and capabilities are given below.

- Data Acquisition—Data may be entered directly into the database through data entry points on the Internet or imported electronically from other data sources. Manual entry is facilitated with secure Web forms customized for each user group. Electronic entry is done through formatting and the use of simple translators. As data are entered into the database, they are validated and checked against rules to ensure that any later analyses will be performed on a consistent data set.
- Data Warehousing—To provide users with the ability to browse and analyze the collected data, an efficient storage method was devised whereby data are stored and cataloged into a specific location for easy retrieval. The data warehouse includes data mining capabilities.
- Browsing—To serve the needs of multiple users interested in differing "views" of the data, the following five browsing modes are included:
  - Project Info—Quick snapshots of the project, including spatial view.
  - Mix Design—Detail displays regarding the job mix formulas (JMFs) used in the project.
  - Construction—Multiple subsections including general site data, HMA data (gradations, volumetrics), density data, and media content.

    - Performance—Historical performance data, as well as traffic and usage statistics.
    - Analysis—Allows creation of plots and performing diagnostics on different construction parameters.
- Queries—Advanced queries can be performed via parameterized Boolean methods (e.g., projects paved in 1999 with an ambient air temperature of less than 59°F) or spatial methods (i.e., visual search for a project based on location on a map).
- Analysis—Both intra- and inter-project analysis capabilities are available by means of graphing (QC charts) and table generation.
- Data Export—Data may be exported into spreadsheet format for more in-depth analyses than what the database allows (e.g., statistical analyses).

The *HMA View* system described by White et al. (2002) includes data backup capabilities and maintains transaction logs. It also includes secured (login and password scheme) client portals for entering and viewing data.

ELVIS

Yuan et al. (2006) reported on the implementation of a Web-based electronic data management system (EDMS) for material QA on a large highway construction project in Texas. The on-going 49-mile design-build toll road project, located on SH 130 southeast of Austin, utilizes an independent construction QA firm for administering QA functions and making acceptance decisions. The QA firm uses a specially designed Electronic Document Management System (EDMS), called *Electronic Laboratory Verification Information System* (*ELVIS*), first implemented in 2004.

ELVIS was developed on a Microsoft® Net platform, is rooted in Structural Query Language (SQL) database, and runs on a Microsoft® Windows 2003 web server shielded by a firewall. As illustrated in figure 2, it consists of eight key functional components. Brief descriptions of each are provided below:

- Integrated database management system (DBMS)—The DBMS is a set of inter-related database tables based on technology that permits the QA firm staff to organize, store, and manage data related to all planned construction quality assurance activities. Data stored in the DBMS include sample identification information, test procedure-based testing data, material specification requirements, PCC and HMA proportion designs, non-conformance records and disposition information, controlled vocabulary languages (CVLs), and encrypted user access data.
    - CVLs are sets of pre-determined terms that are used consistently to describe certain materials, work features, and technical requirements. CVLs are essential in searching, locating, retrieving, and grouping information by linking similar records and resources with a combination of unique terms. CVLs used in the QA program include technician/inspector names, sample type, report type, material/mix code, supplier/producer, specification item, special provision, material grade/class/type, roadway, direction, feature, structure number, and sieve size.

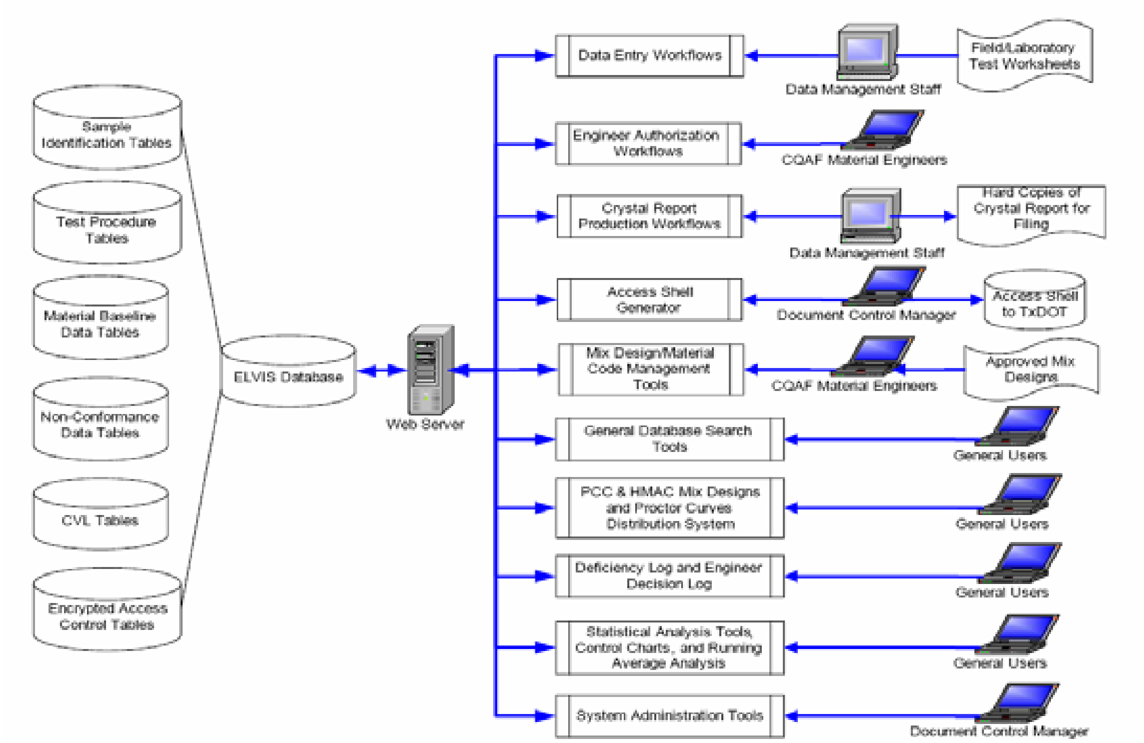


Figure 2. Schematic of *ELVIS* system architecture (Yuan et al., 2006).

- PCC mixture designs stored in the database include batch plant information, mix design code, concrete class, design and specification requirements, batch weights per cubic yard, admixtures, and approval information. A set of integrated database tables is dedicated to store HMA mixture design data, including batch plant information, mix code, grade, asphalt binder information, sources of fine and coarse aggregates, aggregate proportion percentages, JMFs, and approval information. JMF records for each mix design are chronologically indexed in the database for future retrieval.

- Workflow-driven data management functions—Workflow technology was employed to facilitate data management and information process automation. The data management workflows in *ELVIS* consist of three integrated components: data entry workflows, engineer review/authorization workflows, and document control workflows. The system uses Crystal Reports® software to publish database-driven reports to the Web. These reports can be exported to electronic formats (e.g., .pdf files) used by most end users. *ELVIS* supports 43 field and laboratory test procedures for a wide range of highway construction materials, including soil and base materials, PCC, HMA, and coarse and fine aggregates for PCC and HMA mixtures. The system is capable of determining pay adjustments for HMA pavements based on deviations of laboratory molded densities and the percent of in-place air voids, and for pavement ride quality based on the measured International Roughness Index (IRI).
- Material baseline information management applications—*ELVIS* workflows automatically archive proctor curve information, including auto-generated numerical Proctor curve identification number, curve equation parameters, maximum dry density, optimum moisture content, Atterberg limits, percent minus the No. 40 and No. 200

sieves, material description based on laboratory classification, material source, and sample location in the database when Proctor curve tests are authorized.

- Online information delivery system—As a Web-based EDMS, *ELVIS* serves as a secure, real-time, common-information sharing platform among a broad constituency of users, including managers, engineers, QC/QA technicians and inspectors, construction superintendents, material vendors, and designers. In addition to standardized Crystal Reports®, which can be downloaded, printed, and emailed as a .pdf or image file, the system allows users to generate summary data reports in Microsoft Excel® format.
- Engineering decision tracking functions—Depending on the severity of material non-conformance, the independent QA engineers may accept certain out-of-specification material tests based on engineering discretion and the Engineer Decision delegation agreed upon by the Texas Department of Transportation (TxDOT). *ELVIS* automatically tracks and documents out-of-spec materials and test reports, and engineering justifications for acceptance decisions.
- Deficiency management—*ELVIS* is also capable of tracking and monitoring failing material tests, and retests on the reworked products and materials. Using database techniques, the system associates retests with the original failing test. Key information and status of original failing tests and their retests are posted automatically on a Web page. Based on real-time construction deficiency information, QC staff and field engineers can plan and monitor corrective measures. When a construction deficiency has been corrected or reworked and the product has passed retests, QA engineers can close the deficiency by changing the deficiency status from "Pending" to "Closed" through a secure Web page.
- Statistical analysis tools—The application of statistical analysis to the test history of construction materials is used as a guide to identify the material variability and to develop processes to control the variability of manufactured materials (e.g., PCC, HMA, flexible base, and aggregates/products for PCC and HMA mixtures). A series of Web-based statistical analysis tools are built into *ELVIS*, with the system being capable of determining such statistics as mean, variance, range, standard deviation, deviation significance (i.e., number of standard deviation), and running averages.
- System administration tools—An IA program is part of the SH 130 project. Administrated by TxDOT, the IA program evaluates all sampling and testing procedures, personnel, and equipment used by the independent QA firm in making acceptance decisions. To ensure personnel qualifications, *ELVIS* documents and tracks technician certification information (e.g., who is certified by the IA program to perform specific test procedures and the expiration dates of technician certifications on various test methods). Similarly, equipment calibration records and calibration schedules are stored in the system.

Yuan et al. (2006) noted that successful implementation of *ELVIS* has provided a cooperative material test data processing platform and enabled the processing and reporting of up to 400 material acceptance tests per day. All QA test reports are stored systematically in the *ELVIS* database, and authorized users can use secured online access to retrieve and produce any test report in the flexible data format in seconds. Reportedly, the rapid reporting of test results has greatly helped in the management of material quality-related construction deficiencies and improved the builder's quality performance.

2.2.3 Integration of Pavement Management and Other Systems With Construction Quality Databases

In a 2003 study, Hudson et al. examined the question of how existing pavement management data and construction/materials data can be used to evaluate the performance of new materials and techniques, and to validate new design methods. In the first of two phases, visits were made to five States (Maryland, Indiana, Florida, Arizona, and Washington) to discuss aspects of their PMS's and Superpave materials data, and to examine linkages between materials/construction data and pavement management data. Key findings included:

- Absence of a convenient link between essential data on materials characteristics and PMS performance data. Most often caused by the fact that materials/construction data are (a) commonly stored in flat files, (b) difficult to access, and (c) sometimes incomplete.
- Valid analysis of the performance of any design, material, or technique can only be done when relevant data are available electronically.
- Performance data can only be linked to materials/construction data when use is made of a common locator reference.

Hudson et al. (2003) noted that failure is caused by many factors (e.g., mix composition, mix temperature at time of construction, degree of compaction, actual thickness, subgrade properties, drainage problems, high traffic loads) applicable to the lot where failure occurred. Data are not always complete (e.g., actual thickness is often not recorded) or they are difficult to retrieve. As a result, the failed lot cannot be traced to its materials/construction properties. The current best-case scenario is that performance data are averaged over a mile and are compared with average material/construction property values over that mile. In many cases, the data will only allow such a comparison for the average properties for the entire project. Few records are kept about the exact location of lots or sublots. Thus, it is imperative to have the ability to compare performance and materials/construction characteristics on a lot-by-lot basis.

Easy access to all information required for judging the performance of pavements and materials can only be realized when the following conditions are met:

- All data required to evaluate performance of materials, techniques, etc. have to be available in electronic format.
- All individual performance and materials/construction data should be tied to their exact locations, either in divisions of milepoints or in geographic information system (GIS) coordinates.
- The files with these data should be made accessible to the users in the organization that need such data to work. A convenient way to do this is to run these files on servers with proper protection measures. This concept can be extended with the possibility of loading the required data into a web-based system that can work as a data warehouse, data viewer, or data sorter.

Hudson et al. (2003) recommended that relevant data from the materials/construction database and PMS database be made available and transferred electronically to a performance analysis database. This third database can be made of a commercially available spreadsheet system (e.g., Excel® or Lotus) or a Web-based system that extracts relevant information and makes overviews, graphs, and reports.

Key to linking databases, as shown in figure 3, is to have precise, unambiguous location identification and date/time information. Unambiguous locations can be provided by GPS measurements, but they must be tied to traditional location identification information, such as project number, milepoint, lane, direction, date, etc.

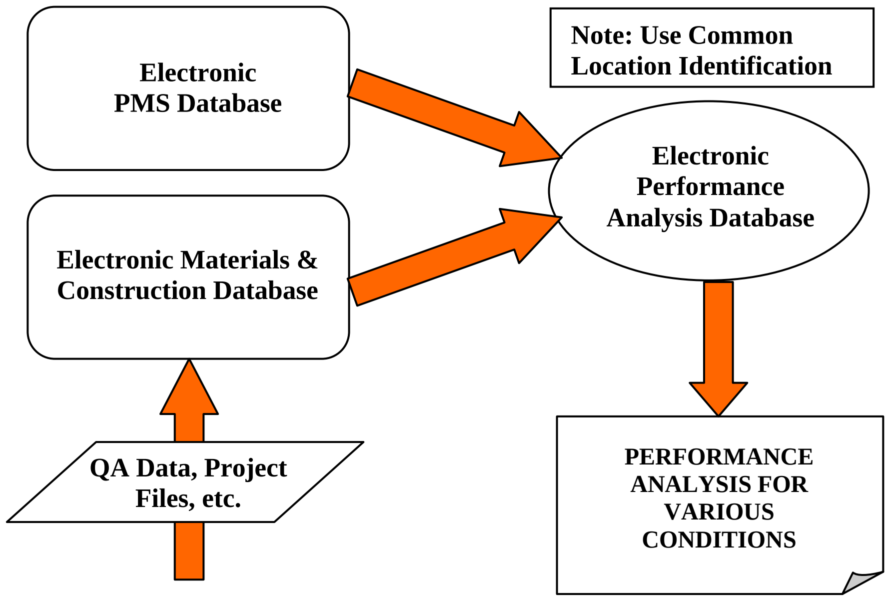


Figure 3. The concept of linking databases (Hudson et al., 2003).

The concept of integrating materials/construction and PMS data was tested in Phase II (nicknamed the Pathfinder study) using seven Superpave projects in Maryland. As a first step in this evaluation, data fields from the QA, pavement design, mix design, and PMS files were identified. The second step involved collecting all the required data for the seven Superpave mixes and entering them into separate electronic databases. The third step involved compiling data into a suitable database for storage, linking, analysis, and reporting, using the *HMA View* Web-based system. The final step involved performing various types of performance analyses.

Results of the Pathfinder study showed that, despite being a cumbersome and time-consuming process, it is possible for a SHA to assemble a database that can be used to evaluate performance of Superpave and other designs, materials, and techniques. It was also learned that there are much more data present in pavement management, pavement design, materials and construction files than are currently used (or accessible) for performance analysis, and that some of the missing information could be collected easily in the future.

A recent study sponsored by the Arizona Department of Transportation (ADOT) resulted in the development of an enhanced PMS designed to help ADOT planners and engineers better develop and execute the 5-year highway construction program (Li et al., 2006). The new system is more comprehensive and more substantially integrated with other ADOT systems, including the construction materials, maintenance activities, and features inventory databases, and the Department's deflection-based overlay thickness design procedure (using data collected with a Falling Weight Deflectometer [FWD]).

The new system was implemented using a Microsoft SQLServer® 2000 database. The database is relational (it uses a commercial relational database management system [RDBMS]), and tables are designed based on functional dependency. The RDBMS allows various types of detailed data, such as inventory, traffic, pavement structure history, maintenance history, and pavement condition data to be recorded on their own segmentation basis. Through relational database design, all the data from various sources are consolidated and logically related by using a common highway ID and location referencing system.

Integration of the FWD-deflection based overlay thickness design procedure makes pavement designers routine users of the new system. Pavement performance is predicted using site-specific modeling with default performance class-based models (used when insufficient data are available for site-specific modeling). A functional module included in the system provides information feedback for evaluating the effectiveness of specific activities in terms of performance and cost for a specific group of sections.

Zhang and Zhou (2002) reported on the implementation of a database and information system for forensic investigation of pavements in Texas. While forensic investigation is a science focusing on the determination of the causes of premature failures, much of the work conducted in this project (and previous related projects [Victorine et al., 1997; Zhang et al., 1999]) centered around the evaluation of existing TxDOT databases and the development of a forensic system (*ForenSys*) capable of accessing important data contained in the other systems. The relevance of this work to construction quality databases is significant in that there's a shared goal of utilizing construction materials and workmanship quality to help diagnose the performance of the as-constructed pavement.

The framework for the *ForenSys* database (figure 4) was first developed in 1998. Completion of a stable and fully implementable system followed in the years thereafter. The newly enhanced and integrated system utilizes the location reference system used in the Department's pavement management information system (PMIS) database (see table 3) and acquires its data from the Layer database (pavement type, layer types, thicknesses, material properties, construction year) and the PMIS database (distress, ride, friction, traffic, highway geometry).

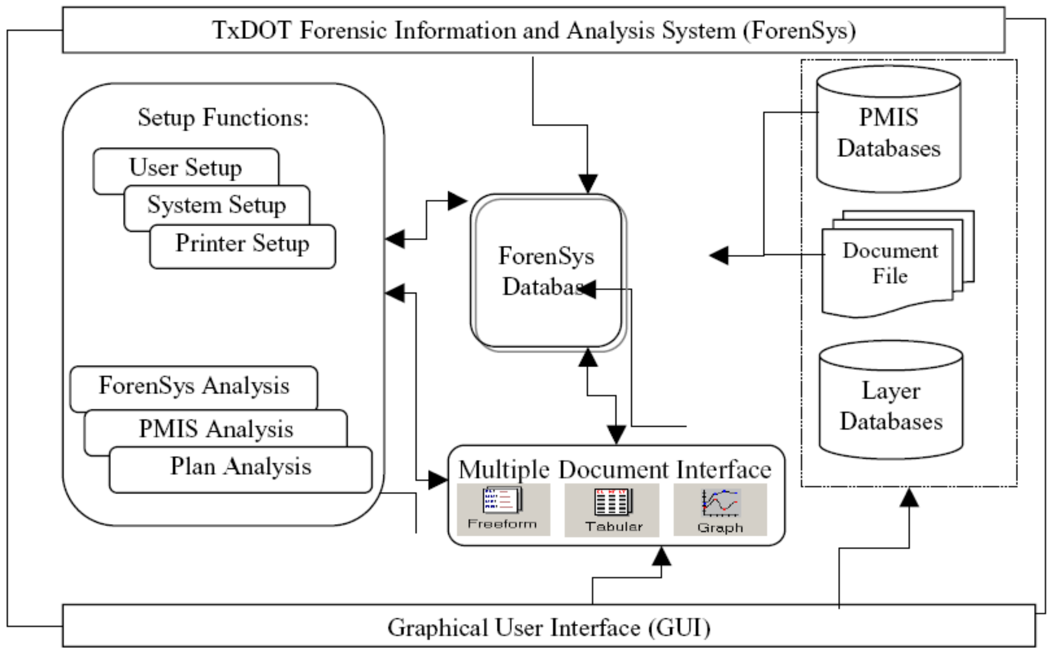


Figure 4. Conceptual framework design for TxDOT *ForenSys* database system (Zhang and Zhou, 2002).

Table 3. Sample location reference data in TxDOT's *ForenSys* database (Zhang and Zhou, 2002).

County Number	Highway, Roadbed ID	Beginning Reference Marker	Beginning Displacement	End Reference Marker	End Displacement
127	BU0067K	0450	0.5	0450	1

The *ForenSys* database software makes the pavement-related data easily accessible to the forensics engineer and provides an interface to easily store, display, and analyze forensic investigation results. Additional system improvements recommended in the report include:

- Supplement relational technology with object-oriented technology to allow the system to handle photographic and other object files, in addition to mere data.
- Upgrade the software from use as a stand-alone system on a single computer to a web-based system easily accessible by authorized forensics personnel.

2.3 SUMMARY

The development and implementation of State construction QA programs in recent years, coupled with the advancements in computer technologies and PRS, has created an environment ripe with opportunities for fully integrated and Web-enabled construction quality databases. This chapter presented many of the quality concepts that have recently been studied and/or put into practice, thereby providing a vision of the future of construction quality databases. This vision is reinforced by the planned and in-progress efforts of others to establish or update current systems to an open, Web-based quality system. The features and capabilities of such a system can be summarized as follows (Benson, 2004; MTO, 2004; ConnDOT, 2006; Mrawira et al., 2002; Harvey, 2000):

- Access by a wide range of agency and non-agency users (e.g., contractors, producers, testing lab personnel, construction engineers and inspectors, researchers, planners) stationed in a variety of locations.
- Real-time use to facilitate timely processing and validation of sample data and test results.
- Various levels of information detail (storage, viewing, and reporting).
- Multiple levels of access security (roles and privileges).
- Secure transactions between users and the quality system.
- Logging and tracking of material samples, related tests, and results.
- Audit information including data entered, who entered the data, who modified the data, and reasons for data revisions.
- Electronic approvals and event notifications.
- Increased data integrity through data capture at the source (including wireless devices).
- Ability to perform rudimentary data analyses and graphing for QC, QA, and IA functions.
- Use of geo-referencing and barcoding technologies.
- Ability to interface/link with other agency systems (e.g., pavement management database, financial/cost accounting system) via fixed location identification indices, time indices, and accounting indices.
- Ability to create ad hoc and pre-defined reports in a variety of formats.
- Functionality for report distribution via e-mail or an approved website.
- Capability for system backups and disaster recovery.

CHAPTER 3. STATE PRACTICES

To expand the knowledge base on the contents and formats of construction quality databases beyond that gained from reviewing published literature, a survey was developed and distributed to several SHAs that were willing to participate. The main goal of the survey was to assimilate information nationwide with regard to collection, storage, and management of various construction quality-related items. The results of the survey helped identify best practices with respect to SHA collection and use of project-generated data to help make construction QA decisions. The findings formed the basis for guidance to be provided to all SHAs to develop the various components of an "ideal" or a model construction quality database.

