Research Report
KTC-02-26/SPR-01-222-1F

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CONTRACTOR PERFORMED QUALITY CONTROL ON KYTC PROJECTS

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176 Raymond Building
University of Kentucky
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(859) 257-4513
(859) 257-1815 (FAX)
1-800-432-0719
www.ktc.uky.edu
ktc@engr.uky.edu

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Contractor Performed Quality Control on KyTC Projects

By

Donn E. Hancher, Ph.D., P.E.
Professor of Civil Engineering

Yuhong Wang
CE Graduate Research Assistant

Kamyar C. Mahboub, Ph.D., P.E.
Associate Professor of Civil Engineering

Kentucky Transportation Center
College of Engineering
University of Kentucky

In cooperation with the Kentucky Transportation Cabinet

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August 2002

September 9, 2002

Mr. Jose M. Sepulveda
Division Administrator
Federal Highway Administration
330 West Broadway
Frankfort, Kentucky 40602

Subject: Implementation State for Final Report entitled
"Contractor Performed Quality Control on KyTC Projects"
Study Number: KYSPR-01-222

Dear Mr. Sepulveda:

The goal of this study was to review the Contractor Performed Quality Control (CPQC) Program currently employed by the Kentucky Transportation Cabinet and provide a base of knowledge for its successful implementation. This was accomplished by working closely with an experienced advisory committee of Cabinet construction personnel, FHWA representatives, and Kentucky Contractors. The CPQC Practices of the other State Departments of Transportation were also extensively studied and incorporated into the final report.

Several issues related to the CPQC program are presented in this report, with emphasis on quality control (QC) /quality assurance (QA) administration, QC/QA procedures, quality acceptance and verification testing, and CPQC training. Specific issues related to CPQC pay items in Kentucky are also discussed. Recommendations have been proposed to enhance the program.

Sincerely,

J. M. Yowell, P.E.
State Highway Engineer

Technical Report Documentation Page

1. Report No. KTC-02-26/SPR-01-222-1F	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle **Contractor Performed Quality Control on KyTC Projects** **(KYSPR-01-222)**		**5. Report Date** August 2002
		6. Performing Organization Code
7. Author(s) Donn E. Hancher, Yuhong Wang, and Kamyar C. Mahboub		**8. Performing Organization Report No.** KTC-02-26/SPR-01-222-1F
9. Performing Organization Name and Address Kentucky Transportation Center, College of Engineering, University of Kentucky, Lexington, Kentucky 40506-0281		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. KYSPR-01-222
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet, State Office Building, Frankfort, Kentucky 40622		**13. Type of Report and Period Covered** Final
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Kentucky Transportation Cabinet and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

This report addresses issues related to transferring the responsibility for quality control from the Kentucky Transportation Cabinet (KyTC) to construction contractors. Surveys of the KyTC, other state departments of transportation, and Kentucky highway contractors were done to identify the advantages, concerns, and modifications of the Contractor Performed Quality Control (CPQC) program. An advisory committee of experienced KyTC engineers, FHWA representatives, and contractor representatives met periodically to identify approaches for handling key issues of the program.

Several key topics related to CPQC are presented in this report, with emphasis on quality control (QC) /quality assurance (QA) administration, QC/QA procedures, quality acceptance and verification testing, and CPQC training. Specific issues related to CPQC pay items in Kentucky are also discussed. Several recommendations have been proposed to enhance the program.

If properly implemented, CPQC can improve a contractor's work performance and help relieve the State's burden for inspection. Additional monitoring of the program is necessary to make further improvements and to include other pay items.

17. Key Words Contractor Performed Quality Control, Quality Control, Quality Assurance, Quality Acceptance, Verification Testing	**18. Distribution Statement** Unlimited with approval of the Kentucky Transportation Cabinet

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 123	**22. Price**

Form DOT 1700.7 (8-72) **Reproduction of Completed Page Authorized**

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Chapter I Introduction

The quality of the constructed project is a major issue in highway construction. For years the inspection responsibility for quality, or quality control, was the responsibility of Departments of Transportation (DOTs). Agencies also performed quality assurance checks to ensure that their own quality control activities were in compliance with desired standards. Contractors simply did the work and the DOT decided if the work was in compliance, and if full payment should be made. However, in recent years, many DOTs have transferred the responsibility for quality control of some construction work to the contractor, with the agencies only performing quality assurance checks. The Kentucky Transportation Cabinet (KyTC) has experienced this transfer of responsibility for several years. However, more research was needed to review this Contractor Performed Quality Control (CPQC) program, identify the existing problems, and find ways to improve its performance.