3.1 SUMMARY OF SURVEY RESULTS

3.1.1 Survey Design and Agency Selection

As mentioned previously, the survey developed in this study was expanded from a 2004 FHWA survey administered to four SHAs; those being Arizona, Kansas, Louisiana, and Pennsylvania. The expanded survey included queries grouped into the following major categories:

- General database related queries.
- QA program management queries.
- QA data collection queries.
- QA process queries.
- Queries regarding database integration.
- Specifications and standards related queries.
- Data analysis queries.

The project team disseminated the survey electronically to key personnel at selected agencies known to have a construction quality database system in place and willing to participate in the survey. These States included Georgia, Minnesota, Washington, New Jersey, Florida, Texas, Oregon, and Maryland.

The personnel whose input was sought during the survey process were those responsible for monitoring construction quality and the collection and use of construction quality data within a given agency. These included State materials and construction engineers, as well as pavement management, design, and research engineers. Also included were agency staffers who are involved in developing, maintaining, or using various other agency databases.

A summary of the agency responses to both the 2004 FHWA survey and the expanded survey performed in this study is presented in the sections below.

3.1.2 General Database-Related Queries and Summary of Agency Responses

Under this category, aspects regarding each agency's database systems were queried, including the number of databases in which construction quality information is stored, data types stored in each database, objectives/purpose of the databases, ownership, data entry duties, data access rights, database platform, database security, extent of project coverage reflected in the database (e.g., all construction projects, warranty projects, design build projects), year in which the database was initiated, linkage with other databases, adequacy of database in meeting agency needs, and other aspects.

The following were the highlights of the agency responses under this category:

- Among the agencies surveyed, the oldest construction quality database appears to be in Louisiana, initiated in 1978 by S.C. Shah. Arizona, Washington, Pennsylvania, and Maryland had databases dating back to the late 1980s or early 1990s. Kansas, Georgia, Minnesota, Florida, and Texas had implemented their systems in the mid- to late 1990s or later.
- Prior to the development of modern construction quality database systems, cumbersome mainframe-based database applications, legacy systems, or paper reports were used to store data. In some instances, there was no central repository to store information.
- Seven of the nine respondents have multiple databases to track construction quality data. Separate databases exist for laboratory testing data, QA data, IA data, etc. Washington and New Jersey reported having a single database.
- A majority of the agencies surveyed have developed their own database systems for construction quality data storage. The *SiteManager* module of the AASHTOWare Trns*port suite of construction management software and the Laboratory Information Management System (LIMS) databases are used by two of the nine responding agencies.
- Six of the seven respondents noted that their database systems are stand-alone. A major drawback perceived by the several survey respondents was the lack of linkage between the construction quality and performance databases.
- As far as types of data stored, project material classification records, daily construction records, test data, and supplier material classification tests are stored in the databases. Pavement performance information is not stored by any of the agencies surveyed, and instead stored in an independent PMS. However, there seems to be no automated method to link performance with construction quality information, although one agency indicated that performance data can be linked with quality data with considerable effort. The main difficulty in establishing a connection between these construction quality and performance databases is due to the different referencing schemes by these databases.
- The main uses of the database were to allow (1) document tracking through the life cycle of the project, and (2) store acceptance and assurance testing results for asphalt concrete (AC), PCC, and soils. Some agencies report use of the data to perform analyses for management and engineering purposes. However, a majority of the agencies would like a broader use of the data (e.g., to perform materials and performance correlations, improve acceptance procedures, update specifications). For example, Arizona is implementing the "ADOT Information Data Warehouse" to utilize their construction QA database, *Field Office Automation System* (*FAST*), for ad-hoc reporting.
- SHA field offices responsible for QA are responsible for entering acceptance testing data into the database in a majority of the agencies surveyed. In some cases, this is the project residency personnel or project engineer. In one agency, all data entry is done by Central Office personnel. Contractor access to the database to enter QC data is not very common;

however, one agency responded that this is possible in their system for design-build projects. SHA materials lab personnel enter the materials testing and mix design data.
- Mostly construction or materials offices within the agencies surveyed own complete rights to the quality databases.
- In nearly all agencies surveyed, access to the database is controlled by hierarchically set login passwords. Access varies by the roles and responsibilities of each individual or division within the agency. Basically, all personnel who need to access a database can access it, including technicians, supervisors, engineers, and contractors. In many agencies, access is restricted to agency personnel only (i.e., contractors or other outside personnel do not have access).
- Nine of 10 survey respondents noted that either most or all conventional construction projects undertaken are represented in their respective construction quality database. Only Minnesota reported that the database is used strictly for design-build projects only.
- Three of the six respondents stated that some segment of the database (test data) is updated on a real-time basis. The others update as needed or at periodic intervals.
- Six of seven respondents stated that while their individual databases may be addressing current needs, improvements are needed to provide (1) a more efficient and comprehensive system (2) a system that is more user-friendly (3) a system that can be linked to other databases, and (4) a system that allows more efficient analysis and reporting.

3.1.3 QA Program Management Queries and Summary of Agency Responses

Under this category, the roles and responsibilities of the various individuals involved in the agency's QA program were queried. Offices and personnel involved with QA data oversight, upload, and storage within each agency were determined, and the nature and administration of IA programs was synthesized. Finally, written procedures, manuals, and documents related to the QA program and its management were collected.

The following were the highlights of the agency responses under this category:

- In most agencies, the responsibility for management and oversight of the QA program lies with either the construction (project field offices) or the materials divisions (laboratories), which are also the owners of their respective segments of the QA databases.
- In agencies that have implemented agency-wide, client-server based QA database systems, the central office has electronic access to the data entered by field offices. This appears to be the case in eight of the nine agencies that responded to the survey question. One agency that did not appear to have such a feature implemented at the time of the survey, reported communicating project information to the central office via hardcopy reports (flat files).
- IA programs are handled by the SHA. All responding agencies indicated that no external agencies or consultants are involved in this process. Most agencies surveyed also do not use contractor QC results for acceptance decisions; agencies perform their own acceptance testing or supplement QC results with independent verifications. The procedures sometimes vary for asphalt versus concrete pavement construction projects.

- QA specifications are most frequently used for testing HMA materials. However, the acceptance of concrete, unbound materials, and earthwork materials varies. For these, some use method specifications or run a verification program.

3.1.4 QA Data Collection Queries and Summary of Agency Responses

The parties responsible for collection of data for the applicable testing, and the respective tools used to collect the data were queried in this category. The types of test data contained in the database (e.g., contractor QC, agency validation, IA) and how they are aggregated and referenced in the database were also determined. In addition, it was also ascertained if other pertinent materials- and construction-related project information (e.g., mix design, inspector notes) and other relevant data (e.g., plant, equipment, contractor, weather, stationing or mileposts) could be stored in the databases.

The following were the highlights of the agency responses under this category:

- Most often, data from the plant, field, or testing laboratories are collected using standard forms or datasheets. Data entry is either electronic or manual. Electronically collected data are directly uploaded from the field offices to the central QA database. Manually completed forms and spreadsheets are sent into data entry stations at the field offices or central labs via faxes, emails, or hardcopies to be entered into the electronic databases.
- All agencies surveyed have a clear set of instructions to ensure uniformity in the data collection practices. Some database applications provide online help to guide the users.
- Four of the eight responding agencies stated that hand-held devices are used to collect a portion of the QA data. For example, Arizona's *FAST* system supports pen-based data entry, where field technicians/inspectors can create test header cards and input test data for later download to the database. Georgia's Weekly Concrete Report has been automated to several hand-held devices. The reports are then downloaded to an Excel® spreadsheet or a Microsoft Access® database. Two agencies that use AASHTO's *SiteManager* software also use a hand-held electronic data entry tool.
- The QA databases of a majority of the agencies responding (seven of nine) allow test results from an IA unit outside the agency or a unit within the agency with no ties to construction to input data into the database.
- Examples of QA data stored in the database for asphalt materials include mix design, binder information, air voids, and densities. Strength and thickness are very commonly stored for concrete materials. Pavement smoothness after construction is also stored for both asphalt and concrete pavements. Other data items that are recorded in the database systems of most agencies (7 of 10) are contractor, plant, weather, distance from plant, hours of paving, type of curing (for PCC pavements), beginning and ending mileposts, course/lift, station, distance from center line, and opening to traffic. These data may not be readily queried, but can be found in log books, inspector notes, etc.
- All agencies surveyed sort and store the QA data by (1) project (2) lot, and (3) date/day of construction. Georgia stated that the data are also arranged by milepost or reference marker. Only two of the nine agencies surveyed stated that the data are also organized by time of construction, sampling, and testing.

- All agencies surveyed indicated that they record individual test results. When replicate testing is performed (e.g., compressive strength cylinder breaks), most agencies record information from each test. When tests are repeated (e.g., referee tests), these data are maintained in the database by most agencies surveyed using appropriate remarks.
- In a majority of the agencies surveyed, the test procedure used is identified along with the party responsible for sampling and testing (e.g., contractor, agency).
- On the question of whether their QA database systems accept contractor QC test results as well as agency's verification test results, 50 percent responded in the affirmative and the remainder in the negative. However, Washington indicated that they are in the process of implementing a new system that will allow outside input into the database.
- A majority of the responding agencies (six of eight) reported that control strip information is not typically recorded with the QA data. However, it appears that the database systems generally support uploading such data into the system. Kansas reports that some test strip information is stored at the District level. Texas reports recording test strip information for asphalt paving (which basically is the first day’s production).

3.1.5 QA Process Queries and Summary of Agency Responses

The focus in this part of the survey was to gather information on the processes used by the agency to control quality on a construction project (statistical control charts, run charts, etc.) and procedures used in acceptance testing (percent within limits [PWL], percent defective [PD], etc.).

The following were the highlights of the agency responses under this category:

- Agencies stated that the type of QC exercised is a function of the material type. For asphalt materials, four of the seven responding agencies stated that statistical control charts are used for QC.
- Control charts are not included in the *SiteManager* software used by some agencies. One agency stated that contractor option is used to exercise QC.
- Five of the eight responding agencies state that PWL specs are used for acceptance testing. Other acceptance testing approaches, such as absolute average deviation (AAD) and lot averages, are used by other responding agencies. Averages of test results are used for acceptance of asphalt and concrete pavement surfaces based on smoothness criteria.
- End-product HMA criteria used for PWL specifications include asphalt content, effective air voids, compaction/density, and smoothness. For PCC, compressive strength and thickness are commonly used.
- In Minnesota, where the QA database system is solely populated with design-build projects at this time, the incentive/disincentive payments for concrete paving are based on:
    - Aggregate Quality—statistical acceptance based on averages and variances for entire production (based on agency results).
    - Concrete Mix Quality—based on average daily results of water/cementitious materials ratio by a lot basis (minimum of 3 tests in a lot). Moistures and Microwave Oven testing are performed by the agency.
    - Combined Aggregate Gradation Quality—based on the 8-18 chart to test for well-graded aggregates. Average results on certain set of sieves using the percent retained

by a lot basis (minimum of three tests in a lot). Payment based on contractor results as verified by the agency testing.

- In Arizona, aggregate properties (sand equivalency, fractured coarse particles, uncompacted voids, gradation) and material spread are used as additional measures to monitor quality of the HMA end product and percent cracked slabs for PCC end product.

3.1.6 Database Integration Queries and Summary of Agency Responses

Under this category, the project team asked about any existing integration of the construction quality database with other databases (design, construction plans, maintenance, pavement management, etc.).

The following were the highlights of the agency responses under this category:

- Overall, it was found that most agencies do not have an easy facility to link QA information with other agency databases such as design, construction plans, traffic, maintenance, condition surveys, and accident history information. All these databases exist separately and are owned by different units within the SHA. However, some agencies have indicated that this information can be linked if requested.
- About half the responding agencies indicate that project cost information is linked to construction QA data on a project-by-project basis.

3.1.7 Specifications and Standards Related Queries and Summary of Agency Responses

Queried under this category were the types of specifications used within an agency (conventional QA, PRS, warranties, etc.), checks and balances in the construction process triggered by QA database, data used for setting performance standards on warranty projects, and pay factor calculation methodologies and basis. Of particular interest was the type of information that is stored and its uses, particularly in relation to the development of QA specifications and the subsequent evaluations of how the specifications are working.

The following were the highlights of the agency responses under this category:

- A majority of the responding agencies (five of seven) stated that they use conventional QA specifications (QC by contractor and acceptance by agency) for their projects.
- PRS are not used at this point by any of the agencies surveyed. However, Texas and Georgia have specifications for wheel tracking tests to evaluate asphalt mixture susceptibility to permanent deformation or rutting. Also, Texas noted that most of the agency's specifications are evolving into PRS.
- Three of the five responding agencies stated that specification non-conformance is highlighted by their current QA system. In this event, construction can be suspended at the discretion of the engineer and based on warnings issued to the contractor or the frequency of problem recurrence. It is not clear if this possibility is put into practice based on the survey.
- It was found that specifications or special provisions governing construction are not always part of the QA database.

- In a majority of the cases, agency test results are used to validate contractor-performed testing.
- Of the agencies that validate contractor test results, only Kansas makes the validation test statistics (e.g., *F*-test and *t*-tests) available as part of the QA database.
- Referee testing is an option available in most specifications.
- Calculated and/or applied pay adjustments are available in most agency databases on a lot-by-lot basis. Pay factors are calculated if actual specifications govern. Otherwise, they are applied.
- Some of the agencies surveyed state that specification tolerances and pay factors are derived based on historical data.
- Warranty-type projects are not common in many of the agencies surveyed. Only Minnesota, Florida, and Washington indicated that they have done some warranty type projects. All design-build projects in Minnesota and Washington are built to warranty specifications. The types of warranties range from materials and workmanship (more common) to more comprehensive performance warranties. Both new and rehabilitated asphalt and concrete pavements have been subject to warranty specifications.
- On a majority of the projects, warranties last from 2 to 5 years. Florida has some projects that are under 10-year warranties.
- Most agencies that use warranties use pavement structural and functional distresses during the warranty period as the choice performance measure. Historical data appear to have been used to set performance goals on these projects.
- QA data from warranty projects are part of the QA databases of agencies that use this type of contracting.

3.1.8 Data Analysis Queries and Summary of Agency Responses

Covered under this category of queries were the types of data analysis supported by the databases and the amenability of the database to perform a variety of engineering analyses and provide valuable feedback to agency on issues such as quality improvements, design, specification revision, pavement management, and research. The focus was on the States' collection and analysis of test results and of other descriptive materials and construction information for both asphalt and concrete paving projects.

The following were the highlights of the agency responses under this category:

- Target audience for data analysis appears to be SHA personnel at construction, materials, and pavement management offices as well as FHWA staff in some cases. These include project resident engineers, upper management, project personnel, materials staff, and specification committee members.
- Uses of the data include (1) settling testing disputes on projects, (2) evaluating work done by contractors in various districts of the agency, (3) monitoring trends with time and different pavement materials, and to (4) monitoring performance. However, agencies did report that data analysis was cumbersome and that more analysis can be performed if the data interfacing was more user-friendly.

- Most agencies state that representative project or lot statistical parameters can be determined for QA (e.g., mean and variability, PWL). However, data analysis is time-intensive at this point due to inability to generate ad hoc reports.
  - Project or lot statistical parameters are used mostly to pay the contractor. However, these statistics are also used in some of the agencies to monitor and refine QA programs and for research purposes.
  - The parameters are also used in developing new specifications or validating and revising existing specifications in three of the seven responding agencies, sometimes in one agency, and not used at all in the remainder of the agencies.
- A majority of the responding agencies state that their QA data can be analyzed on a project-by-project basis to determine whether quality is improving or to check design assumptions. However, such analyses are not commonly performed because of their difficulty, and because there is a lack of easy integration with other databases (e.g., PMS).
- A majority of the surveyed agencies suggested that the data cannot be used to develop performance prediction models due to the inappropriate linkage with other databases. Only two of the eight agencies surveyed suggest that this is being currently done.
- A majority of the responding agencies suggest that the data in the QA database systems can be analyzed to assess contractor performance (e.g., comparing contractor QC data with verification data). This appears to be of interest to agencies and they routinely perform this analysis on individual projects despite significant problems with data integration.
- Other types of analyses that are routinely performed include computing overall incentive/disincentive on a project-by-project basis, overall maximum pay adjustment, etc. Arizona reports that their yet-to-be-released Information Data Warehouse system has ad hoc reporting capabilities. This allows data to be custom-queried and extracted quickly so the user can now perform analyses of materials characteristics that, in the past, were very difficult to perform. This will likely pave the way for more in-depth engineering analysis of QA data to improve existing specifications, practices, and quality of pavement structures.
- It also appears that a lack of dedicated positions within an agency to perform data analysis limits the amount of analysis that can be done.
- None of the agencies surveyed appears to have performed a cost-benefit analysis of maintaining a high-quality QA database system. As a result, the potential benefits of such systems may not be fully realized.

3.2 DETAILED INVESTIGATIONS (BY STATE)

3.2.1 Introduction

In addition to electronic solicitation of information, detailed telephone and on-site interviews were conducted with staff from a few selected agencies. These reviews focused on gathering additional details regarding the database architectures, data types in the databases, data collection procedures, acceptance procedures, data analyses models, and desired features and expected changes in databases. The goal of this exercise was to use the information gathered to establish best practices for each of these aspects of the prototype QA database system that will emerge from this research.

In shortlisting candidate agencies to conduct in-depth interviews, the project team attempted to capture the depth and breadth of nationwide practices with regard to storing and using construction quality data. Based on this criterion, the project team selected Arizona, Georgia, Washington, and Texas to conduct further in-depth reviews of various aspects of their construction quality database systems. A detailed telephone interview was conducted with Arizona personnel, and on-site interviews were conducted with staff from the remainder of the agencies. The information obtained from these interviews is summarized in this section.

3.2.2 In-depth Review of ADOT Construction Quality Database Systems

Philosophy of Quality in Highway Construction at ADOT

ADOT uses a two-pronged approach to ensure highway construction quality. Their materials QA program, established in accordance with Title 23, Part 637, Code of Federal Regulations, (FHWA, 1995), is intended to ensure that all materials incorporated into ADOT projects satisfy specification requirements. The program embodies a traditional approach to QA, with the contractor responsible for QC testing, and the Department responsible for acceptance and IA testing. An incentive/disincentive program is employed to reward/penalize contractors based on key HMA and PCC materials and construction properties.

ADOT's construction workmanship program utilizes a comprehensive inspection checklist to monitor conformity of construction products and processes to standard specifications and drawings. The quantified checklists utilize the method of attributes (i.e., pass/fail, yes/no) to allow quick and inexpensive checks on thousands of individual requirements not covered by material tests. Incentives are used on design-build projects, with incentive payments based on the number of reworks.

The Department's materials QA program is administered by the QA Section of the Materials Group, while the construction workmanship program is managed by the Construction Operations Section of the Construction Group.

Database Architecture

Two databases are used in storing and accessing data for the materials QA program: the *Central Materials Testing Program* (*CMTP*) and the *FAST*. The *CMTP* is used to enter, calculate, track, and report on the various samples and testing methods used in the central office lab (Wiechman, 2005). The major testing areas included in the program are soils and aggregate, AC mix design, and asphalt binder material testing. The *FAST* system handles remaining acceptance data obtained in labs other than the central office lab. Types of data captured in *FAST* are sampling and testing information for soils and aggregate, AC, and PCC.

The construction workmanship program utilizes a Web-based, SQL database system to store and access checklist data that cover all major specification sections and many standard drawings.

Like the *FAST* and *CMTP* systems, the *Construction Operations Checklist Application* (*COCA*) also resides on the Department network.

Construction Quality Related Systems

A summary of the three database systems used by ADOT to monitor and report on construction quality is presented below:

- *FAST*—Implemented in 1993 and since modified on various occasions, *FAST* can be used by field and lab personnel responsible for sampling and testing soils and aggregate and AC and PCC materials associated with most ADOT projects. The *FAST* database is a Microsoft SQL Server 2000® system. It accepts both acceptance and IA data. The data can be categorized by project, material type, lot, and individual test numbers. Both individual test results and averages are accepted by the system, as well as the results of repeated tests. *FAST* is client-server based, with varying levels of access afforded to individual (i.e., technicians, supervisors, engineers, administrators) and group users (different labs). Data entry for the system is based on hard cards, and the system supports a pen-based data notebook, where field technicians/inspectors can create test header cards and input test data for later download. Data analysis is primarily available on project-by-project basis, with PWL, averaging, and other techniques used in determining acceptance and calculating pay factors. The system has some interactivity capabilities with *CMTP* and ADOT's *Advantage* financial system. However, linkages with other databases, such as the pavement management and traffic databases, are limited due to different referencing systems (i.e., stations versus mileposts).
- *CMTP*—The *CMTP* is a relational database which can be used by field and lab personnel for AC mix designs, as well as sampling and testing of soils, aggregates, and asphalt binder. Although not as comprehensive as the *FAST* system, *CMTP* has several of the same features as *FAST*, is reportedly more efficient and easier to use, and has good ad-hoc reporting capabilities. Like the *FAST* system, *CMTP* can interact with the *Advantage* financial system, but is limited in linkages with other databases.
- *COCA*—First implemented in 1994, a third-generation version of *COCA* is currently being implemented. The program operates off an SQL platform in a client-server environment, but off-line usage for data entry is an option. Data are entered by construction personnel using portable computers or via downloads from laptops. Standard checklist forms are embedded within the program for data entry, with inspection results capable of being added by project and lot (one checklist typically represents 1 lot). Data are not directly compatible with other agency systems.

Data Input and Analysis

Many different quality characteristics are evaluated in the materials QA program. QC data include sand equivalency, fractured coarse particles, and uncompacted voids for aggregates used in end-product AC mixes; effective voids, gradation, and asphalt content for end-product AC mixes; and edge slump for PCC. Acceptance of AC and PCC materials is based on the following quality characteristics and quality measures:

AC

- Asphalt content and gradation: disincentive pay factors based on PWL.
- Effective voids: incentive/disincentive pay factors based on PWL.
- Material spread (i.e., thickness): average variance from required thickness, as determined by actual versus theoretical tonnages.
- Compaction/density: incentive/disincentive pay factors based on PWL.
- Smoothness: incentive/disincentive pay factors based on IRI and pay factor equation.

PCC

- Compressive strength (28-day): incentive/disincentive pay factors based on PWL.
- Thickness: incentive/disincentive pay factors based on PWL.
- Smoothness: incentive/disincentive pay factors based on profile index with a 5-mm (0.2-in) blanking band ($PI_{5.0}$).

It should be noted that input of end-product PCC data into *FAST* is not currently available.

Beyond analyses for QC, acceptance, and IA functions, the types of analysis performed by ADOT using *FAST*/*CMTP* data pertain to evaluating the performance of various materials and techniques. Such evaluations, however, require that data from the PMS and other databases be extracted and properly matched with the construction quality data, which is not an easy task.

In addition to assessing contractor's/subcontractor's conformance to specifications (and determining incentive payments on design-build projects), analysis of *COCA* data can be done to examine Departmental performance, inspection management applications, and specification requirements.

Future Directions

The *FAST* system is reported as being fairly comprehensive, yet somewhat difficult to use. In particular, the ability to extract data on a global basis and to perform ad-hoc reporting is limited. An effort is currently underway within ADOT to improve the *FAST* system in these and other areas (e.g., input of end-product PCC data). Some aspects of the *CMTP* system, such as the interfaces and ad-hoc reporting capabilities, are being considered in the update. Also, ways of linking *FAST*/*CMTP* and other databases are being contemplated.

The construction workmanship program is expected to be further expanded and used in the future, quite likely to the point of forcing resident engineers to learn it by a certain time period. The *COCA* system is currently being upgraded, primarily in the reporting capabilities area.

3.2.3 In-depth Review of GDOT Construction Quality Database Systems

Philosophy of Quality in Highway Construction at GDOT

GDOT places a lot of emphasis on ensuring quality even before the materials are constructed in the field. GDOT has in place a certification management system to ensure that their technicians are qualified and asphalt plants (for example) are rated based on the quality they produce (assessed from QC records). GDOT also pre-qualifies material suppliers and producers and uses accredited laboratories. This QA system could potentially reduce the cost and effort required to ensure quality during construction.

Database Architecture

The Office of Materials and Research (OMR) at GDOT manages and operates several database systems and applications related to materials and construction quality. Each department within OMR has specific functions with regard to QC with little or no overlap in their day-to-day activities. This is partly the reason why their database systems have developed independently and currently do not interact.

The level at which OMR systems are automated across its functional areas is heavily geared toward sample testing and data storage. The least amount of automation is in test results distribution. As such, a large portion of the systems in place focus on the management of samples, testing of samples, and printing of test results. Table 4 shows the distribution of information technology (IT) systems by platform (Access®, Excel®, etc.) across the four key business areas.

Table 4. Distribution of systems across functional areas at GDOT OMR.

Functional Area	Access® SQL	Excel®	Computer Application	VAX	Word® or Paper-based	Total
Certification Management	6	1	1	1	2	11
Equipment Management	0	2	0	1	0	3
Investigations	8	7	12	2	5	34
Sample Management	6	11	0	2	12	31
Total	**20**	**21**	**13**	**6**	**19**	**79**

Construction Quality-Related Systems

A summary of the systems currently used to collect and store testing data related to construction quality is presented below:

- *Field Data Collection System* (*FDCS*)—Used by test engineers in the field and producer QC technicians to collect various information regarding soil, concrete, asphalt, raw materials, fences, and other OMR-certified materials. It is a collection of data entry forms for different GDOT specifications. The system has two main functions: a field-deployable portion that field engineers use to capture data and test results, and a centralized portion that is used by the OMR staff in Atlanta to aggregate test results across the State into a single location for use in reporting and analysis. Both parts of the application are based on an Access® 97 platform that has been highly customized with external Visual Basic® 6 application extensions. *FDCS* is used by several branches (Concrete Services, IA, Pit and Quarry, Inspection Services, Testing Management). Data are stored in an Access® database. It can be used to calculate pay factors based on test result data and plant ratings. The program can operate as a stand-alone application or within a server-client environment.

- *PhysChem*—Stores and maintains laboratory test result data in an Access® database for 24 materials test types performed by the Physical and Chemical Testing Branch, including reference data for approved sources and material codes.
- Concrete 319—This form is basically a paper report containing results of tests performed on concrete cylinders. The application that yields the data required for these reports is called *Concrete Cylinder Test Reports*. This application is mainframe-based.
- Pavement Testing—This database is an incomplete application which is currently used exclusively for storing results from roadway tests (smoothness) in order to generate reports required by the FHWA. This application was built using Access® and was anticipated to address more test areas than it is currently being used for. Once the application is completed, it is anticipated to include all the functionality currently offered by the old VAX systems and spreadsheets. The Access® application uses a SQL Server database.

Future Directions

GDOT has embarked on the path of developing a customizable software product, Materials Information Management System (MIMS), to improve the efficiency, accuracy, and integration of laboratory and field test samples tracking and reporting. Figure 5 presents line diagrams detailing how the various database systems within the GDOT will interact with MIMS. The software and associated databases will be centrally located and accessible by users throughout the State; access will be through an internet/intranet environment to provide a larger base of accessibility in remote locations. The improvements to current systems involve automating various OMR processes via interactions with shared databases and selected testing equipment. MIMS data will be used to support QA activities that include statistical analysis of material test results. MIMS will have the ability to securely upload or import QC test data from external sources (e.g., vendors, contractors, consultants).

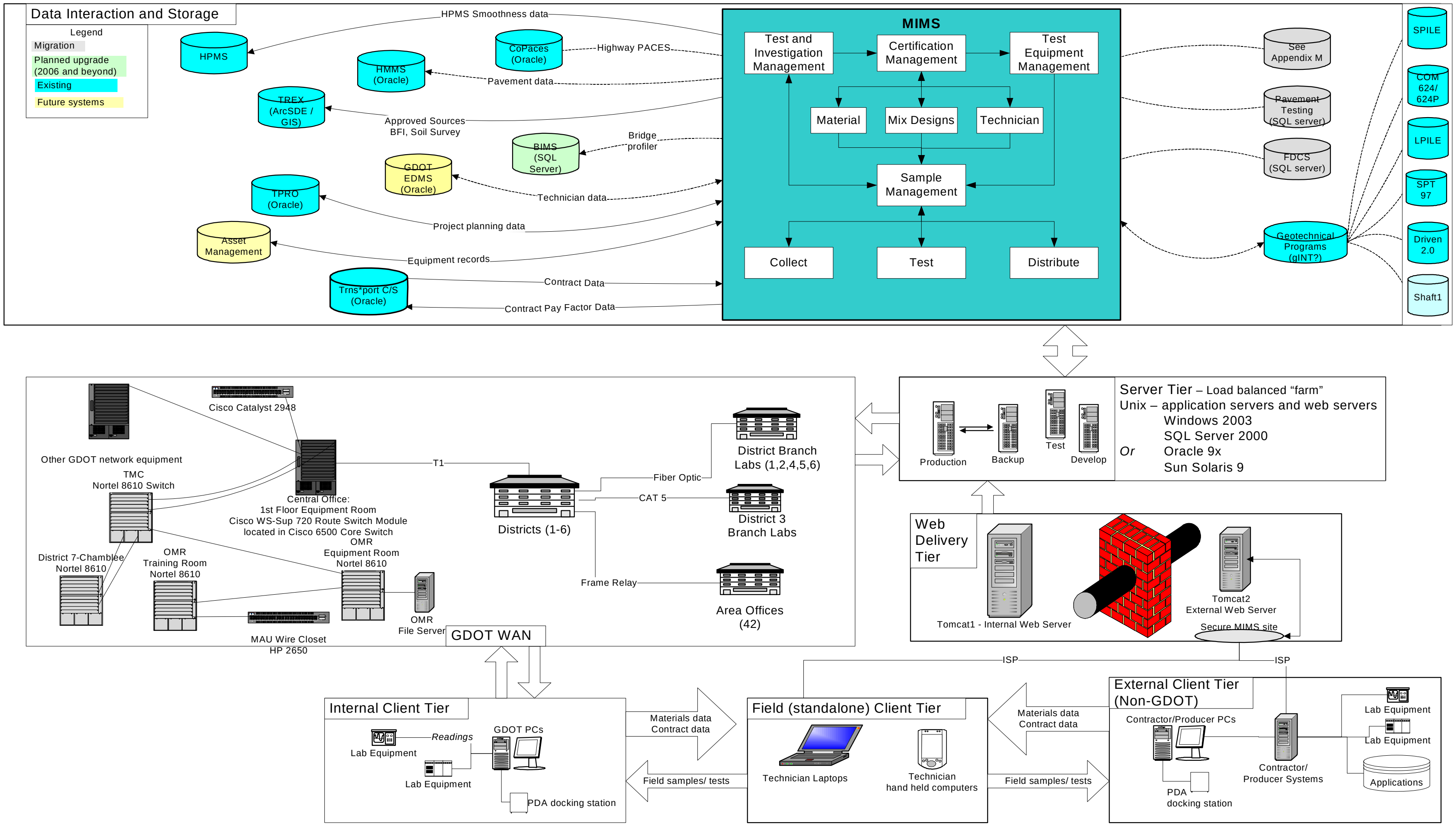


Figure 5. Conceptual sketch of GDOT's planned integrated database systems (courtesy GDOT).

A key success factor is the ability to track the progression of samples from collection, receipt, and testing through the reporting of test results to GDOT personnel. Test data may be collected in the laboratory or at the construction or plant sites with portable devices (e.g., laptop or Personal Digital Assistant [PDA]) and then transferred to the central database. Construction project-based information will be used by the Materials Audit process for issuance of the Materials Certificate. The ability to interact with the AASHTOWare Trans*port's *Contracts Administration Module* (*CAS*), of which GDOT is a licensee, is desired.

Overall, it appears that GDOT has in place a number of database and software systems created independently to serve specific functions for the different department groupings within the OMR. The primary shortcoming of the current system is that these databases are not integrated, although efforts to address this are underway with the development of the MIMS system. The MIMS system is structured to address construction quality—emphasis is placed on ensuring quality through certification of technicians and material producers.

Construction QA is addressed within MIMS. This information is used not only to flag non-conformance but also to calculate pay factors and quality ratings for material producers (e.g., asphalt plants). A concern expressed by GDOT is that currently no link is in place to relate material information collected as part of the QA process with performance information (e.g., rutting, cracking, roughness, friction). There is a great of deal of interest in doing such linking. It is also not clear if this will be addressed by MIMS.

3.2.4 In-depth Review of TxDOT Construction Quality Database Systems

Philosophy of Quality in Highway Construction at TxDOT

Traditionally, TxDOT's construction quality-related materials testing programs included direct sampling and testing of the work performed by the contractor on-site at the project or at a supplier's plant for control of the construction job. The emphasis is now changing to sampling and testing done by the supplier or contractor, and sampling and testing by TxDOT for verification purposes. TxDOT is moving its efforts to monitoring techniques and programs where particular material suppliers go through a certification process that is periodically updated, independent of a particular construction project.

Construction Quality-Related Systems

TxDOT uses multiple databases to store and access information with regard to construction quality. Descriptions of the various databases are provided below:

- AASHTOWare Trns*prt *SiteManager*—This client/server application is the main database for all construction quality-related data used by TxDOT. *SiteManager* was implemented as a pilot project in 1999 in two districts. Based on the success of that test, the program became fully operational in 2003. Information and data from all construction projects go into *SiteManager*, including testing data, daily reports, payment quantities, change orders, bid items, mix design records, and construction diaries. All project information that is input into *SiteManager* has a Control Section Job (CSJ) number.

Without the CSJ number, information cannot be tracked or extracted from the database. Access to the database is set up at 20 different levels within TxDOT. Each level can access certain portions of the database that affect their operations. Data are entered into *SiteManager* by field construction personnel. The Construction Division owns this database, and the Information Systems Division maintains it.

- Calibration Manager—This database is used to track the calibration of all test equipment in terms of certification for the AASHTO Material Reference Laboratory (AMRL), the Cement and Concrete Reference Laboratory (CCRL), etc. This database is not linked to *SiteManager*. This database is used by all districts.
- Proficiency Database—This database is used to track the certification for all personnel. It is tied to *SiteManager* in terms of personnel that are authorized to complete tests for construction projects.
- LIMS—This database is used by the materials group. All materials test data goes into this database. It is a stand-alone database and not linked to *SiteManager*.
- Letting Database—This database is for general information and data on construction projects. The letting database was used on a research project, which is still on-going, to track and evaluate Superpave mixtures.

Data Input and Analysis

The *SiteManager* database contains detailed information and data on each construction project. It includes QC, acceptance, and IA data. Data are aggregated by project (CSJ) number, lot number, and by day. Individual test data, including replicate and referee testing data, are entered into the database. HMA materials require control charts; however, these are not entered into the database. Data are collected using paper forms or hand-held portable pen-based devices. Laboratory materials data are collected on spreadsheets for the LIMS database.

The data are used to calculate means, variances, pay factors, etc., on a lot or project basis. The data can also be used for forensic studies. However, the data analysis beyond contractor payment-related calculations is limited at the present time because of the labor-intensive nature of data extraction and linkage with other performance and materials databases.

Future Directions

Overall, it appears that *SiteManager* is meeting the needs of the TxDOT in terms of what it was originally developed to do (i.e., serve as a contract management tool). Some of the perceived shortcomings of *SiteManager* are (1) it is not user-friendly, (2) it takes a lot of time and resources (e.g., high-speed Internet access) to enter and use the database, and (3) it is not linked to other agency databases, such as the PMS and materials databases. This limits the usefulness of the data included in *SiteManager*. There are plans to consider linking all of these databases; however, it may take several years before this goal is realized.

3.2.5 In-depth Review of FDOT Construction Quality Database Systems

Philosophy of Quality in Highway Construction at FDOT

FDOT's State Materials and Construction offices are involved with ensuring that the materials used in transportation construction projects meet the required specifications and are built in accordance with departmental standards. Specifically, the Quality Systems section is responsible for providing the methods and measures for QA in testing, inspection, and evaluation provided by the State Materials Office (SMO). This section also provides support for the Office of Construction, other units of the SMO, and District Materials Offices in assuring the quality of materials incorporated into the department's projects.

FDOT has an active IA program, departmental and private sector laboratory qualification program to certify testing laboratories, a materials acceptance program to certify material sources and products, and a producer certification program. Extensive checklists exist for QC of various construction materials and guide list for the construction of various work items. In other words, a lot of emphasis is placed in pre-construction quality and to ensure uniform and standard practices during construction across the department. FDOT makes extensive use of design-build contracting on construction projects and warranty specifications. A total of 184 HMA projects and 7 PCC projects have been constructed to date under warranties that extend from 3 to 10 years.

Construction Quality Related Systems

The database systems used by FDOT to store and access information with regard to construction quality are:

- AASHTOWare Trans*port *SiteManager*—This database was implemented in 1996 and covers contract administration processes after the contracts are awarded. It is implemented on an Oracle® platform and currently has 1,100 to 1,300 users statewide. Access is password protected and applications to access are available through a Metaframe server which can be reached by local area network (LAN) or virtual private network (VPN).
- Electronic Document Management System (EDMS)—EDMS is a two-part system—construction document management system (CDMS) and Materials Document Management System (MDMS). MDMS is currently under development. EDMS, along with *SiteManager*, is managed by the State Construction Office.
- LIMS—This database is used by the State Materials Office. It covers all materials processes, including testing, laboratory qualifications, producer qualifications, qualified products, technician qualifications as used in sampling and testing, final project material certification, and the IA program. LIMS gets information from Trns*port and will also interact with MDMS when it is fully implemented. Access to LIMS is password protected and it too has between 1,100 and 1,300 users statewide.

The purpose of the construction quality databases is to track performance, project acceptance, specification update, pay item update, and to provide efficient data collection (automation), and effective information generation (reporting).

Data Input and Analysis

The quality databases include a data side and a document side. On the data side, various forms of data collection are used (e.g., spreadsheets, paper forms, emails, faxes). Construction inspectors and technicians use hand-held portable devices in conjunction with *SiteManager* for automated data entry for testing. The LIMS database has been customized by FDOT and allows independent QA test results, contractor QC results, agency's validation test results, and project acceptance test results. Data are grouped by project number, contract number, road number, and pay item number.

Examples of types of data stored for the various materials includes:

- HMA—Air voids, binder content, gradation information at the plant. Density and smoothness on the roadway. Pay factor information for all quality characteristics as well as composite pay factor by lot (smoothness does not have a pay factor). Acceptance of asphalt materials is based on PWL specifications.
- PCC—Compressive strength, core thickness, permeability/durability, cement content and composition, and temperature at the time of placement. Acceptance of PCC materials on the roadway is based on pass/fail criteria.
- Unbound materials—Density, Limerock Bearing Ratio (LBR), and thickness.

The types of analysis performed by FDOT using the data pertain to evaluating contractor performance on projects, performance of various programs and processes, performance of labs, performance trends of various materials, etc.

Future Directions

FDOT staff cited many difficulties in performing data analysis. As one staff member summed up the situation, the database is "data rich and information poor." For example, it is very difficult to connect a low pay factor section in the database with a field lot because HMA mix is measured at plant and may be put down in different places during construction. The lack of dedicated staff to perform data analysis was cited as another factor that leads to lack of analysis. However, FDOT has a great interest to test the right thing in the right way and in the right quantity. Department staff expressed a great deal of interest in improving performance from a materials point of view and recognized that the current systems do not often lend themselves to "closing the loop" on showing improved performance when changes are made to specifications, pay factors, testing, etc. FDOT has dedicated staff to generate reports and work with database issues. In the event performance analysis is to be performed, pavement management staff will have to coordinate with the staff familiar with the database.

Some of the issues that prevent effective data analysis are centered on the lack of a common referencing scheme. FDOT is actively working on this issue. A few options that are being looked into are developing a GIS for data storage and retrieval and the adoption of Extensible Markup Language (XML) schema for transportation applications in a framework to be called TransXML. Both these activities are in development at this time.

3.2.6 In-depth Review of WSDOT Construction Quality Database Systems

Philosophy of Quality in Highway Construction at WSDOT

WSDOT's State Materials Office is responsible for the management and oversight of the QA program within the State. This office has maintained a very efficient system. The State subscribes to the philosophy that "QC always costs less than removing and replacing," and ensures that its specifications are met and quality materials used and quality construction is achieved in all department projects. The district offices and project residency are actively involved in the QA program. The Regional Project Engineer is responsible for the collection of data and data storage, and each region is responsible for making data available to the central office through the database maintained by WSDOT. WSDOT conducts all acceptance testing and does not use contractor results in QA.

WSDOT has used a combination of volumetric (gradation, VFA, VMA, etc) and non-volumetric properties (density, binder content) to characterize HMA material and construction quality. The State believes that collectively these two sets of properties measure HMA material and construction quality reasonably well.

WSDOT has just begun using design-build contracting on construction projects and requires warranty specifications on all design-build projects. WSDOT has used warranty specifications on new HMA, HMA overlay, and PCC rehabilitation projects. A 5-year term is used on warranty jobs at this time. For both flexible and rigid pavements, performance is monitored on the basis of ride quality, pavement friction, pavement surface condition, structural capacity, and material quality. Performance is monitored at several times during the warranty life, as deemed necessary by WSDOT. If pavement distress exceeds permissible levels, the design-builder is notified anytime until 60 days prior to the expiration of warranty.

Construction Quality-Related Systems

Washington is one of two States surveyed that maintains a single database to store all project-related information. At the time of the survey, WSDOT was in the process of transitioning from an old database to a new program. The existing system (referred to as the "old database" in this write-up), *Quality Assurance Specifications*, has been in use since the late 1980s and has undergone two significant upgrades over the past two decades. The program has been used primarily to store HMA and aggregate data and to compute pay factors for the contractors. WSDOT has been involved in relatively fewer PCC projects, so concrete test data are not included in this database; the agency maintains a separate database for storing concrete materials data.

Test data in *Quality Assurance Specifications* are stored by lots and sublots. The database also stores contract information and mix design information, but does not necessarily provide the framework for storing all test data collected during the construction and acceptance process. The contractor does not have access to this database. The database was developed using a PowerBuilder platform.

The new WSDOT, developed in-house, offers the agency and contractor additional features. This is a Web-based tool and is referred to as *Statistical Analysis of Materials* (*SAM*), triggered by the need to monitor design-build projects. The goal was to consolidate data into one large QA construction system that can be used both within and outside the department. Training and reference aids have also been developed to assist the agency in implementation of the system. The conceptual diagram showing a layout of this system is shown in figure 6. The database will hold materials design and test data for HMA, PCC, and unbound materials, as well as maintenance data.