1.1. Background and Significance of Work

The performance of contractors in highway construction is a significant area of interest to highway departments. Obtaining the greatest value for the dollar is the primary objective for all departments. A major concern has always been the actual quality of the work performed and DOTs have devoted major attention and resources to quality control and quality assurance activities.

Several DOTs in the United States have decided to transfer the responsibility for standard quality control processes on their construction projects to contractors, with only quality assurance performed by the DOTs. The primary advantage is to make quality a higher priority for the contractor; also, this may reduce the inspection load for the DOTs. The

KyTC has initiated the CPQC program on several pay items; however, the results, specifications, and processes of this program have not been fully evaluated. Also, many of the highway contractors in Kentucky may not be able to take on these new responsibilities. Research was needed to address concerns associated with this new practice if the Cabinet should decide to more fully implement the CPQC program on its construction projects.

1.2 Goal and Objectives of the Study

The goal of this study was to provide the Kentucky Transportation Cabinet with an evaluation of the feasibility and implementation needs to transfer the quality control function on its highway construction projects to contractors. The following objectives were identified for this study:

1. Review the requirements and results of utilizing contractor quality control on construction projects performed by other State DOTs.
2. Evaluate the potential benefits and concerns of utilizing contractor quality control for KyTC construction projects.
3. Evaluate the resulting quality assurance requirements for the KyTC to perform on its construction projects.
4. Recommend guidelines for revising and/or using the CPQC program for KyTC construction projects, including potential standard specifications and KyTC operating procedures.

Chapter II Research Accomplishments

The research team used various methods to gather information concerning Contractor Performed Quality Control (CPQC) on highway construction projects. A series of activities were conducted to accomplish this research.

- A literature review was performed to determine what research had already been done in this area and the CPQC specifications in other states.
- A research advisory committee was formed to review the work of the researchers and give input throughout the course of the project.
- A nationwide survey was conducted to get information on this topic from DOTs and Kentucky highway contractors.
- Cabinet's KMIMS database was accessed and analyzed for the purposes of this study.
- A second survey specific for Kentucky district engineers and highway contractors was performed to review the CPQC practices on KyTC projects.

2.1 Literature Review

The research team conducted a comprehensive review of published literature, research project reports, and specifications from other DOTs on this topic. The results of the review were summarized to provide a comprehensive understanding of the topic and provide a basis for this study. The team found that existing research concerning Contractor Performed Quality Control (CPQC) mainly focused on the following areas:

- Quality Control and Quality Assurance Organization
- Quality Control Methods and Procedures
- Quality Acceptance
- Quality Verification by DOTs
- Training Programs for CPQC

Another goal of the literature review was to identify the processes and approaches used in various areas of quality control, quality acceptance, and verification methods for potential implementation in Kentucky.

2.2 Meetings with Industry Groups

Several meetings were held with the research advisory committee of this study at the University of Kentucky. Some other meetings were held in the Division of Materials and one in the District Office in Lexington, Kentucky. A workshop on CPQC was also held in the U.S. Army Corps of Engineers office in Louisville, Kentucky. Valuable input was received from these meetings, which is incorporated into various parts of this report. Table 2.1 provides a list of study advisory committee members and their respective organizational affiliation.

Chairman:	David Clark, P.E. District 3 Materials Engineer
Vice-chairman:	Bob Lewis, P.E. Transportation Engineer Branch Manager Administration Section and Roadway
Principal Investigator:	Donn E. Hancher, Ph.D., P.E. University of Kentucky
Co-Principal Investigator:	Kamyar C. Mahboub, Ph.D., P.E. University of Kentucky
C.O. Materials Rep.	Wesley Glass, P.E. Director (Acting) of Division of Materials
FHWA Rep.	Bob Farley Area Engineer
Dist. Const. Rep.	Bill Chaney Resident Engineer-District #8
Contr. Rep.-Grade & Drain	John Haydon, President Haydon Brothers Contracting
Contr. Rep.-Asphalt	Johnny Giles, Quality Control Manager Mago Construction Company
Contr. Rep- Concrete	Michael Shayeson, President The W. L. Harper Co.
Contr. Rep.- Structures	Tom Haydon, President Haydon Bridge Company
KAHC Rep.	Ron Gray, Associate Director Ky. Assoc. Highway Contractors
U.K. Researcher	Yuhong Wang University of Kentucky

Table 2.1 List of Research Advisory Committee

2.3 National Surveys on Contractor Performed Quality Control (CPQC) Practices

In order to better understand the CPQC program, this research conducted two separate surveys. The first survey, completed by September 30, 2000, was conducted among State DOTs and selected Kentucky contractors. The two groups received a similar survey, copies of which are included in Appendix I and II.