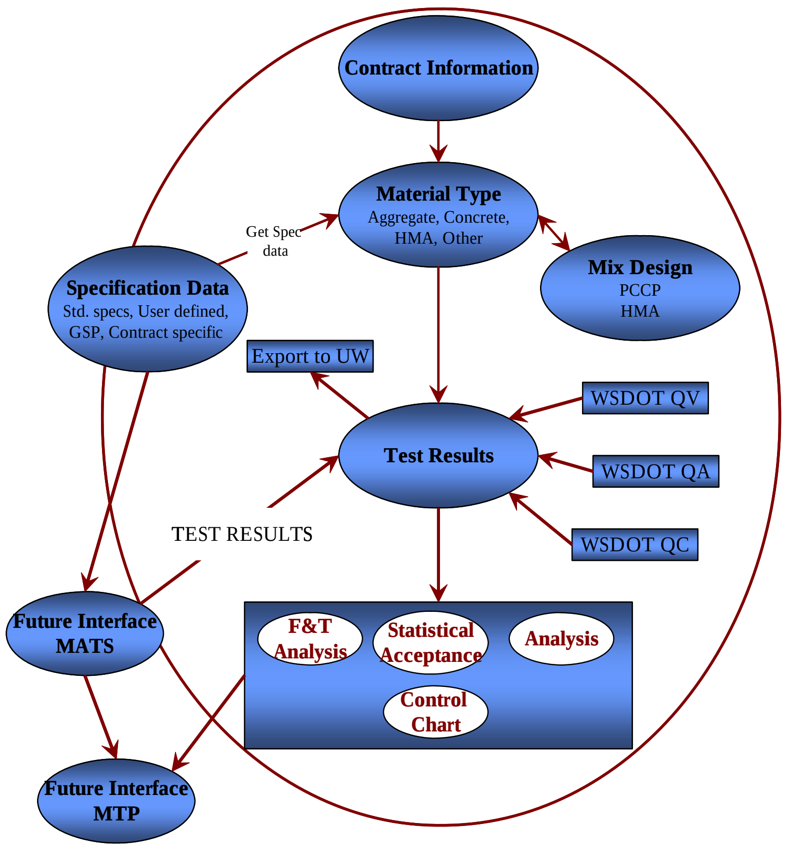


Figure 6. Context diagram for *Statistical Analysis of Materials* (courtesy WSDOT).

SAM offers advanced security features, and the administrator can customize the system to allow different levels of viewing and data input privileges for various users. It also offers additional analysis features, such as F- and t-test analysis, statistical acceptance, and control charts.

Data Analysis

WSDOT analyses primarily are limited to the calculation of pay factors and standard statistics on test data. These are performed on an as-needed basis external to their existing database system by the agency or the individual conducting the analysis. For example, during the conduct of a recent forensic evaluation of a pavement that experienced early failures (unpublished report), it was recognized that the State had to rely on test data from cores rather than utilize data from obtained during construction. The study, while making recommendations to improve the specifications for aggregate, binder, mix design, and mix placement procedures, also emphasizes the need for an *Electronic Project Engineering Office* (*EPEO*) system.

The *EPEO* system will offer better data collection and analysis capabilities and enable the linking of material properties with pavement performance. The *EPEO* will also allow agency staff up the chain of command to immediately take note of poor construction and to stop project engineers from modifying pay factors. In addition, the *EPEO* will make data immediately available to the contractors for their use.

WSDOT also recognizes the benefits of extracting QA data by lots and linking it to performance data from the PMS. At this point, the agency performs this on a case-by-case basis. Such analyses currently require a time-consuming but essential data extraction from the QA database system and linking of that data to the performance data set. The implementation of the *SAM* database system will address some of these issues. The practicality and effectiveness of correlating test data with performance is yet to be verified. There exists an opinion within the agency at this time that meaningful correlations can only be derived in pavements that have very poor performance, because most pavements built with the State specifications are held to a fairly high construction quality standard. Unless test and material data can be identified for localized areas, the correlation to performance might not be meaningful. These thoughts are to be verified in a future independent study.

Future Directions

WSDOT's long-term goal is to have contractor QC on all materials for roadway construction. WSDOT will however continue to maintain all acceptance testing. Contractors are now encouraged to develop their own mix designs for HMA, which until recently was the responsibility of the WSDOT.

WSDOT plans to also continue to upgrade the current version of *SAM* to incorporate advanced features that provide a more user-friendly interface for analysis tools and viewing test results.

CHAPTER 4. DEVELOPMENT OF MODEL DATABASE

4.1 PURPOSE AND OBJECTIVE OF THE DATABASE

4.1.1 Introduction

The guidelines for the development of a construction quality database were developed after a thorough assessment of the various uses within the agency and benefits it can provide. Information collected from the survey responses and the in-depth interviews provided insight into the multiple databases maintained by the agencies, the data categories stored, the analysis performed, links to other SHA databases, and the reports generated. It is evident that the nature of information collected, the level of detail in the process, and the length over which this information is retained differ significantly from agency to agency. In each of the agencies surveyed, the systems have been established with certain goals that are State-specific, and most represent an as-built database. Furthermore, the current systems differ considerably in their architecture, purpose, data collection and access procedures.

Recommendations from this study will provide a set of comprehensive guidelines that can help SHAs upgrade and maintain more systematic and efficient database systems to manage their information. It is not expected that an agency will develop a new system based on these recommendations; instead, these recommendations will be useful for agencies desiring to upgrade or improve their database system to make it more useful to the agency. The recommendations describe the mechanics of developing efficient databases and cover basic database functions.

It was also found during the surveys that the States have been collecting extensive data for several years, but do not often or necessarily utilize it to draw valuable conclusions or to perform advanced analysis for broader use. In other words, agencies appear to be "data rich and information poor," as stated by one agency. Another interesting statement made was that agencies are "mostly focused on entering, not retrieving data." One main reason for this status-quo is that there are no dedicated positions assigned with the responsibility to oversee an overall efficient management of the various databases. This position will involve significant inter-departmental coordination, and the selected individual for this role should have a wide understanding of the functions and needs of all departments involved.

During the surveys, pavement management staffs in most agencies expressed an interest in (and recognize the benefits of) correlating construction quality to pavement performance data, or linking it across other databases, such as cost data or safety data. They realized that they were not "closing the loop" to show how improvements in specifications and construction affect performance. The major limitation in implementing this type of an analysis is the fact that the databases have been established with different referencing systems leaving no common tie to match all data collected on a given pavement section.

Databases also have seen very limited use in cost-benefit analysis, so important for agencies in establishing policies or in making changes to their specifications/practices. For instance, States implementing PRS (where all AQCs are measured in the same sublots/lots) will perhaps be able to correlate increase in initial construction cost against increase in service life. However, without a further link to life-cycle costs, the increase in design life cannot be translated to a decrease in life-cycle costs. An efficient database system should provide agencies an opportunity to clearly assess/appraise the benefits they receive in making changes to their construction practices. Likewise, improvements in safety and accident records can also be traced through appropriate linking of individual databases to specific sections of pavement.

The guidelines provided in this report were therefore developed based on a thorough evaluation of current and future needs of an agency, while not using any specific agency's database system as the basis for the recommendations.

4.1.2 Agency and Contractor Needs

A construction quality database has several users, including both agency and contractor personnel. Needs of the users of the database were fully considered while formulating the features and components of a model construction quality database.

The SHA and the contractor have the following *minimum* requirements from a database:

- User-friendly interface and configuration.
- Access by several individuals and departments, such as materials testing lab, construction engineers, field inspectors, designers, management, contractors, subcontractors, and researchers who might all operate from different locations.
- Different levels of access security and operational privileges, such as viewing data, entering data, modifying data, generating outputs, analyzing data, etc., depending on role in the organization or role in the project (inspector vs. contractor).
- The ability to make "user group" assignments; users can belong to multiple groups.
- Audit and tracking information to trace users and their activities.
- Offline use of input modules or linkage to wireless devices to aid in timely data entry and processing.
- System for logging and tracking of material samples, related tests, and results.
- Capability to store construction details and contractor activities for each lot such as PCC curing practices, thickness of HMA lift in each paving operation, and traffic opening time, etc.
- Aid in decision-making for QA, PRS, and warranty projects.
- Ability to perform fundamental and routine analysis for QA operations, including pay factor calculations.
- Ability to generate system outputs and ad hoc or standardized reports that can be electronically distributed or published online.
- Ability to interface/link with other agency systems (e.g., PMS database, financial/cost accounting system) via lot location identification.
- Analysis capabilities to perform advanced analysis to correlate construction and material test data with performance (pavement management) and cost (bids, maintenance) databases.

- Common referencing across other key databases to perform analysis types listed in item above.
- Potential to use or switch to GPS coordinate referencing and bar coding technologies.
- Flexibility to customize the analysis for specific cases when required.
- Overall system stability (e.g., backups and disaster recovery) and security (e.g., firewall protection on machines accessing central database).

4.2 MODEL CONSTRUCTION QUALITY DATABASE

The features and the software architecture of a model database are discussed in this section. Also summarized are the list of outputs and the analysis capabilities of this database.

4.2.1 Referencing System

The referencing system is the technique adopted to identify specific points or segments of a pavement. The referencing method is a very critical component of the system and forms the crosswalk between different databases for data integration. Data from one dataset, say the construction quality database, can be cross-referenced with the corresponding data from a second database (say, PMS or traffic) only by matching the referencing scheme.

The findings from this study suggest that lots are definable entities in a construction database that can be linked to a PMS. Lots are defined by the beginning and end stations. It is essential that data in PMS and maintenance records be maintained with the same referencing system to make meaningful correlations between datasets. Agencies should consider incorporating this common referencing scheme for immediate implementation or in their short-term plans. Without a common referencing system, no comparison of construction quality with performance can be accomplished.

For the long term, use of GIS, a spatial referencing method, will provide greater flexibility in identifying attribute data, and is amenable for use in relational database systems and in databases where dynamic segmentation is necessary. Some agencies are implementing or conducting pilot projects to use GPS technologies in collecting inventory and survey records. In these cases, GIS-based referencing is a natural path to follow. The study recommends that agencies adopt a GIS-based referencing when establishing new databases, as well as in their efforts to improve the current system.

4.2.2 Software Architecture and Features of the Database

Overview of Software Architecture

The proposed database is a Web-based or wide-area network (WAN) based system that can be accessed by several users in various district offices of the State through their shared networks. In other words, all communication channels are via the Internet. A client-server architecture that enables multi-user updating and SQL communication can be used across the client and server. A database server can provide reliable data storage, access, integrity, and security to clients over the Internet. This system will allow the storage of data in one comprehensive system, eliminating duplication and improving the accuracy of information retrieved by all end-users.

A software application (or a set of applications, as the case may be) providing the interface to input data and generate outputs will be installed on every client machine. In addition, this system aims at enabling an electronic data entry tool for field staff thereby eliminating the need for paper records and duplication of efforts in entering field test data. This can be achieved by the use of a static data entry form (similar to an input data file for a specific input category) that can function on an offline machine (e.g., a pen-based, handheld device). The completed form or input file can be eventually uploaded to the central server after field staff returns to the client machine. Figure 7 illustrates the automatic file upload feature. Data entry forms can be created using any programming language that support web-based technology (e.g., ASP.NET, Perl, Python). The applications that drive the data entry have to be developed using a graphical user interface (GUI) standard.

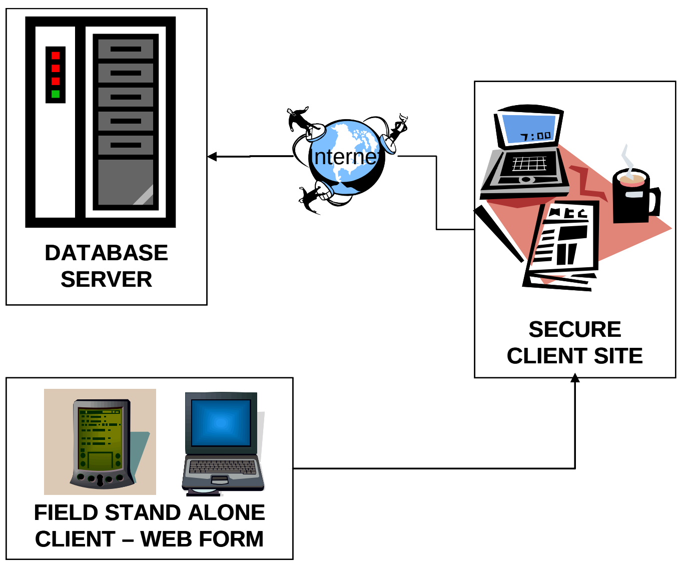
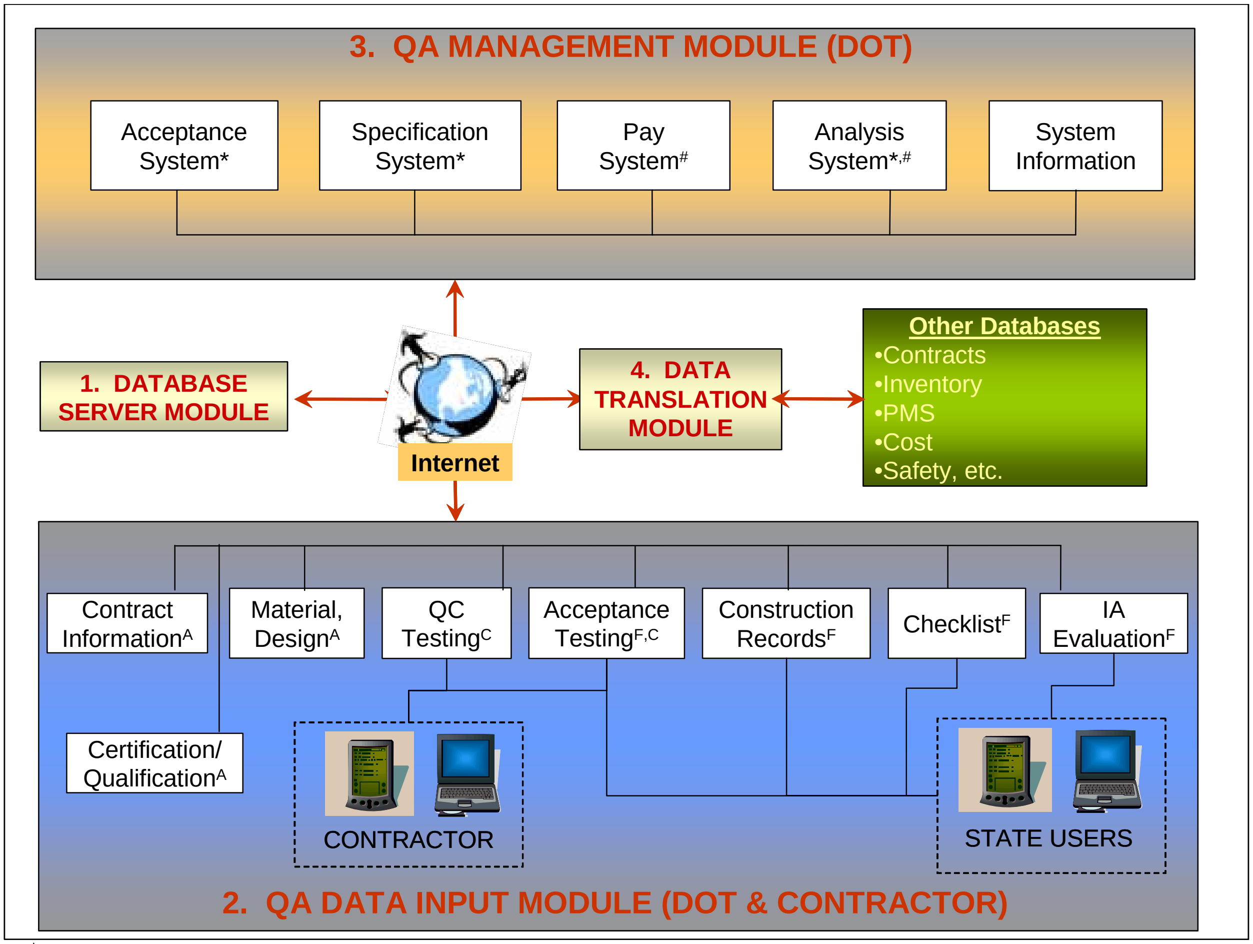


Figure 7. Conceptual sketch – field data transferred from Web forms to database server.

Database Modules and Feature

Figure 8 shows the architecture proposed for an effective construction quality database system that will meet the agency and contractor needs identified in this study. This section discusses the main data categories in the database, while detailed discussion of input data types are discussed in section 4.2.3.



[A] Data input by project management staff from SHA's central or district office.
[F] Data input by agency field personnel and may be input using standalone input interface.
[C] Data input by contractor, may be input using stand-alone input interface.
[*] Information common to the entire system and entered by the agency.
[#] Analysis/calculations performed for specific needs may require data integration with other databases.

Figure 8. Architecture for construction quality database system.

The proposed system consists of four modules, as described in the sections below.

Database Server Module:

The database server module forms the core of the architecture and functions as the key component of the construction quality database system. All other modules connect with the server though the Internet. The database server stores system data information and provides services for different users through the internet. This server is centrally located and will provide QA services to specified or authorized users in remote locations. The level of access and privileges for each user—agency or contractor personnel—will be customized depending on the role of the individual in relation to the project and/or organization. Data can be uploaded or retrieved through the internet using a simple customizable software program as an interface, which will be installed on every client machine.

QA Data Input Module:

The QA data input module will be used to record all information relevant to each construction project and for each contract. This module provides an interface and a storage feature for all data relevant to the project, from the time of project initiation to the final acceptance of the construction. It includes data entered by various agency and contractor personnel through the production stage, plant mix design, lab testing, and construction testing. Note that the QA data input module merely provides a framework to input data in several categories, but will not provide the analysis engine required to perform detailed QA analysis. The following is a list of all categories and a brief description of the data elements to be included for each data category:

- **General**—This includes general information pertinent to the construction project and entered by the project manager of the job from within the SHA. The project is identified preferably by the contract number but adequate references to the route number, lanes, and milepost will also be made. Contract documents and other general comments and information can be entered here.

- **Certification and Qualification**—This category includes a list of laboratories certified to perform QA testing for the State. Also included is a list of certified material suppliers and qualified in-house staff to perform various tests.

- **Material and Design**—This category refers to details of the materials and job mix formula (JMF) being used in the construction. Examples of data items included in this category are concrete mix design, HMA mix design, and gradation of aggregates. Test data from production stage performed by the agency to certify the materials for use in construction is also be stored here. A provision to import standard mix designs that are typical to the agency (stored in material library files) is provided here.

- **QC Testing—**This category refers to all test data collected from the QC operations during construction typically by the contractor (or the testing subcontractor). These data can be entered either through the client machine or using the web form on a standalone program on any PC/handheld device. In the latter case, QC data should be uploaded back to the database server system. Examples of data in this category include mat density and concrete slump.

- **Acceptance Testing**—This category includes acceptance data collected by the agency, or the contractor in cases where contractor data is used for acceptance, after the completion of construction for each lot. Again, the flexibility to use web forms to upload data from a stand alone machine to the server is offered in this case. Examples of data inputs in the construction testing class include thickness, HMA aggregate gradation, mat density, compressive strength of PCC, smoothness, etc. This information will be used by the system to calculate pay factors.

- **Construction Records**—This category consists of all information relevant to the construction operation and the conditions prevailing at the time of construction. Weather conditions during construction, lift thicknesses used in HMA paving, observed segregation in HMA, curing methods adopted for PCC, construction sequence, and change in construction equipment are examples of data inputs in this category.

- **Checklist**—This category consists of data indicating the conformance of several items in the specifications that are not routinely tested. A checklist for each material type (HMA, PCC, earthwork, stabilized materials) is recommended for the database, and each checklist covers several attributes. The recommendation stems from the construction checklist maintained by the ADOT. The data input in this category assumes three values, “conformance,” “nonconformance,” or “N/A” for each attribute in the checklist. These data are entered by the agency personnel, and are offered the flexibility for use in offline web forms.

- **IA Evaluation**—This category includes data collected by the agency for IA purposes. These data can be collected on standalone machines in the field for future upload to the database server.

Note that data items entered in the last seven categories above use the same reference system created in the first category (General). For acceptance testing and some QC testing, the user enters data for each lot for each material.

During the development of this module, as well as during the implementation stage, due consideration should be given to the level of data that are input into the database. Care should be taken to enter unbiased data. In the event biasness of any form exists in the data, the bias issue has to be noted so that the data can be used with caution during the analysis stage.

QA Management Module:

The QA management module utilizes data input into this module to analyze the quality of construction in the project. There are five subsystems in this module:

- **Acceptance System**—This category contains the necessary calculations to determine the acceptance of the construction based on QA data in the database server. It includes the accept/reject procedures and is governed by the Specification System in the QA management module.

- **Specification System**—This category contains the current specifications of the State and monitors the adequacy of specifications. Agencies can routinely perform analysis to identify inconsistencies in specifications with relation to desired performance and to evaluate the effectiveness of specifications. The system will make possible continued improvements to performance-related specifications and QA system. Note that the Acceptance System utilizes data from the Specification System to calculate pay factors. The Specification System should also be appropriately linked to the input module so that the specifications for each material can be compared against the quality of construction.

- **Pay System**—This system uses data from the Acceptance System to provide guidelines for pay factors commensurate with the construction quality provided.

- **Analysis System**—This system will provide statistical analysis, quality performance simulations and other modeling tools for QA data. A detailed discussion of data analysis is presented in chapter 5 of this document.

- **Information/Output System**—This system will be an information manager for QA data information. It will include QA data queries and retrievals, generate reports and track qualifications of material producers, testing laboratories and technicians, etc.

Data Translation Module:

This module provides the tools to translate data information to communicate with other systems (such as the PMS) with a standard format. This module acts as a communication channel with other systems to provide desired QA testing data to other systems, as well as provide a platform to request other data (e.g., performance, traffic, cost, safety) into this system.

4.2.3 Data Types in Input Categories

This section discusses the data types in the various input categories of the database. The discussion here points to tests that are considered critical or important for maintaining an efficient database and a cost-effective QA program in the agency. HMA, PCC, and unbound material test data, smoothness, and construction records are included in this discussion. Clearly, this discussion might not cover the entire set of tests and input data collected by all agencies; each agency will have to address issues specific to its needs.

Hot-Mix Asphalt

SHAs use a variety of different HMA mixtures to pave roads. Some of these mixtures serve specific purposes. Porous Friction Course (PFC) mixtures, for example, are typically used to reduce splash/spray conditions and noise. Dense-graded asphalt mixtures are the most commonly used and have been in use for decades on low-to-high traffic volume roads.

Recent advances in pavement technology have led to the development of "performance" oriented mixture design approaches. Superpave was developed to address the demands of higher traffic volumes on roads and the stone-on-stone design approach of stone matrix asphalt (SMA) mixtures was developed to eliminate permanent deformation or rutting. Thus, pavement engineers have a larger selection of candidate mixtures that may be used to address performance concerns. Characteristics of these mixtures may differ significantly and as a result the performance criteria of one mixture may not necessarily apply to another. Consequently, mix design and specification criteria for mixture QC and verification for different asphalt mixtures may vary and must be established separately.

For QC purposes, it is necessary to distinguish between different types of asphalt mixtures serving specific purposes. These may be broadly categorized into the following groups:

- Dense-graded HMA.
- Superpave or Performance-Designed HMA.

- Porous Friction or Open-Graded HMA (PFC, OGFC).
- Stone-Matrix Asphalt (SMA).

These asphalt mixtures may be further sub-divided into grouping relating to aggregate size and gradation to distinguish coarse, intermediate, and fine mixtures. This separates mixtures for base and surface course applications. This sub-division is necessary, as the volumetric property criteria of HMA are related to aggregate size and gradation. Division of asphalt mixtures by binder or asphalt grade generally is not necessary, although performance criteria applied to performance-designed mixtures may vary for softer binder grades relative to stiffer binder grades.

QC procedures for HMA must address the quality of (a) materials or mixture components, (b) the mixture design process for identifying an appropriate JMF, and then (c) the production phase during mixture placement and construction.

Materials:

Materials used for the manufacture of HMA include aggregate, asphalt binder, additives (lime or anti-stripping agents), fibers (for SMA and PFC), reclaimed asphalt pavement (RAP), and other recycled materials. It is the agency's responsibility to ensure that the quality of the individual components comprising the asphalt mixture is adequate. This is done well before the materials are used for construction of the HMA so that it is not necessary to control or verify material component quality during construction, except perhaps to verify the grade of the asphalt binder. Furthermore, material components may be used for manufacturing a range of different products and used on different projects. For this reason, it may be adequate to record the supplier of the materials, the aggregate classification and stockpiles used and the binder grade. It is important, however, to be able to reference properties of the base materials comprising the HMA. These properties would be entered and stored in a separate database table from the asphalt mixture information with links to primary fields identifying material codes common to both.

The aggregate component of HMA typically makes up 80 percent by volume of the mixture. Aggregates form the skeletal structure of the mixture and provide structural stability. Therefore, it is necessary to ensure the aggregates have adequate strength and resist abrasion. Other critical factors influencing mixture compaction and performance are aggregate shape, angularity and crushed faces. Crushed cubical aggregates perform better than rounded or flat and elongated particles. It is recommended that SHAs establish Aggregate Quality Monitoring Programs (AQMPs) to track the properties of aggregates at the source or quarry. Recycled Asphalt Pavement (RAP) is commonly used in asphalt mixtures. SHAs may place a restriction on the percentage of RAP allowed in certain HMA mixtures.

The following is a listing of requirements typically used to evaluate aggregate quality:

- Surface Aggregate Classification (source, strength, friction properties, etc).
- Particle size distribution (gradation).
- Deleterious material (dirt or objectionable materials).
- Decantation.

- Micro-Deval abrasion.
- Los Angeles abrasion.
- Magnesium or sodium sulfate soundness.
- Coarse and fine aggregate angularity.
- Flat and elongated particles.
- Linear shrinkage (fine aggregate).
- Sand equivalent.
- Bulk specific gravity.

The asphalt binder component of HMA is categorized by binder grade in the U.S. using a performance grade (PG) system that evaluates the performance characteristics of the asphalt binder in terms of performance properties. The most relevant of these include:

- Flash point.
- Viscosity (determines the mixing and compaction temperatures).
- Mass loss after rolling thin-film oven test (RTFOT).
- Dynamic shear rheometer (DSR) stiffness (before and after binder aging).
- Creep stiffness.
- Direct tension.
- Elastic recovery (for modified binders).
- Specific gravity.

Mixture Design:

The final mixture design defines the JMF that will be targeted during the construction process. This entails the selection of an aggregate structure or blend of aggregate components and optimum binder content for asphalt mixtures. The mixture gradation and binder content are selected to ensure desired properties and performance. The JMF may change during production, and database structures must make provision for this change, as control and verification of material quality is always applied in reference to the approved JMF. In a construction quality database, this may be achieved by placing the JMF information in a separate table and providing a link to the QA data in another table that includes a field identifying the JMF to be applied. At a minimum, the JMF information will include target aggregate gradation and binder content.

Mix design and verification information to be collected include:

- Design and JMF changes.
- Asphalt content.
- Aggregate gradation (ignition oven or solvent extraction method).
- Laboratory-compacted density.
- Volumetric properties (VMA, VFA, etc).
- Film thickness (calculation based on AC content and gradation).
- Maximum theoretical specific gravity.
- Ignition oven calibration.
- Indirect tensile strength (tensile strength ratio).

- Wheel tracking test results (e.g., Hamburg, APA), if appropriate.
- Boil test (to evaluate stripping potential).
- Drain-down (PFC and SMA mixtures only).
- Cantabro Loss (PFC mixtures only).

The mix designer will select a mix design traffic category, which affects property limits and parameters such as design compaction level, aggregate angularity criteria, volumetric property criteria (VMA, VFA), etc.

Aggregate gradation is an important factor influencing asphalt mixture performance (Roberts et al., 1996). Some agencies have gradation requirements for the fine aggregate and mineral filler components of mixtures, but all apply gradation limits (master gradation bands) defining extents within which an aggregate gradation must fall. Gradation requirements for different mixture types will vary and control may not necessarily be required for each of the sieve sizes listed in the table. Mixture gradation control is critical during the mixture design and production phases.

Asphalt mixtures can be susceptible to moisture damage. The phenomenon known as “stripping” occurs when the bitumen coating on aggregates is removed under the action of water. This susceptibility to moisture damage may be evaluated using indirect tensile strength tests and the application of a tensile strength ratio (TSR) as defined in ASTM D 4867 (ASTM, 2004). The resistance to moisture damage and permanent deformation of asphalt mixtures is increasingly being assessed using wheel tracking devices such as the Hamburg Wheel Tracking Device (HWTD) and Asphalt Pavement Analyzer (APA).

As mentioned previously, asphalt mixture design is a laboratory procedure to determine the optimum binder content for an aggregate blend. Testing is usually done at different binder contents, and an optimum binder content is selected for desired mixture properties. If possible, a link should be made available to the mixture design information to obtain volumetric properties at the design binder content, as well as relevant mixing and compaction temperatures applied. The volumetric properties can easily be calculated and incorporated into construction quality databases.

Mixture Production:

Before addressing the mixture production QC and assurance inputs required for construction quality databases, certain external factors should be considered. These include recording construction equipment used on the job site, as well as technician certification requirements. Other relevant but perhaps not critical information includes project personnel, material delivery and storage details. This information is usually required as part of the Quality Control Plan (QCP) but seldom referenced when addressing production quality.

Asphalt mixtures are usually evaluated in intervals known as lots, which may be defined by time (e.g., a day’s production) or by tonnage. Control and verification testing are done on sublots, typically four, which make up the lot. Control and verification testing plans vary. Some states require contractor QC testing of every sublot with agency verification done randomly on the lot. In Texas, for example, both the contractor and the SHA test each of the four sublots during production.

With regard to mixture production, a distinction must be made between production testing and placement testing. Production testing required could include:

- Laboratory compaction density.
- Rice gravity.
- Gradation.
- Asphalt content.
- Control charts.
- Moisture content.
- Wheel tracking tests.
- Micro-Deval abrasion.
- Boil test.
- Aging ratio.

Placement testing is done during and after construction and may include:

- In-place density.
- Field compactor rolling patterns.
- Control charts.
- Ride quality measurements.
- Segregation control (density profile).
- Longitudinal joint density.
- Thermal profile.
- Tack coat adhesion (for multiple asphalt layers).
- Permeability (PFC mixtures only).

In addition, the paving date and time of each sublot should be noted as well as air temperature during paving operations, as this significantly influences mixture compaction and control of segregation related problems.

Portland Cement Concrete

QC procedures for PCC must address three main aspects (a) materials and mix design (b) hardened concrete properties, and (c) the placement and construction aspects.

Materials:

Concrete is a homogeneous mixture of cementitious materials, coarse aggregate, fine aggregate, and water. In most cases, certain admixtures are added to improve or control specific properties. Each component of the mix affects the properties of fresh and hardened concrete and therefore the characteristics of each of these materials have to be input into the database. Further, SHAs maintain material specifications for each individual component as well as mix design. Some of these specifications also relate to fresh concrete properties. The following inputs regarding the materials are recommended:

- Cement type—affects strength gain and shrinkage properties.
- Cement content—affects strength gain and shrinkage properties.
- Water-cementitious materials ratio—affects strength, shrinkage, coefficient of thermal expansion, permeability.
- Aggregate type—affects strength, shrinkage, coefficient of thermal expansion, workability, and moisture absorption.
- Aggregate gradation—affects the packing density, strength properties, workability issues.
- Percentage of other cementitious materials (such as fly ash)—affects long-term strength, early shrinkage, heat of hydration, workability, permeability, etc.
- Admixture type—affects workability, shrinkage, expansion, and freeze-thaw properties.
- Unit weight—affects strength and indicates level of consolidation.
- Slump—affects workability and controls segregation problems.
- Air content—affects freeze thaw resistance.

Hardened Concrete Properties:

The main hardened concrete properties that control pavement design and performance relate to strength characteristics and volumetric changes. Most agency specifications spell out a minimum strength value for the concrete at 28 days and at the time of opening to traffic. The following tests and input data are recommended for hardened concrete properties:

- Compressive strength—regarded by agencies as the controlling strength parameter and also forms a convenient comparison for future strength tests on cores removed from the pavement.
- Flexural strength—affects cracking in pavement and a key parameter for fatigue damage calculations.
- Coefficient of thermal expansion—a very important material property that has received attention in recent years; affects deformations resulting from thermal gradients and determines the amount of permanent built-in curl in the slab thereby significantly affecting fatigue damage and cracking in pavement.
- Shrinkage—controls early age distress due to loss of moisture, affects the extent of permanent deformation as a result of moisture gradients, and affects long term fatigue damage and cracking in pavement. This test is performed on laboratory specimens.
- Permeability—a key indicator of durability and is affected by quality of mix and the temperature of mix during placement and curing.

Placement and Construction:

Construction operations have a tremendous impact on the overall quality of the pavement and long-term performance. SHA specifications contain several items to control construction activities. The tests and input data from the placement stage that are considered important:

- Thickness—regarded as one of the main AQCs for rigid pavements and affects the long term performance of the pavement.

- Dowel bar and tie bar alignment—affects performance of transverse and longitudinal joints, and joint faulting.

In addition, the paving date and time of each sublot should be noted, as well as air temperature during paving operations, as this significantly influences shrinkage, built-in curl warp, joint opening, etc.

Unbound Materials

Unbound materials consist of the existing subgrade layer at the project site, as well as any additional aggregate layers placed. The existing subgrade has to be compacted and rolled to the specified density levels. For all unbound layers, the following tests are recommended:

- Dry Density.
- Gradation.
- Minus 200 Material.
- Moisture Content.
- Atterberg Limits.
- Strength, Dynamic Cone Penetrometer, CBR, R-value.
- Resilient Modulus.

Smoothness and Surface Characteristics

Ride quality measurements, typically reported in terms of IRI or PI, can be measured using profilographs or inertial profilers. Smoothness measurements are taken along a section of road and averaged from measures in the left and right wheelpaths for both flexible and rigid pavements. Also recommended are tests for friction and texture to determine the skid resistance and noise abatement features of the surface layer.

4.3.4 Outputs and Analysis

The outputs and analysis desired from the system control the design and architecture of the database system; outputs required from the database drive the inputs. The following are examples of outputs that can be obtained from the recommended construction quality system:

- Pay factors for all materials of interest in a format desired by the SHA.
- Generation of statistical reports and graphs for use by the SHA in a standard format (e.g., .doc, .xls, .txt, .txt, .html, .rtf, .pdf).
  - Contract report on pay factor.
  - Actual pay factor awarded to the contractor.
  - Other parameters for calculating variability.
- Chronological data for quality and compliance audits and for historical reference.
- Mixture design information for HMA and PCC.
- Construction Quality Report for a specific contract or project.
- Contractor Quality Report for a specific contractor on their projects.

- Appropriate QA data, location, climate, and other information needed to conduct an analysis for the correlation of the quality of construction (measured by the various AQCs) with the future performance of the pavement.
    - Construction sequence or field notes.
    - Conformance to specifications for all attributes in checklist database.
- Appropriate QA data, location, and other information needed to evaluate the specifications under which the project was built.
    - Sample size.
    - Test procedure.
    - Location of sample.
    - Estimation of variability and statistical parameters.

In addition, several analyses can be performed using data from the database as well as by linking it with data from other agency databases (e.g., performance, traffic, safety, cost). Detailed discussion on types of data analysis and examples are provided in chapter 5.

4.3.5 Benefits

A well-developed construction quality database system offers the following benefits:

- Automation of data entry across various units (e.g., materials, construction, specifications, etc.) of the agency.
- Centralized entry and storage of testing data and contract documents in an electronic format that is easily accessible by the central office, district offices, project field offices, and other agency personnel or their consultants.
- Possibility for hierarchical data access.
- Ability to securely upload or import QC test data and IA data from external sources (e.g., vendors, contractors, consultants).
- Electronic approvals.
- Automated means to calculate pay factors and make acceptance decisions.
- Ability to highlight specification non-conformance in real-time (i.e., during construction) and the opportunity to take timely remedial actions by the agency's decision makers. This includes specifications that are tested as well as those inspected during the preparation of construction checklists.
- Generation of ad-hoc and standardized reports in a manner that can be easily incorporated into documents.

Ability to perform various engineering analyses including:

- Rating asphalt and concrete plants based on quality they produce, which can be assessed from QC records in the database. The agency can pre-qualify material suppliers and producers, which can result in cost savings in QA programs.
- Testing the effectiveness of current specifications or QA processes and to revise them as necessary based on performance or cost analysis.
- Assessing contractor performance.
- Tracking overall system performance and the performance of new and innovative materials, construction, and testing technologies.

- Forensic evaluation of pavements (with both good and poor performance) using lot-specific materials, construction, and climatic data.
- Aiding in improving pavement design and pavement management processes.
- Aiding in the development of pavement performance models.
- Establish basis for materials and performance warranties as well as performance-based specifications.

CHAPTER 5. ANALYSIS OF DATA IN CONSTRUCTION QUALITY DATABASES - EXAMPLES

5.1 DATA ANALYSIS – POTENTIAL AND USES

Thus far, attention has been called to the various uses of a well-developed and organized construction quality database system. The implementation of a system that has well-integrated components (or individual databases) that can be linked with each other using a common reference system has additional benefits to the owner agency. These benefits can range across the technical, administrative, and legislative levels to improve the quality of construction and enhance the agency's operations overall. The system can be designed to generate periodic reports, the nature of which would depend on the complexity of the database system and the sophistication of the linkage between the various individual database components. This section presents potential analyses that agencies can perform.

At the simplest level of a construction quality database system, the data would include basic materials and construction AQCs, such as lot-by-lot acceptance test results for smoothness, strength, and thickness for PCC paving; and smoothness, density, and mixture properties for HMA paving. These data can be used to determine fundamental statistical parameters and assess variability in the test results. Note that these analyses can be performed on data groups representing a specific year of construction, test equipment, contractor, district, project, or other factors. In addition, if the database houses both agency and contractor test results, suitable data can be extracted to compare the two test populations using standard statistical hypothesis tests, such as the *t*-test and *F*-test. The availability of contractor QC test results will make available additional information for use during forensic investigations when AQC specifications are not met or when premature pavement failures occur.

At an intermediate level of construction quality database maintenance, the database would be linked to a condition survey database, such as the agency's PMS. In this case, the analysis could be extended to correlate the material and construction tests data with material performance. These analyses can then form the basis for establishing thresholds for warranty specifications and to estimate risks in warranties.

Agencies maintaining an advanced level of construction quality database systems which can be integrated with other databases or project information, such as a cost database, can perform complex analysis to assess the cost-effectiveness of the agency's specifications and agency practices. Cost databases should typically include material and construction costs, maintenance costs, and user costs to determine life-cycle costs accurately. In such cases, cost analysis can be performed to strike an optimum balance between quality and cost or performance and cost for the specific material types and construction practices followed by the agency. Further, life-cycle costs can be established as an AQC for different pavement types. The objective of the analysis is to minimize the life-cycle cost for each pavement type, and this information can be used to refine pavement type selection procedures within the agency over time. For example, studies that compared cost effectiveness of pavement types (ACPA, 2001; Cross and Parsons, 2002) would benefit from a comprehensive QA database linked to the agency's cost database.

5.2 ANALYSIS ILLUSTRATIONS

This section provides examples of statistical analyses that can be performed for all three levels of databases discussed above. These analyses are simple examples that were developed using field test data or using data simulated artificially so that the various analysis capabilities of a construction quality database can be illustrated. Also, these examples represent only a subset of potential analyses that can be performed and by no means signify the overall scope of analysis using a construction quality database.

5.2.1 Estimation of Variability and Comparison of Test Results

This example illustrates the use of statistical analyses to test for differences of means between contractor and agency testing, testing the normality of the data, a comparison of the variation in construction of two contractors, and an evaluation of the adequacy of the sampling plan for thickness. Data were generated through simulation for this example.

Description of Project and AQCs

Two different contractors constructed jointed plain concrete (JPC) pavements under two separate contracts along a highway. Lots built by each contractor were numbered 1 through 10 by contractor A and 11 through 20 by contractor B. Each lot was approximately 0.8 to 2.4 km (0.5 to 1.5 mi) long and consisted of two-lane paving and four sublots each. The AQCs included slab thickness as one key parameter that was analyzed.

Simulated Construction Process

Two randomly located core samples were taken and measured for thickness from each of the four sublots within a given lot. The contractor testing was done by an independent laboratory, while the State testing was performed by the district laboratory. Note that the random samples were simulated from a normal distribution for the purpose of this example. The population means of sublots along each lot were varied slightly to simulate results that would occur along a project. Each project had the same design thickness and the population means were set equal. The project variances were set at different values to determine if this difference could be found through the sampling and testing process. Simulated results from construction testing for slab thickness for the two contracts are shown in tables 5 and 6.

Table 5. Data from simulated AQC slab thickness in 10 lots built by contractor A.

Lot #	Sublot #	Slab Thickness, in						
		Contractor A				State		
		Sample 1	Sample 2	Mean	Std Dev	Sample 1	Sample 2	Mean
1	1	8.1	7.8	8.1	0.3			8.0
	2	8.2	8.4			7.9	8.1	
	3	7.7	8.4					
	4	8.3	8.1					
2	1	7.7	7.9	7.9	0.2			8.6
	2	8.1	7.7					
	3	8.1	8.1			8.7	8.5	
	4	7.8	7.7					
3	1	7.4	7.8	7.8	0.2			7.5
	2	8.1	7.5			7.6	7.4	
	3	8.1	7.9					
	4	7.7	7.9					
4	1	8.5	8.6	8.4	0.2			9.1
	2	8.1	8.7					
	3	8.2	8.5					
	4	8.5	8.4			9.3	8.8	
5	1	7.5	7.9	7.5	0.2			6.8
	2	7.4	7.4			6.7	6.9	
	3	7.2	7.5					
	4	7.3	7.6			7.1	6.7	
6	1	7.8	7.5	7.9	0.2	8.2	8.3	8.2
	2	8.1	7.9					
	3	7.9	8.4					
	4	8.0	7.9					
7	1	7.8	7.9	8.0	0.2			8.5
	2	7.8	7.7					
	3	7.9	8.0			8.7	8.3	
	4	8.2	8.3					
8	1	7.4	7.6	7.6	0.2			7.5
	2	7.8	7.6					
	3	7.7	7.7					
	4	7.8	7.2			7.7	7.2	
9	1	8.8	8.4	8.5	0.2			8.9
	2	8.4	8.5			8.9	9.0	
	3	8.3	8.4			9.0	8.7	
	4	8.8	8.5					
10	1	7.3	7.3	7.4	0.2			7.0
	2	7.4	7.4			7.0	7.0	
	3	7.3	7.5					
	4	7.5	7.8					

1 in = 25.4 mm

Table 6. Data from simulated AQC slab thickness for 10 lots built by contractor B.

Lot #	Sublot #	Slab Thickness, in						
		Contractor B				State		
		Sample 1	Sample 2	Mean	Std Dev	Sample 1	Sample 2	Mean
11	1	7.9	8.2	7.9	0.7	8.2	7.9	8.1
	2	8.0	6.7					
	3	7.8	9.3					
	4	7.4	7.7					
12	1	8.4	7.8	8.3	0.4			8.2
	2	8.0	9.0					
	3	7.8	8.5			8.1	8.3	
	4	8.1	8.4					
13	1	8.0	7.5	7.9	0.6	7.5	7.7	7.6
	2	8.9	8.2					
	3	7.0	7.4					
	4	8.2	8.2			7.7	7.5	
14	1	8.8	9.3	8.8	0.4			9.0
	2	8.2	9.0					
	3	9.5	8.8			8.9	9.1	
	4	8.5	8.6					
15	1	6.9	7.3	7.2	0.4			6.8
	2	7.0	7.7			6.9	6.7	
	3	7.9	6.8					
	4	6.9	7.0					
16	1	7.3	7.7	7.8	0.6	8.0	7.9	7.9
	2	7.8	9.2			7.6	8.3	
	3	7.5	7.3					
	4	7.4	8.0					
17	1	7.8	7.8	7.9	0.5			8.5
	2	7.6	9.0					
	3	8.2	7.6					
	4	7.8	7.8			8.8	8.2	
18	1	7.3	7.0	7.5	0.4			7.6
	2	8.0	7.7			7.8	7.6	
	3	7.3	7.2					
	4	8.1	7.5			7.7	7.2	
19	1	7.9	8.9	8.7	0.4	8.6	8.9	8.8
	2	8.8	8.8					
	3	9.0	8.7			9.0	8.7	
	4	9.0	8.7					
20	1	7.3	6.1	7.1	0.5			7.2
	2	6.7	7.8					
	3	6.8	7.2			7.3	7.1	
	4	7.3	7.4					

1 in = 25.4 mm

Analysis of Data

The basic data provide an opportunity for a highway agency to evaluate the following, through appropriate statistical parameters and analyses:

- Comparison of contractor QA results with State IA results. Are the contractor measured thickness results significantly different from the limited measurements made by the State?
- Distribution of test results - is it normal? Do the slab thickness results follow the traditional normal distribution?
- Did each contractor produce the same variability in quality level for slab thickness or was there a significant difference?
- What is the percent deficient thickness for each contract? Will each of the lots have the same expected life?
- How adequate is the sampling plan to estimate the true mean of the lot?