The survey sought to find the scope of CPQC pay items and specification changes to redefine the responsibility of agencies and contractors. The survey also asked the respondents to evaluate their CPQC programs, indicate its major advantages and concerns, and identify the factors influencing the implementation of this program.

Of the surveys that were mailed, responses were received from 30 State Transportation Departments and 13 Contractors.

2.3.1 CPQC Projects for Department of Transportations (DOTs)

Table 2.2 lists the highway construction pay items that have been implemented for CPQC. Most of the states, as shown in the table, are using a CPQC program. The CPQC pay items concentrate on hot mixed asphalt pavement, concrete pavement, and concrete bridge decks. Except for the Oregon DOT, KyTC's CPQC program covers more pay items than several other state DOTs.

DOTs	Grading / Earthwork	PCCP	HMA	Concrete Bridge Deck	Painting (Bridge)	Pavement Striping	Traffic Control System	Others
Arizona	X	X	X					
Arkansas	X	X	X	X				Aggregate Base Courses
Connecticut			X					
Florida	X	X	X	X				
Hawaii								
Idaho	X		X					1 project with concrete QA
Illinois		X	X	X	X			
Indiana		X	X	X	X			Aggregate
Kansas		X	X					
Kentucky	X	X	X	X	X	X		Crushed stone base acceptance
Louisiana	X	X	X	X				Surface treatment
Maine			X	X				
Maryland		X	X	X				
Michigan		X	X	X				
Minnesota	X	X	X	X				
Mississippi			X	X				
Missouri			X					
Nebraska			X					
New Mexico			X					Base Course
New York			X					
Nevada								
North Dakota			X					
Ohio	OHIO does utilize D/B, warranty, I/DI, consultant inspectors just for specific area.							
Oklahoma		X	X	X				
Oregon	X	X	X	X	X	X	X	All construction projects
Texas			X					
Utah			X					
Washington								
West Virginia		X	X	X				
Wisconsin		X	X	X	X	X		

Table 2.2 Pay Items being implemented for CPQC in different DOTs

2.3.2 Evaluation of the CPQC Program

Table 2.3 presents a summary rating of the CPQC programs as viewed by different DOTs in terms of project quality, overall project cost, project schedule, and project disputes on a 1-5 scale (1-very negative, 3-no effect, 5-very positive). Table 2.4 lists the same evaluation by contractors. The last row of the table presents the average value of each evaluation items. The DOTs responses show that the influence of CPQC on project quality and disputes is positive, on overall project cost is negative, and on project schedule remains the same. The contractors' responses show that the influence of CPQC on project quality, schedule, and disputes is positive, and on overall project cost remains the same.

DOT	Project Quality	Overall Project Cost	Project Schedule	Project Disputes
Arizona	3	1	3	4
Arkansas	4	3	3	4
Connecticut	Too early to tell			
Florida	5	4	3	4
Hawaii	Unidentified			
Idaho	4	3	3	3
Illinois	4	4	3	4
Indiana	4	3	3	4
Kansas	5	3	3	3
Kentucky	4	2	3	
Louisiana	4	3	3	4
Maine	4	4	3	2
Maryland	4	3	3	4
Minnesota	4	3	3	2
Mississippi	Unidentified			
Missouri	5	2	3	3
Nebraska	5	3	3	3
New Mexico	4	2	3	3
New York	Unidentified			
Nevada	1	1	2	1
North Dakota	4	Unidentified	3	4
Ohio	Unidentified			
Oklahoma	4	3	3	4
Oregon	4	4	3	4
Texas	4	2	3	3
Utah	Unidentified			
Washington	Unidentified			
West Virginia	3	2	3	4
Wisconsin	4	3	4	4
Average	**3.95**	**2.76**	**3**	**3.38**

Table 2.3 Rating of the CPQC Program by DOTs

Contractors	Project Quality	Overall Project Cost	Project Schedule	Project Disputes
Contractor 1	4	2	4	3
Contractor 2	3	4	5	5
Contractor 3	3	3	4	3
Contractor 4	5	5	5	5
Contractor 5	4	4	4	5
Contractor 6	2	1	3	1
Contractor 7	3	2	4	2
Contractor 8	5	4	3	3
Contractor 9	4	4	4	5
Contractor 10	3	1	3	2
Contractor 11	3	2	3	3
Contractor 12	5	4	4	5
Average	**3.67**	**3.00**	**3.83**	**3.50**

Table 2.4 Rating of the CPQC Program by Kentucky Contractors

2.3.3 Advantages of the CPQC Program

The advantages of the CPQC program reported by the DOTs and the contractors are summarized in Table 2.5. Out of the 30 DOTs who responded, the major advantages of CPQC considered by them are: contractors are responsible for their own products, reduction of state personnel, gaining knowledge by contractors, and improved quality. Out of the 12 contractors who responded, the major advantages of CPQC are : contractors are more suitable for control, improved schedule, and improved quality.