The mean and standard deviation were calculated for the thickness values recorded in the project by the State and the contractor, as tabulated in table 7. This table shows that the mean thicknesses appear to be similar, but the standard deviation of the thickness measurements in lots 11 through 20 built by contractor B is higher than those measured in lots 1 through 10 built by contractor A. Data in table 5 show that the thicknesses ranged from 183 to 224 mm (7.2 to 8.8 in) for contractor A, and table 6 shows a range of 155 to 241 mm (6.1 to 9.5 in) for contractor B. Since the target value was 203 mm (8.0 in), some of these samples will be out of the specification (which had a minimum rejection level of 178 mm [7.0 in]). This aspect is not discussed further herein. The test data indicate that paving operations performed by contractor B show a higher variability. But is it significantly higher?

The first evaluation is to determine if the contractor results are significantly different from those of the State for each project. With contractor A (contract 1), the mean is 201 mm (7.92 in) versus the state's value of 203 mm (8.01 in). The closeness of these values indicates no practical difference. If there was a significant difference, this would indicate to the State that the contractor's data were suspect. It is also possible that the State's measurement system may be out of calibration.

The first evaluation is made using the *t*-test with paired-sublot mean values (contractor mean lot values compared with State mean lot values). The null hypothesis to be tested is that there is no difference between the means of the paired-lot samples for either contract. Based on a 0.05 level of significance, the results in table 8 show the calculated t-statistic is far below the critical value. Thus, there is no evidence that the contractor's results are significantly different than the State's for either contractor. Since it is known that the data from the contractor and State were randomly selected from the same normal distribution, this result agrees with the true underlying population of thickness values in each contract.

Next, the analysis can be extended to compare the mean sublot core thickness obtained from the contractor testing and from the State testing. Results show reasonable correlation. This is in agreement with the *t*-test that failed to reject the null hypothesis at the 0.05 level of significance that the mean lot values were from the same population. Figure 9 shows no significant bias of results between the State and contractor (e.g., one being consistently above or below the other). The best-fit lines show a slope of 1.01 and 1.00 (both close to 1.0) for contractors A and B, respectively.

Table 7. Summary of results for lot mean thicknesses from State and contractor AQC tests.

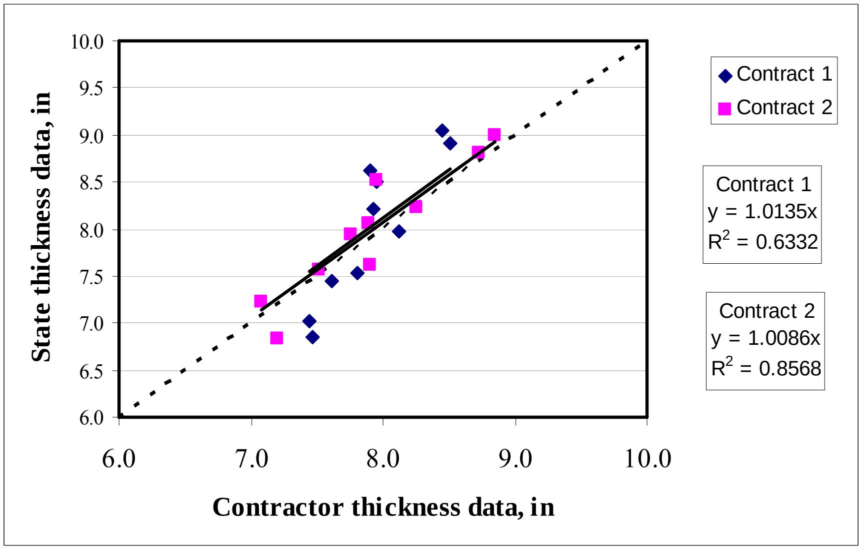
Thickness Statistic	Contractor A (lots 1 through 10)	Contractor B (lots 11 through 20)
Mean slab thickness (contractor AQC), in	7.92	7.91
Mean slab thickness (State AQC), in	8.01	7.98
Standard deviation of lot mean thickness (Contractor)	0.21	0.50

1 in = 25.4 mm

Table 8. Comparison of lot means of core thickness measured by contractor and State using a paired *t*-test analysis.

Statistics	Contract 1		Contract 2	
	Contractor A	State	Contractor B	State
Mean, in	7.920165	8.013726	7.913088	7.977227
Variance	0.134691	0.601718	0.33735	0.475823
Observations	10	10	10	10
Pearson Correlation	0.900368		0.929097	
Hypothesized Mean Difference	0		0	
Df	9		9	
t Stat	−0.62546		–0.77389	
P(T<=t) one-tail	0.273599		0.229422	
t Critical one-tail	1.833113		1.833113	
P(T<=t) two-tail	0.547198		0.458843	
t Critical two-tail	2.262157		2.262157	

1 in = 25.4 mm



1 in = 25.4 mm

Figure 9. Comparison of State and contractor mean sublot core thicknesses.

Another important issue is whether the contractor and agency test results show significantly different variation. This can be evaluated using the standard *F*-test, which compares the two variances. The *F*-test is easily implemented using the Data Analysis functions in Excel®. For the *F*-test, the first step is to compute the variance for the contractor's tests, S_c^2, and the agency's tests, S_a^2 for each contract. The *F*-test examines the null hypothesis: H_0: $S_a^2 = S_c^2$. The *F*-value is calculated as the ratio of these variances (always use the larger of the variances in the numerator so the ratio will be greater than 1). The closer this value is to 1.0, the closer the variances of the two data sets. After selecting a level of significance—0.05 in the case of this example—for the test the critical *F*-value (F_{crit}) can be determined using *F*-tables of the *F*-distribution, which are a function of level of significance and degrees of freedom (n-1) associated with each set of test results. Excel® computes both the *F* and F_{crit} values.

The results of the *F*-tests are presented in table 9. *F*-test performed for the data in this analysis shows that the null hypothesis is not rejected at the 0.05 level for contractor B indicating that the variance in thickness results of the contractor and the State are not significantly different. However, the results for contractor A show that the variance in thickness measured by the contractor and the State are significantly different. In fact, it is demonstrated that with the number of thickness readings collected by the State, the variance in State readings for contract 2 is lesser than for contract 1. Note that individual readings in each sublot (and not lot means) were included in this test.

Table 9. Summary of analysis to test differences between core thickness variances between the contractors and the State.

Statistic	Contractor A (lots 1 through 10)		Contractor B (lots 11 through 20)	
	State results	Contractor results	State results	Contractor results
Mean, in	7.991637	7.920165	7.978984	7.913088
Variance	0.67877	0.16229897	0.424154	0.536978
Observations	24	80	28	80
Df	23	79	27	79
F	4.182219		1.265996	
F Critical one-tail	1.666815		1.759423	

1 in = 25.4 mm

The next result illustrates the statistical analysis to determine if one contractor has a significantly higher variation in slab thickness than the other contractor. Results of *F*-test analysis (one-tailed to determine if one contractor has higher variance than the other) performed with the data collected by the two contractors are presented in table 10. The F-value of 3.03 exceeds the critical value of 1.45, indicating that there is a significant difference in variation in the thickness measurements between the two contractors. The variance in thickness measurements for contractor B is much higher than that for contractor A, indicating that the quality of construction of the former is less controlled and perhaps could exhibit a different performance over time. Locations along the project having thinner slabs would show a reduced life, all other properties being equal.

Table 10. Summary of analysis to test differences between core thickness variances between contractor A and B using only contractor tested data.

Parameter	Contractor A	Contractor B
Mean, in	7.920165	7.913088
Variance	0.16229897	0.536978
Observations	80	80
Df	79	79
F	3.308570948	
P(F<=f) one-tail	1.2709E-07	
F Critical one-tail	1.451152321	

1 in = 25.4 mm

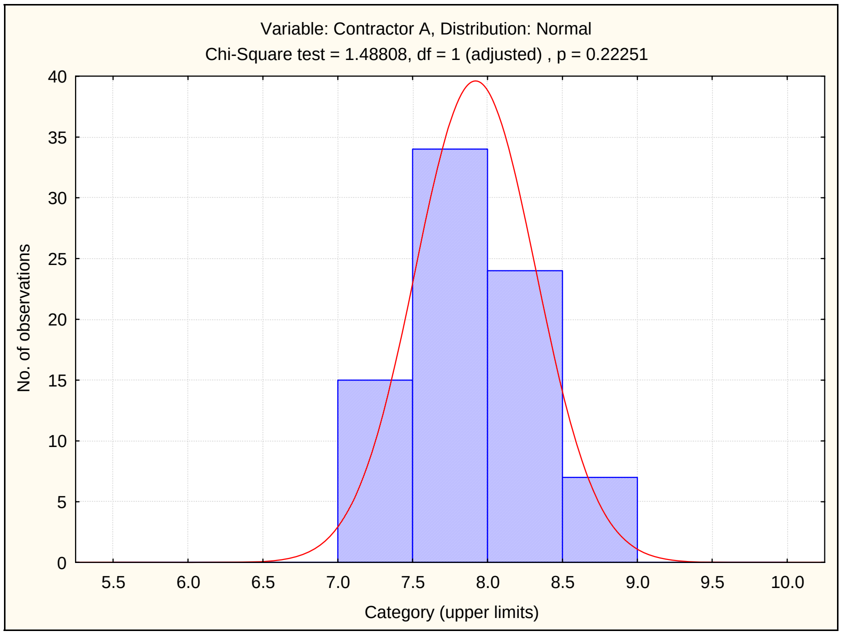
Another interesting comparison that can be made is to derive the frequency distributions for each project and test them for normality. This is accomplished using the Chi-square test for goodness of fit, which examines if the distribution of the data about the mean follows a normal distribution. The distributions for thickness measurements by contractor A and B are presented in figures 10 and 11. The larger variability in contractor B's results is evident through a comparison of the distributions shown in these figures. The computed Chi-square statistic is 1.488 and 1.927 for contracts 1 and 2, which are well below the critical value of 3.84 and 7.8 for these contracts respectively. These results indicate that they both follow a normal distribution at 95% confidence level, which is expected because the data was generated using a normal distribution for the purpose of this example.

Finally, the test data can be combined to calculate the percent deficient slab thickness for each of the contracts. For these projects, the specifications call for special remedial action (removal and replacement) for any area that has a thickness of less than 178 mm (7 in). The percent area less than 178 mm (7 in) can be estimated as follows. All of the contractor and State data can be combined to compute an overall mean and standard deviation for each contract. It has already been shown that the thickness values approximately follow a normal distribution. Since this results in a fairly large data set (e.g., > 30), it can be assumed that the population mean and standard deviation are known and the standardized normal deviate, Z, can be used to make the calculation.

$$Z = \frac{7-\mu}{\sigma} \qquad \text{Equation 1}$$

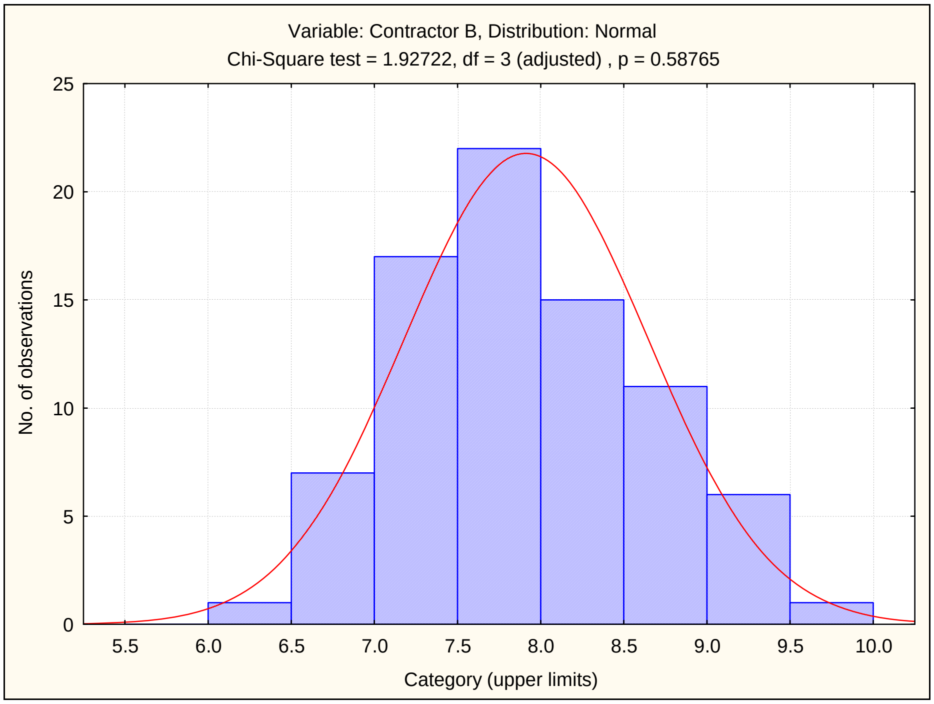
where μ is the mean and σ the standard deviation of entire contract dataset, based on contractor and State data.

The value of Z was calculated to be –1.78 and –1.31 for contracts 1 and 2, respectively. From a normal distribution table, this shows a percent area of 3.75% for contract 1, and 9.5% for contract 2 related to the percentage of defective samples.



1 in = 25.4 mm

Figure 10. Frequency histogram and validation of normal distribution through Chi-square test for thickness measurements by contractor A.



1 in = 25.4 mm

Figure 11. Frequency histogram and validation of normal distribution through Chi-square test for thickness measurements by contractor B.

Contract 2 has a much greater percent deficient indicating that contract 2 resulted in much higher variation in construction process than contract 1. Thus, even though the mean thicknesses are the same between the two contracts, this higher variation in slab cracking will lead to a much earlier amount of cracking in contract 2 than 1 because thinner slabs mean more rapid fatigue cracking. In fact, 25mm (1 in) is a very significant difference that could reduce the time to, say, 10 percent cracked slabs (often used as a failure criterion) by one-half or more.

Summary and Recommendations

In summary, the statistical analyses in this example, which are based on basic QA data for two projects, show the following results:

- The underlying distribution of slab thickness as measured by coring is approximately normal. (Note that the sampling did reproduce the underlying fact that the data were simulated from a normal distribution.)
- There was no significant difference between the contractor measurements and the State check measurements overall for lot means of thickness within the same contract. This also reproduces the underlying simulation process, wherein both contractor and State samples came from the same mean and standard deviation normal distribution.
- There was a significant difference between the variance of thickness for contract 1 and contract 2. Contract 2 exhibited significantly more variation than 1. This was exactly what existed in the underlying populations for contract 1 and 2.

- The percent defective (e.g., < 178 mm [7 in]) was estimated showing contract 2 with 9.5 and contract 1 with 3.75. This will result in far more rapid fatigue crack development in contract 2 than 1, shortening the service life or increasing the amount of maintenance of contract 2. This occurred even though the means were similar for each contractor.

Thus, even basic QA data can be analyzed to show a number of important practical conclusions about the as-constructed characteristics of a given contract or multiple contracts. More analyses can be performed that address such things as within contract variability from lot to lot and how these data may be used to improve the specification.

5.2.2 Contractor Test Results Used in the Acceptance Decision

Although most SHAs have transferred primary responsibility for QC of asphalt materials to the producers doing the work, the issue to allow contractor test results for acceptance control and payment remains. A database that tracks both contractor and agency test results would allow SHAs to verify contractors' QC tests to provide resolution on issues like contractor payment. The FHWA allows SHAs to use the contractor's test results for payment, provided the States verify that the contractor's results are representative of the actual material being reproduced. This requirement is statistically challenging.

Verification testing could be limited. For example, the State may select (randomly) to test a single sub-lot compared to the contractor that tests each sub-lot for QC. While the State and contractor tests may compare within statistical limits, the risk to the agency of accepting unacceptable quality work (Type II error) is great. This problem is being addressed under NCHRP Project 10-58 (02), "Using Contractor-Performed Tests in Quality Assurance." *NCHRP Synthesis 346* (Hughes, 2005) discusses State construction QA programs and the Title 23, CFR 637 regulation adopted by FHWA in 1995 that requires each SHA to develop a QA program for the National Highway System (NHS). It emphasizes that verification of contractor test results by the State be done through the use of independent samples. The use of split samples can only address differences in test procedures. A database of both State assurance and contractor control test results collected independently (and randomly), spanning several lots or days of work combined, would allow a more thorough evaluation of material conformance.

Verification of Contractor Test Results

As mentioned previously, there are two procedures for verification of independently obtained test results, the *F*-test and *t*-test, which usually are used together. This procedure involves two hypothesis tests, where the null hypothesis, H_0, for each test is that the contractor's test and the agency's tests are from the same population. The *F*-test is applied to ensure that the variabilities of the two data sets are equal and the *t*-test to ensure that the means of the two data sets are equal. Both tests require more than one agency test result before a comparison can be made. The application of this verification procedure is easily illustrated in this example.

Consider the contractor and agency air void test results shown in table 11. For each of the four sublots from every lot of AC paved, the contractor obtains a sample randomly and performs a density test to determine the air voids content of the sample. This measure is used to evaluate compaction density and is used for pay factor calculation. To verify the result, the agency independently runs the same test from a single, randomly obtained core from a lot. One procedure used when comparing a single agency test result with multiple contractor test results is to define the allowable interval within which the agency test result must fall as:

$$\overline{X} \pm CR \qquad \text{Equation 2}$$

where $\overline{X}$ and R are the mean and range, respectively, of the contractor test results, and C is a factor that varies with the number of contractor test results (Burati et al., 2003). While this procedure is simple and quick to perform, it is not as effective in detecting differences between data sets as the F- and t-tests.

Description of Project and AQCs

Table 11 presents the air void test results on a flexible pavement construction project undertaken by a contractor. The project included 14 lots, each of which was divided into 4 sublots by the contractor. Contractor results include measurements in each sublot, while the agency's acceptance testing was performed on each lot.

Table 11. AC air void test results, percent.

Lot/Sublot	Contractor–AC Air Voids, percent				Agency–AC Air Voids, percent (random)
	Sublot 1	Sublot 2	Sublot 3	Sublot 4	
1	5.6	7.1	6.2	6.3	6.2
2	8.5	6.8	8.3	5	8.5
3	6.6	6.4	7.3	8	8
4	8.8	6.7	7.2	6.4	7.2
5	6.7	7.1	8.8	5.2	5.2
6	7.3	5.3	7.5	6.6	6.6
7	5.6	5.8	6.8	8.9	6.8
8	7.9	7.2	8.5	6.1	8.5
9	7.6	6.4	9.2	7.6	7.6
10	9.2	7.6	7.1	7.9	7.1
11	8.9	6.8	7.7	7.9	6.8
12	8.8	5.6	7.5	7.2	7.5
13	5.6	5.8	7.7	6.9	6.9
14	8.3	5.3	6.7	6.2	5.3

Data Analysis

Both the F-test and t-test can be implemented easily using the Data Analysis functions in Excel®. Table 12 shows the results of an F-test run on the example data shown in table 11. The test was run using a level of significance or alpha of 0.01. This is the probability of rejecting a null hypothesis when it is actually true. Typical levels of significance are 0.1, 0.05, and 0.01. Note that the Excel®-calculated F values are determined for a one-tail F distribution. For a two-tail

F-test in Excel®, the level of significance input must be halved ($\alpha = 0.005$). This will be the case when evaluating the null hypothesis, H_0: $S_a^2 = S_c^2$. Since $F < F_{crit}$ (i.e., 1.225 < 3.885), there is no reason to believe that the two sets of data have different variabilities. That is, they could have come from the same population.

Table 12. *F*-Test - Two-sample for variances at a level of significance of 0.01.

Statistic	Contractor	Agency
Mean Air Voids, %	7.107142857	7.014285714
Variance	1.241766234	1.013626374
Observations	56	14
Df	55	13
F	1.225072932	
P(F<=f) one-tail	0.358971263	
F Critical one-tail	3.884815671	

Given that the standard deviations of the two data sets are sufficiently similar, the Student *t*-test can be used to evaluate the hypothesis of equal means. If not, an alternative—the Cochran variant of the *t*-test (assuming unequal variances)—must be run to evaluate the hypothesis of equal means. Both *t*-test variants can be evaluated using the Data Analysis routines in Excel®. Table 13 shows the results of a *t*-test assuming equal variances at the 0.01 significance level.

Table 13. *t*-Test: Two-sample assuming equal variances ($\alpha = 0.01$).

Statistic	Contractor	Agency
Mean Air Voids, %	7.107142857	7.014285714
Variance	1.241766234	1.013626374
Observations	56	14
Pooled Variance	1.198151261	
Hypothesized Mean Difference	0	
Df	68	
t Stat	0.283902034	
P(T<=t) one-tail	0.388674059	
t Critical one-tail	2.382445783	
P(T<=t) two-tail	0.777348117	
t Critical two-tail	2.650081279	

Results of the *t*-test shown in table 13 indicate that *t*-statistic is less than t-crit (0.284 < 2.650); therefore, the hypothesis of equal means cannot be rejected at the 99 percent confidence level. Note that use was made of the two-tail distribution for evaluating the hypothesis of equal means. We can therefore assume that both data sets came from the same population and that the agency results verify the contractor results. This provides the agency with confidence in using the contractor's results for acceptance decisions.

5.2.3 Illustration of Relationships between Pavement Construction AQCs and Performance

This example was derived using simulation and the latest models from the Mechanistic-Empirical Pavement Design Guide (MEPDG) (Applied Research Associates, 2004). The example shows through reasonable simulation that it is possible to obtain a relationship between measured AQC test results and the subsequent performance of the pavement over a period of 15 years. This information can be used for many purposes including the improvement of the construction specification.

Description of Project and AQCs

Portions of a JPC pavement project were constructed over 2 months (July and October) that included a total of 20 lots. Each lot was approximately 0.8 to 2.4 km (0.5 to 1.5 mi) long, consisting of two-lane paving and four sublots each. The AQCs included initial IRI, compressive strength at 28 days, and slab thickness.

Simulated Construction Process

Two random samples of strength (cylinders behind the paver), cores for slab thickness, and IRI averaged in the wheelpaths of each lane were taken from each of the sublots within a given lot. The random samples were actually simulated from normal distributions for the purpose of this example. The population mean of each lot was varied in a way to demonstrate what might occur from an inconsistent contractor (e.g., higher variability between lots which might be built on different days). The mean AQCs obtained from sampling (from a normal distribution) varied substantially from lot to lot along the project, demonstrating inconsistent quality of construction. Results from construction testing for slab thickness, compressive strength at 28 days, and initial IRI are shown in table 14.

Future Performance Prediction

The beginning and ending of each lot were referenced in the field and recorded, making it possible to correlate directly with performance data measured by the pavement management bureau over a period of 15 years. This link is obviously required to make this correlation. The pavement showed fairly wide-ranging performance along the project over the 15 years. A summary of performance data measured at the end of the 15-year period for slab cracking (percent slabs transverse cracks), mean joint faulting, and IRI (in the outer traffic lane) is shown in table 15. Note that the performance data were simulated using the MEPDG prediction models.

Analysis of Data

Simple plots showing the mean lot AQCs versus projected cracking, faulting, and initial IRI illustrate the correlations that might be achieved in an actual situation. Figures 12 through 15 show the correlations that appear to be significant. Other correlations did not show any relationship to each other. All three of the AQCs for this project appear to have an impact on distress and IRI after 15 years of performance of this project. Further, as shown in figure 16, the month of construction was found to have a significant effect on the magnitude of joint faulting.

Table 14. Data from simulated AQC slab thickness, core strength, and initial IRI in 20 lots measured two lanes along project.

Lot #	Sublot #	Thickness, in			Compressive Strength, lb/in^2			IRI, in/mi			Constr. month
		core 1	core 2	Mean	cyl 1	cyl 2	Mean	WP 1	WP 2	Mean	
1	1	7.9	8.5	8.02	6990	7097	6101	47	56	51	oct
	2	7.5	8.7		6560	5673		38	64		
	3	8.1	7.1		5538	6922		52	52		
	4	8.5	7.9		5853	4180		33	64		
2	1	9.0	8.3	8.55	6048	6027	6008	51	73	66	oct
	2	8.5	8.4		5916	4761		74	59		
	3	9.4	8.2		7559	5974		63	70		
	4	8.2	8.4		6231	5546		61	74		
3	1	7.5	8.3	7.68	5869	4287	5536	57	59	62	oct
	2	7.1	7.9		5930	6973		69	59		
	3	7.7	7.9		4715	5158		71	57		
	4	7.6	7.4		6010	5345		65	57		
4	1	8.4	9.0	9.04	5662	7142	5957	60	74	67	oct
	2	9.0	9.0		6683	6293		69	64		
	3	8.8	10.0		6595	5887		69	60		
	4	9.1	9.0		4799	4592		65	78		
5	1	7.1	6.5	7.10	8380	4452	6550	66	58	67	july
	2	7.2	7.1		6363	7239		61	86		
	3	7.3	6.9		6585	5866		72	63		
	4	7.4	7.2		5997	7520		79	54		
6	1	8.7	7.7	8.10	7495	5491	6528	68	55	64	july
	2	7.8	8.1		6539	6706		55	74		
	3	8.6	8.6		7522	5844		74	44		
	4	7.3	8.1		7476	5153		70	74		

1 in = 25.4 mm; 1 lb/in^2 = 6.895x10-3 MPa; 1 in/mi = 0.015875 m/km

Table 14. Data from simulated AQC slab thickness, core strength, and initial IRI in 20 lots measured two lanes along project (continued).

Lot #	Sublot #	Thickness, in			Compressive Strength, lb/in^2			IRI, in/mi			Constr. month
		core 1	core 2	Mean	cyl 1	cyl 2	Mean	WP 1	WP 2	Mean	
7	1	9.1	8.4	8.30	7826	8150	6755	61	22	52	oct
	2	8.4	8.1		6194	7674		60	59		
	3	7.8	8.1		4025	7818		57	45		
	4	8.1	8.4		5895	6459		43	69		
8	1	7.6	7.7	7.46	6789	8156	7655	50	55	54	july
	2	7.6	7.4		6362	8351		80	54		
	3	6.9	6.9		7769	6927		47	49		
	4	7.6	8.0		9062	7821		36	61		
9	1	9.7	9.2	9.06	8022	7388	7241	48	67	51	oct
	2	9.5	8.5		6139	7113		48	44		
	3	8.2	8.8		7083	7875		41	50		
	4	9.3	9.4		6718	7588		60	53		
10	1	8.2	6.9	7.50	6896	7386	7169	57	62	61	oct
	2	7.4	7.4		5663	8359		58	57		
	3	7.5	7.7		5833	7758		71	63		
	4	7.4	7.5		8173	7283		47	70		
11	1	7.3	8.4	7.97	5816	6906	6100	101	106	92	oct
	2	8.6	7.9		5726	5728		82	93		
	3	7.9	8.2		6469	5064		96	56		
	4	7.7	7.8		7293	5801		109	93		
12	1	8.0	8.1	8.51	5009	5285	6403	100	82	91	oct
	2	8.8	8.7		6643	7017		99	86		
	3	8.3	8.9		7363	7382		103	81		
	4	8.8	8.5		6321	6203		78	100		

1 in = 25.4 mm; 1 lb/in^2 = 6.895x10-3 MPa; 1 in/mi = 0.015875 m/km

Table 14. Data from simulated AQC slab thickness, core strength, and initial IRI in 20 lots measured two lanes along project (continued).

Lot #	Sublot #	Thickness, in			Compressive Strength, lb/in²			IRI, in/mi			Constr. month
		core 1	core 2	Mean	cyl 1	cyl 2	Mean	WP 1	WP 2	Mean	
13	1	7.9	7.6	7.47	5435	4486	5611	94	64	77	oct
	2	7.0	6.7		4902	5153		67	80		
	3	8.3	7.5		6508	6119		76	83		
	4	7.3	7.4		6524	5759		74	78		
14	1	8.2	9.9	8.79	6874	7035	6254	86	89	82	oct
	2	8.8	8.1		6605	6057		84	81		
	3	8.7	8.2		5429	6324		68	67		
	4	9.9	8.5		5169	6537		85	95		
15	1	6.6	7.8	7.00	6301	6015	5682	104	92	89	july
	2	7.4	6.5		6396	6092		100	76		
	3	7.3	6.5		3819	5421		67	83		
	4	6.3	7.6		6253	5157		95	98		
16	1	7.9	7.8	8.05	7202	7710	7248	114	83	98	july
	2	7.8	8.1		8207	6868		95	96		
	3	8.1	8.1		6782	6707		97	102		
	4	8.6	8.0		6985	7527		96	97		
17	1	8.2	8.2	8.48	8188	6351	6590	78	100	83	oct
	2	8.7	8.7		6395	6352		72	89		
	3	9.1	8.3		6852	7532		87	85		
	4	8.5	8.2		5923	5125		76	79		
18	1	8.3	7.7	7.96	7613	7834	7322	96	96	98	july
	2	7.3	8.6		8236	5159		91	102		
	3	7.9	8.0		8190	7571		90	114		
	4	7.2	8.8		7163	6809		95	104		

1 in = 25.4 mm; 1 lb/in^2 = 6.895x10-3 MPa; 1 in/mi = 0.015875 m/km

Table 14. Data from simulated AQC slab thickness, core strength, and initial IRI in 20 lots measured two lanes along project (continued).

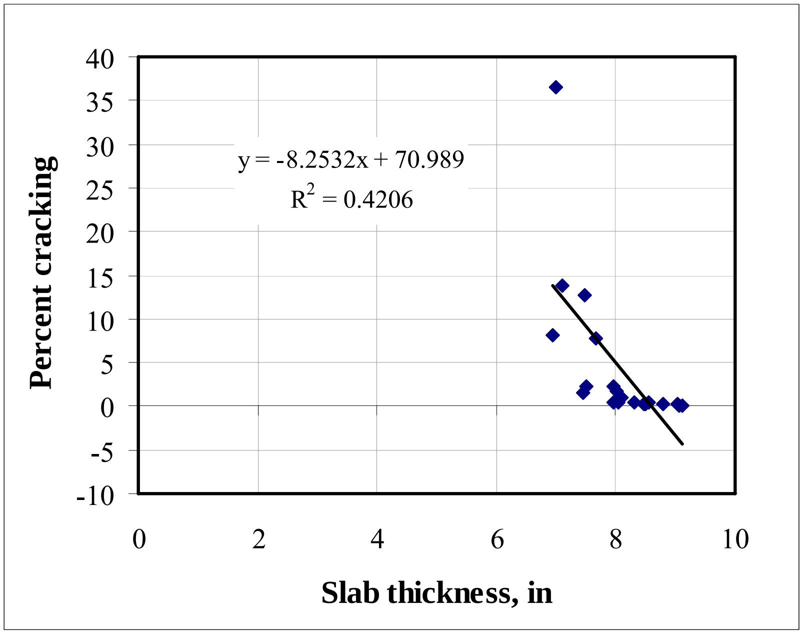
Lot #	Sublot #	Thickness, in			Compressive Strength, lb/in^2			IRI, in/mi			Constr. month
		core 1	core 2	Mean	cyl 1	cyl 2	Mean	WP 1	WP 2	Mean	
19	1	8.8	9.5	9.12	7175	7215	7103	72	62	77	oct
	2	9.5	9.0		7697	6580		80	85		
	3	8.7	9.1		8285	7209		82	87		
	4	8.3	10.0		6706	5959		84	68		
20	1	6.5	6.7	6.94	7362	7895	7139	64	77	78	oct
	2	6.8	7.0		7033	7292		83	82		
	3	6.8	7.2		7484	6850		72	94		
	4	7.2	7.2		6892	6304		66	86		

1 in = 25.4 mm; 1 lb/in^2 = 6.895x10-3 MPa; 1 in/mi = 0.015875 m/km

Table 15. Summary of cracking, joint faulting, and smoothness (IRI) after 15 years.

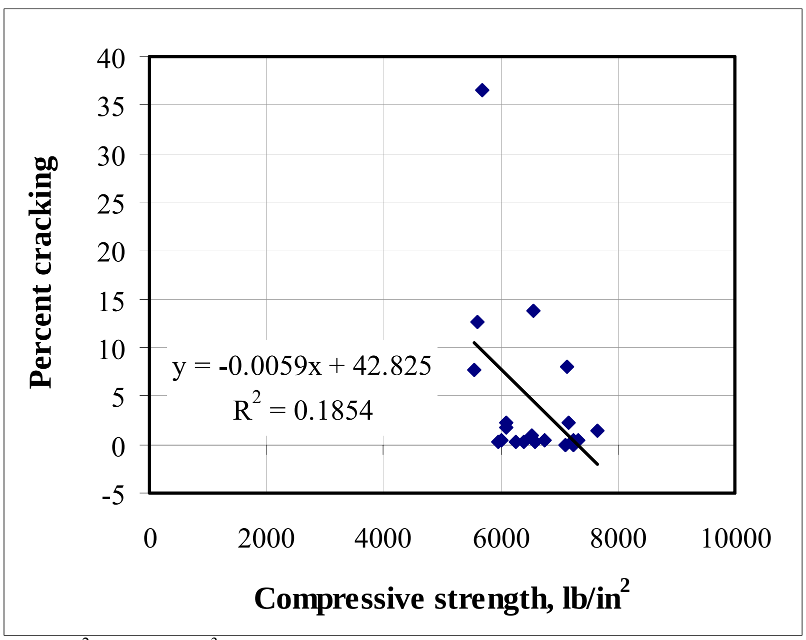
Lot#	Mean Cracking, %	Mean Faulting, in	Mean IRI, in/mi
1	1.8	0.1029	120.2
2	0.5	0.097	130.6
3	7.7	0.0916	130.4
4	0.2	0.0823	134.5
5	13.8	0.0894	140.2
6	0.9	0.1265	145.4
7	0.4	0.1019	119.7
8	1.5	0.101	122.6
9	0	0.0758	104.8
10	2.2	0.0867	122.2
11	2.2	0.1012	161.0
12	0.3	0.0966	155.7
13	12.7	0.086	146.7
14	0.2	0.0888	142.4
15	36.5	0.0843	178.1
16	0.4	0.1233	176.6
17	0.3	0.0969	148.1
18	0.5	0.1192	175.4
19	0	0.0746	130.2
20	8.1	0.0754	138.8

Note: These values were computed using the mean lot AQCs and other inputs using the MEPDG for each lot.
1 in = 25.4 mm
1 in/mi = 0.015875 m/km



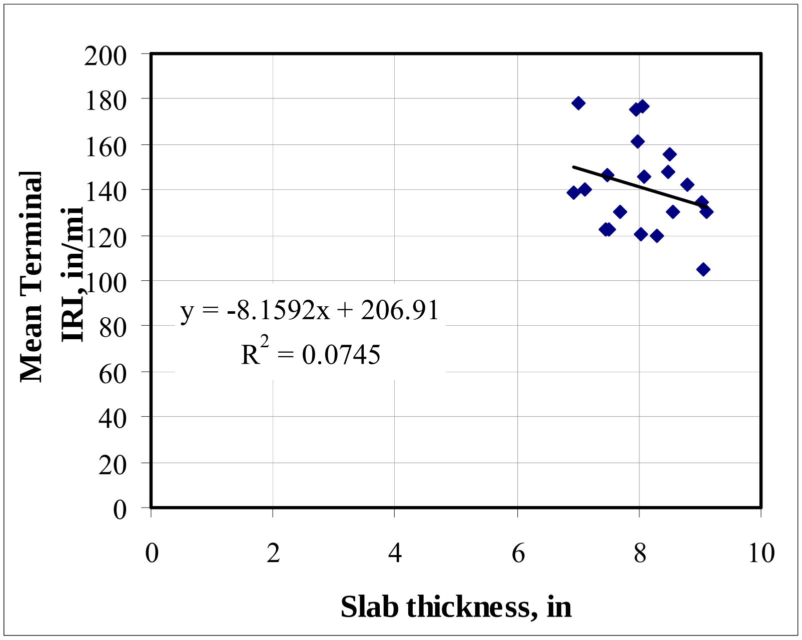
1 in = 25.4 mm

Figure 12. Lot slab thickness versus percent slab cracking along project.



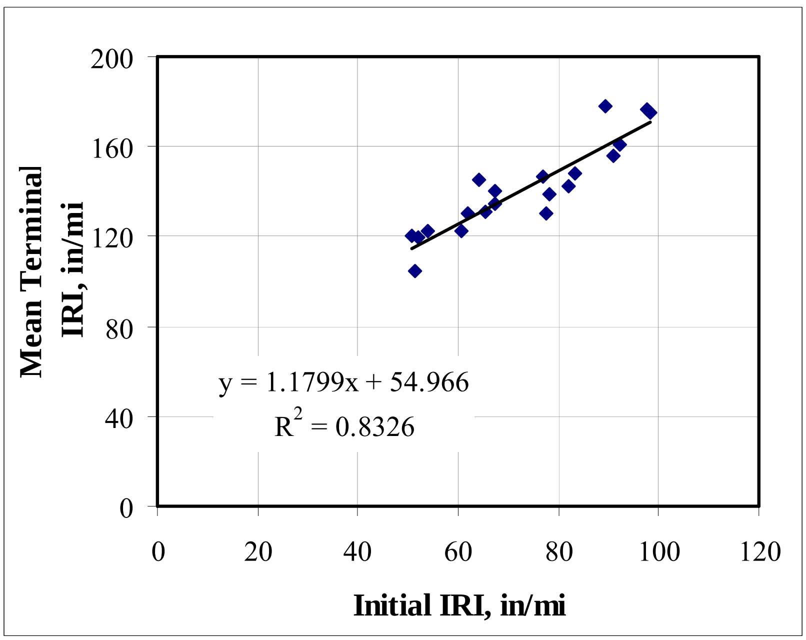
1 lb/in^2 = 6.895x10^{-3} MPa

Figure 13. Lot compressive strength versus percent slab cracking along project.



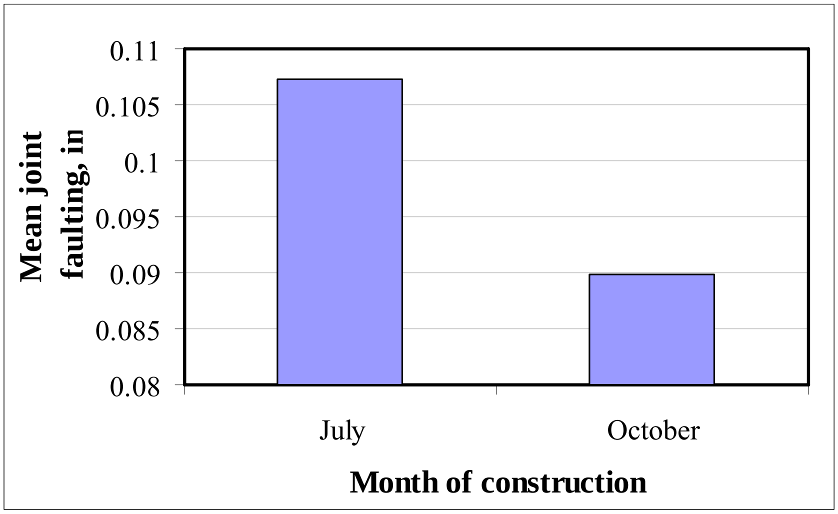
1 in = 25.4 mm; 1 in/mi = 0.015875 m/km

Figure 14. Lot slab thickness versus IRI along project.



1 in/mi = 0.015875 m/km

Figure 15. Lot initial IRI versus percent mean terminal IRI of lots along project.



1 in = 25.4 mm

Figure 16. Lot month of construction versus mean joint faulting along project.

While these plots show general trends, a statistical analysis of variance (ANOVA) was conducted to determine if any of the AQCs have a significant effect on distress and IRI. The results obtained are as follows:

- Slab cracking along this project at 15 years was significantly affected (at the 0.05 level) by lot mean thickness and lot mean compressive strength (at 28 days). ANOVA results that show the effect of AQCs on slab cracking are shown in table 16. As shown in figures 12 and 13, a thinner slab and lower slab strength result in greater transverse slab cracking over 15 years. This can be explained mechanistically by higher bending stresses and fatigue damage resulting from reduced thickness and strength values.

Table 16. ANOVA results showing the effect of AQCs on slab cracking

Source	DF	Type 1SS	Mean sq	F value	Pr> F
Mean thk	**1**	**597.8955**	**597.895**	**17.6**	**0.0008**
mean f'c	**1**	**228.4178**	**228.418**	**6.73**	**0.0204**
IRI lot	1	21.91266	21.9127	0.65	0.4344
c month	1	61.46464	61.4646	1.81	0.1985

- Joint faulting along this project over 15 years was not significantly affected by any of the AQCs (at the 0.05 level), but was affected by the lot construction month, as shown in the ANOVA results in table 17. Figure 16 shows that faulting is significantly higher for those lots placed in July as compared to October. The concrete temperature and ambient temperature were both likely much warmer in July than in October. This would result in much greater temperature change from peak temperature during construction to coldest conditions during the winter, resulting in wider joints during cold months during the 15-year period. This leads to lower load transfer and increased joint faulting. Decreasing the maximum temperature during setting is helpful for many reasons, including faulting.

Table 17. ANOVA results showing the effect of AQCs on joint faulting.

Source	DF	Type 1SS	Mean sq	F value	Pr> F
Mean thk	**1**	1.057E-05	1.06E-05	0.06	0.8141
mean f'c	**1**	0.0001021	0.000102	0.55	0.4683
IRI lot	1	2.699E-05	2.7E-05	0.15	0.7074
c month	**1**	**0.0013434**	**0.001343**	**7.28**	**0.0165**

- IRI over 15 years (called terminal IRI, herein) along this project was significantly affected (at the 0.05 level) by AQCs lot mean thickness, initial IRI, and also by the month of construction. It was also somewhat affected by concrete strength. The thinner the slab, the greater the IRI, as shown in figure 14. This is because thinner slabs have greater slab cracking. The higher the initial IRI after construction, the higher the IRI after 15 years, as shown in figure 15. This plot shows an obviously strong correlation. The month of construction also had an effect on IRI due to the effect on joint faulting. Results of ANOVA analysis are presented in table 18.

Table 18. ANOVA results showing the effect of AQCs on IRI.

Source	DF	Type 1SS	Mean sq	F value	Pr> F
Mean thk	**1**	910.83112	910.8311	58.36	<.0001
Mean f'c	**1**	63.793992	63.79399	4.09	0.0614
IRI lot	1	4810.5482	4810.548	308.25	<.0001
c month	**1**	712.94625	712.9463	45.68	<.0001

The purpose of this example was to illustrate through reasonable simulation how typical AQC data measured along a given project (lot by lot) could be correlated with future performance of each lot. There were 20 lots along the project which consisted of two lanes of JPC pavement placed with a slip-form paver. The population mean of each lot was varied for each of the AQCs in a reasonable way, as might exist along a construction project. The variation was introduced to demonstrate an inconsistent contractor who performed good to poor quality work along the project. Two samples were then taken from a normally distributed lot population for each of the AQCs in each of the sublots. All of these AQC data were averaged to obtain a lot mean for each AQC.

The original construction lots were defined by reference points that were later linked to pavement management performance measurements over time. This link is absolutely essential. The expected performance was predicted using the AQC data for each lot, along with inputs such as coefficient of thermal expansion of concrete and traffic loadings (that were constant between lots) to predict the performance of each lot.

The performance was predicted year-by-year for each construction lot over a 15-year time period. The analysis could have used any other performance period, or points along a timeline. The AQC data were then correlated with future performance trends to identify relationships between measured AQC test results and the subsequent performance of the pavement over a period of 15 years.

In this example, the slab thickness AQC was found to correlate with slab cracking and long-term IRI. The slab compressive strength was found to correlate with slab cracking. The initial IRI after construction was found to correlate to the long-term IRI and slab thickness. In addition, the month of construction was found to correlate to joint faulting and long-term IRI.

If these results were found for an actual project they could be used to demonstrate how important various AQC are to the service life of a pavement. They could then be used to revise the specification to make it more effective. For example, since slab thickness was found to be so significant, the range of thicknesses from lot to lot may need to be controlled more tightly. In this example, the lot means varied from 152 to 231 mm (6.9 to 9.1 in), which seems to be much too wide a range. This alone, regardless of other AQC variations, caused a significant change in slab cracking.

Variation in 28-day compressive strength ranged from 38.1 to 52.8 MPa (5,536 to 7,655 lb/in^2), which led to significant changes in cracking and IRI. Perhaps this AQC should be controlled more tightly also. The initial IRI of the lots varied from 0.81 to 1.56 m/km (51 to 98 in/mi) and was very significant in affecting the IRI throughout the first 15 years of the pavement life. Perhaps this factor and its variation along a project need to be much more tightly controlled, as it also affects pavement smoothness significantly. The IRI at the end of the 15-year time period averaged at 2.24 m/km (141 in/mi) and ranged from 2.46 to 4.35 m/km (155 to 274 in/mi). This clearly needs to be "smoothed out" along the project so that the user can enjoy a more consistent ride quality.

The results also indicated that construction period or climate (July and October) had a significant effect on the future performance. Those lots built in July had significantly greater faulting and higher IRI after 15 years than those built in October. This may indicate a need to reduce curing temperature (or set temperature) more closely to maximize pavement life. This could be done, for example, through the use of supplementary cementitious materials (SCMs), such as fly ash, and/or changing the curing specification.

This example shows a construction project with well-referenced AQC data that are linked to pavement performance data over time (from the PMS files). The correlations achieved between AQCs and performance shows the importance of establishing and maintaining databases to improve the overall quality and efficiency of construction quality systems. These results can then be used to justify the need to improve quality through improved specifications. This project was set up to be "inconsistent" along its length and to show that performance would vary lot by lot. These results showed some significant correlations with performance. The need to improve these specifications is evident.

5.2.4 Relating AQC, Cost and Performance Data

Historically, QA, costs, and performance information of materials collected by SHAs as used in road construction are archived and processed separately. The challenge in relating these data is identifying unique data fields that are consistent across the different database platforms.

In a study undertaken for the TxDOT, three data fields were identified as critical for relating cost and performance information (Smit et al., 2004). These fields relate to identifying the location and extents of a construction project and include date (construction or letting), route number, and the beginning and ending reference markers or mile-points defining the extents of the project. As a result of the aforementioned study, TxDOT now requires these data fields as mandatory inputs in construction cost (letting) and QA databases. TxDOT maintains two databases to track construction costs. The first is an as-designed or planned Design and Construction Information System (DCIS), and the second an as-built database forming part of the *SiteManager* suite of programs. The latter database also includes QA information for construction materials collected from agency and contractor tests.

Roadway performance data are collected at the project and network levels. The benefit of network-level data is that the performance of the road network can be tracked over time. TxDOT measures ride quality and rates pavement distress on the State highway network annually. Distresses measured include shallow and deep rutting, alligator cracking, failures, longitudinal and transverse cracking, block cracking, patching, raveling and flushing. These distresses are used to develop ride, distress and condition scores. These data are archived in the PMIS database that includes a mapping function to allow a visual assessment of the condition of pavements in Texas. Although PMIS is able to rate the condition of State highways, this information cannot be directly related to the performance of asphalt mixtures, for example, on these highways. This is because the PMIS rates the roadway network and not the materials on the road directly. This is easily addressed, however, if one is able to locate where on a section of road an asphalt mixture was paved.

Another hurdle to overcome when relating network-level performance data is the uncertainty of the exact location on the road where the performance data were collected. In the case of multi-lane roads, PMIS data are collected on whichever lane visually appears to be the most distressed. More often than not, this is the outside lane of the road, which typically is subjected to a higher percentage of heavy truck traffic. Consequently, in adjudicating performance scores for asphalt mixtures on multi-lane roads, it is necessary to consider where and on which lane the specific asphalt mixture is paved. There are a number of factors influencing the PMIS performance measures, not only the quality of the asphalt material. Factors such as climate, traffic, and subsurface structural condition would also need to be considered in an overall evaluation of material performance. Climate databases are easily referenced. TxDOT includes traffic data in the PMIS database based on counts at selected weigh stations around the State. Finally, perhaps the most difficult aspect to track successfully over time is maintenance. TxDOT maintains a Maintenance Management Information System (MMIS) database. This database system tracks when and where maintenance activities are applied on the roadway network including crack sealing, pothole repair etc and the costs involved.

Description of Project and AQCs

To illustrate the benefits of being able to relate cost, construction quality, and performance databases, consider the following practical example that attempts to relate QC during construction to performance in the field. Two 19-mm Superpave mixtures were paved in 1997 as surface layers on roads in Texas. General information for these projects is shown in table 19. This example will use actual QC, cost, and performance data collected from various databases that ideally would be linked to allow on-the-fly analyses.

Table 19. General information of 19-mm Superpave projects.

Control	Poor	Good
Project #	0207-05-060	0044-03-038
District	Atlanta	Wichita Falls
County	Harrison	Clay
Route	SH-43	US-82
Beginning Milepost	16.9	3.9
Ending Milepost	21	15.5
Quantity, tons	10160.50	30127.08
Cost, $/ton	35.68	30.02

1 ton = 0.907 tonnes

The construction quantity and cost information of the mixtures shown in table 19 were extracted from the TxDOT DCIS database. The database field required to retrieve this information from the DCIS was the project number.

Construction quality information for these projects was obtained from a TxDOT publication (TxDOT, 1998). On one of the projects, the QC was very poor compared to the other on which construction quality was controlled very well. This is evidenced in the binder contents measured for each sublot during construction. Figure 17 illustrates the deviation of the binder contents from the job mix formula (JMF) target for the two projects. On the poorly controlled project, there is a wide variation in construction binder contents and the mean deviation is less than zero, indicating that the mixture was consistently under-asphalted.

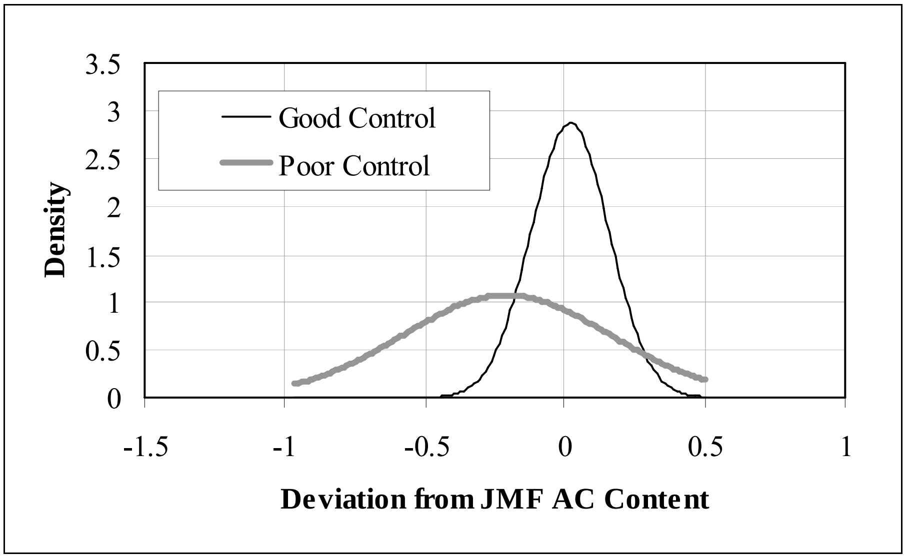
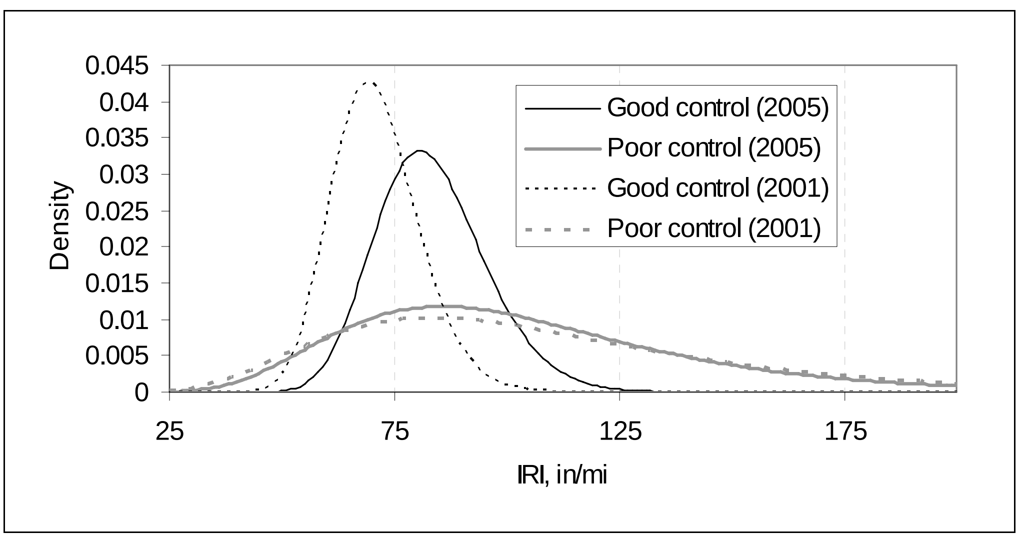


Figure 17. Variation in construction binder contents.

A possible consequence of poor QC during construction is the subsequent poorer performance of the mixtures in the field. Figure 18 shows the distribution of roughness measurements collected for both project sites a few years following construction in 2001 and again in 2005. These data were queried from the TxDOT PMIS using the location information in table 19. Location information in the PMIS is in terms of Texas Reference Marker (TRM), but it is possible to calculate a TRM from roadway mile-point using the mile-point reference marker equivalency (MPRME) database. Figure 18 indicates that the project with poor QC resulted in a pavement that was rougher and that had a greater variation in roughness compared to the project with good QC during construction.



1 in/mi = 0.015875 m/km

Figure 18. Average IRI roughness measurement distributions.

Figure 19 shows annual maintenance costs for the two projects collected from the TxDOT MMIS database.

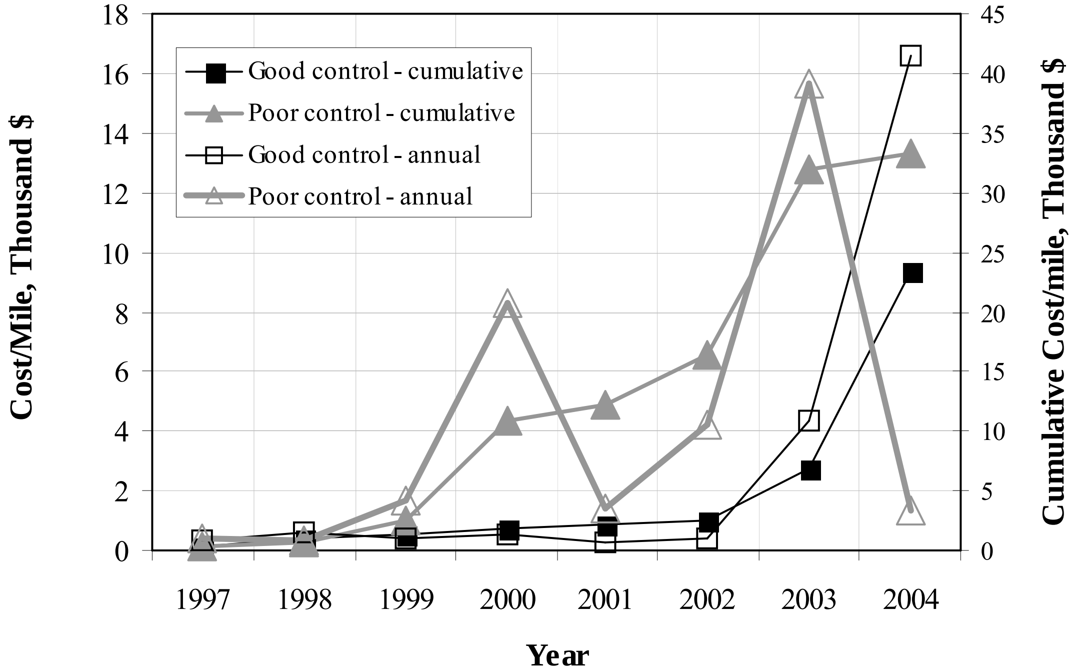


Figure 19. Maintenance costs from construction date.

Clearly, the Superpave mixture from the project with better QC during construction has been more cost effective. A comparison of the sum of present worth (PW) of costs including construction and maintenance over 7 years from the date of construction indicates that the project with better QC was the better investment. Calculated PW for the two projects (good and poor) were $62,249.17/km ($99,598.67/mi) and 74,087.10/km ($118,539.37/mi) respectively, using an interest rate of 8 percent. Ironically, the poorer performing project carried 5 times the traffic in terms of equivalent standard axle loads (ESALs, determined from the Texas Reference Marker database) compared to the better performing project. As a result the economic impact due to total user vehicle operating costs (VOC) would be higher with the rougher pavement.

A system that facilitates the evaluation of the quality, cost, and performance information of asphalt mixtures provides pavement engineers with a tool to calculate the relative cost-benefit ratio of asphalt pavements. While SHAs may have databases and infrastructure to evaluate the quality, cost, and performance of asphalt mixtures, generally lacking is the ability to quickly assimilate this information to derive cost-benefit. The current study provides impetus towards the development of a tool for this purpose.

5.2.5 Use of Construction Database for Development of Performance-Related Specifications and Warranties

One of the most important uses of historical construction databases is aid in the development of new or improved specifications. Two such specifications are PRS and performance warranties. A number of highway agencies have developed and/or implemented these specifications for asphalt and concrete pavement construction (Hoerner and Darter, 1999). The following briefly summarizes the major concepts involved in using the construction quality database for development of PRS and warranties.

To validate the PRS, the following information is required and can be obtained from the model database:

- Previous projects where good QA has been performed. Also useful, but not required, is the performance of a number of QA lots that has been measured over time.
- History of means and standard deviations of AQCs desired for use in asphalt and concrete pavements (e.g., PI, IRI, compressive strength, binder content). These values obtained from several projects will form the basis of the targets and standard deviations needed to develop the PRS.
- History of bid prices for HMA and PCC pavement.
- Performance data to check the predictions of the PRS equations for distress and IRI (desired but not required as long as the PRS models are applicable to the project to be built).
- History of pay factor results on similar projects to compare to PRS results in sensitivity analysis.

Warranties require the following information that can be obtained from the model database described:

- Performance data for key performance indicators (distress types and smoothness) that are of interest in the warranty specifications (e.g., alligator cracking, rutting, IRI, raveling, bleeding, slab cracking, joint faulting) over time for the general design and materials used in the project.
- Preparation of survival plots and calculations showing each of these performance indicators over time for as many similar projects as possible (e.g., doweled JPC, deep-strength HMA, HMA overlays of PCC, Superpave).
- Analysis of the plots and calculation of statistics giving percent “failures” for various warranty time periods and limiting performance criteria. Figure 20 has been prepared using actual long-term pavement performance (LTPP) JPC data to illustrate this concept for three different failure criteria—1, 5, and 10 percent slabs cracked—and for 5-, 7-, and 10-year warranty periods.
- Selection of a warranty period and the corresponding percentage of projects that would have failed and succeeded the warranty period.
- Analysis of the results to determine the risk involved to the owner agency and the contractor if using the performance warranty.

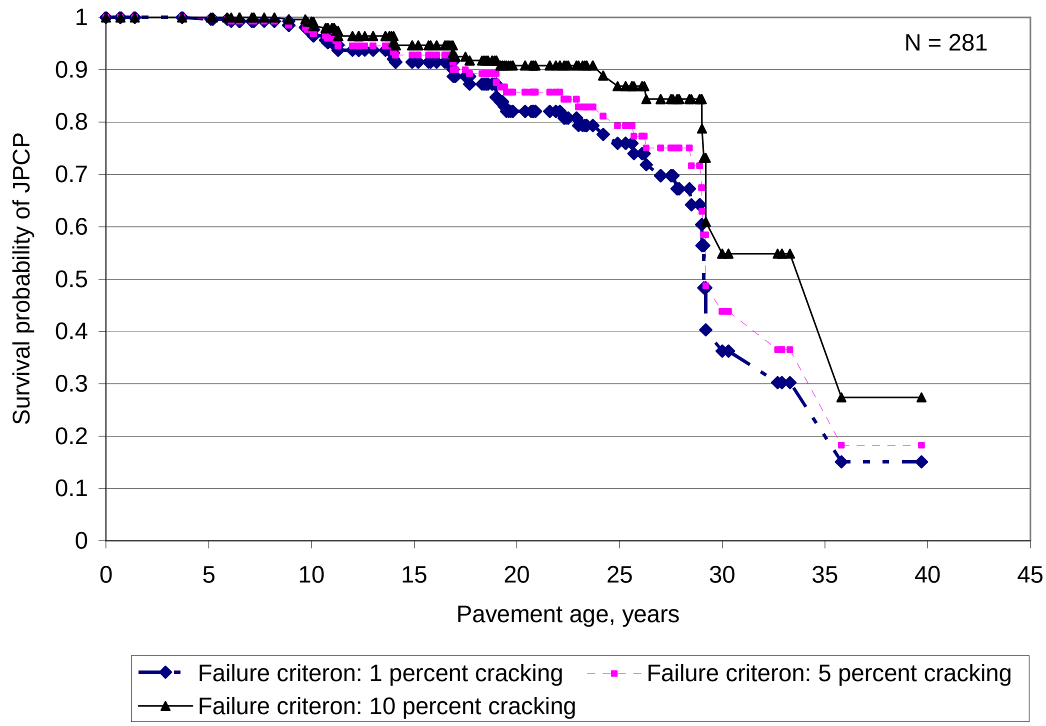


Figure 20. Example survival plots at varying failure criteria for LTPP JPC projects designed and built by highway agencies nationwide.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

6.1 SUMMARY

SHA QA programs are designed to provide a means for the State and the contractor to build good quality and long-life pavements. A variety of laboratory and field tests are conducted at different stages of the project, from material selection and mix design to final construction. These tests measure the properties of materials placed and the overall quality of construction. In the process, both the agency and the contractor collect a large amount of data that are stored in different formats, depending on the agency's practices. Most agencies either maintain a construction quality database or are moving towards automating the data collection and storage process. Across different States, these databases have been designed to meet their specific needs, and current systems differ considerably in their architecture, purpose, and data collection procedures.

The main objective of this study was to recommend guidelines for SHAs to establish and maintain efficient database systems to record construction quality information for asphalt and concrete paving projects. These recommendations are based on a summary of best practices gathered from various States and on the project team's vision of a model construction quality database system.

As a first step, researchers contacted SHAs that have been proactive in establishing and maintaining construction quality systems. A detailed survey helped to understand their practices on their general database system, QA program, data collection procedures, acceptance process, data analysis, and integration with other agency databases. With some of the agencies, the surveys were then followed up with in-depth reviews and site visits to collect detailed information. Generally speaking, it was found that while agencies possess a system that meets their current needs with good data storage facility, the current systems do not offer them the flexibility to easily perform data analysis for broader use. In other words, while the agencies are able to calculate pay factors and make acceptance decisions, the database cannot easily be linked to other databases in the agency to monitor effectiveness of their specifications, or correlate construction quality to field performance, or to tie it back with life-cycle cost analysis. The reasons for these limitations were identified.

The product of this study is the development of a model database that has attempted to address the current and future needs of the surveyed agencies, while also incorporating the positive features that exist in the current database systems across the nation. These recommendations can be used as guidelines by agencies that are either establishing a new database or are in the process of upgrading their current versions. Also suggested are statistical analyses that can be performed using data solely in the construction quality database system, as well as with data linked to other databases. Overall, there are a multitude of benefits to using an efficient construction quality database system, as it can help support several vital activities.

6.2 RECOMMENDATIONS

The recommended database is a Web-based system with client server architecture with a feature to use a standalone machine or a hand-held device for field data collection and subsequent uploading to the server. The system consists of four main modules, as described in chapter 4:

- **Database Server Module**—the core of the architecture storing all system data information and that all client machines connect to through the internet.
- **QA Data Input Module**—the module which provides the framework and format to make data inputs in several categories including general contract information, materials and design, QC testing, acceptance testing, construction records, checklists, and IA testing.
- **QA Management Module**—the module providing the necessary information from State specifications and that uses the data from the QA data input module to calculate pay factors, establish acceptance or rejection decisions, and perform statistical analysis.
- **Data Translation (Referencing) Module**—the module that provides the necessary link and tools to translate data from other agency databases to carry out the analysis on datasets created by integrating two or more databases. This is the critical "missing link" in all current construction quality databases.

In addition to providing an automated project test data entry and storage, a well-designed construction quality database offers several other very important benefits that should be driving agencies to improve and redesign their current systems. These benefits include the generation of several critical outputs and generation of advanced engineering analysis to constantly improve construction quality, pavement performance, and improved life-cycle costs. Benefit analyses are needed that show the costs and benefits of additional staffing to support and conduct these advanced engineering analyses. There are definitely several States that recognize this importance and would like to pursue it.

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- Kansas Department of Transportation.
- Louisiana Department of Transportation.
- Maryland Department of Transportation.
- Minnesota Department of Transportation.
- New Jersey Department of Transportation.
- Pennsylvania Department of Transportation.
- Oregon Department of Transportation.
- Texas Department of Transportation.
- Washington Department of Transportation.

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