DOTs		Contractors	
Advantages	Percent of support	Advantages	Percent of Support
Contractor responsible for their own products	60%		
Reduction of state personnel	57%		
Gain of knowledge by contractors	23%	Gain of knowledge by contractors	17%
Quality improvement	23%	Improving quality	25%
Contractor more suitable for control	7%	Contractor more suitable for control	33%
Systematic evaluation of production by contractors	3%		
Increasing communication	3%		
Sharing risk and responsibility	3%		
Improving schedule	7%	Improving schedule	33%
Improving dispute resolution	10%	Better dispute resolution	8%
Detailed QC plan	3%		

Table 2.5 Advantages of the CPQC Program

2.3.4 Major Concerns of the CPQC Program

The major concerns of the CPQC program by both the DOTs and the contractors are summarized in Table 2.6. According to the survey results, the top three major concerns of the DOTs are: validity of contractor test data, insufficient certified technicians, and insufficient quality assurance by DOTs. The top four concerns of the contractors are: capability of technicians, facilities cost of QC, lack of trust, and lack of training.

DOTs		Contractors	
Concerns	**Percent of support**	**Concerns**	**Percent of Support**
Validity of test data	30%	Capability of technicians and facilities	67%
Insufficient certified technicians pool	20%	Cost of QC	33%
Insufficient Quality assurance	24%	Lack of Trust	25%
Lack of training	13%	Lack of training	25%
DOT losing expertise	10%	Honesty of some contractors	17%
Contractor operating at lower end of specification	10%	Expensive independent test agencies	8%
Fear of losing control on projects	10%	Different goals of contractor and DOTs	8%
Lack of understanding	10%		
Uniformity in making decisions	7%		
Validity of statistical analysis	7%		
Contractor's deviation from QC plan	7%		
Contractor using QC data only for acceptance, not for control	7%		
QC as a separate bid	7%		
Lack of trust	7%		
Proper sampling approaches	7%		
Technician the lab qualification	7%		
Insufficient tests	3%		
Qualification of test technicians	3%		
Failure to make timely correction	3%		
Receiving test results timely	3%		
Selling concept to industry	3%		
Agency's personnel's fear of losing their jobs	3%		
Contractor's focus on incentive/disincentive only	3%		
Inconsistent test results	3%		
Insufficient sample size	3%		

Table 2.6 Major Concerns of the CPQC Program

2.3.5 Additional Comments

Several states provided additional comments on the subject of contractor quality control. Their comments seem to concentrate on the following topics:

- The incentive/disincentive plan may be unnecessary.
- Dispute resolution must be well thought out and very detailed to address "all" situations.

- Documentation / reporting requirements (forms / documentation submittal timeframes) should be well defined
- A strong leader should be identified inside DOT organization to secure as a change catalyst.
- Every standard practice should be questioned despite shift to contractor QC.
- Percent within limits (PWL) can be used on both Concrete and HMA QC/QA.
- Product approvals in this area can be moved to "certified suppliers".
- Present QC/QA specifications are semi-statistical (Allowable limits are based on standard deviations.). Preferred specifications are "percent defective" specifications.

Several contractors also provided additional comments on the subject of CPQC. Their comments seem to concentrate on the following topics:

- The testing for quality control could become quite expensive.
- For bridge builders, the main quality control concern will be with our ready mix concrete supplier, and we have very little control over their operation.
- If we are heading in the direction of end product specifications, the concept of Contractor Performed Quality Control is entirely appropriate.

2.4 Kentucky Survey on CPQC Practices

The second survey, completed by February 8, 2002, was conducted among the Districts of the KyTC, the Division of Materials, and selected Kentucky contractors. The two groups received the same survey form. A copy of the survey form for the KyTC is included in Appendix III.

The survey sought to find the number of projects for each pay item on which CPQC has been implemented, the evaluation of existing CPQC programs, its advantages, and major concerns. The survey received responses from 28 engineers and 8 contractors.

2.4.1 Pay Items Implementing CPQC Program

The work items using CPQC includes hot mix asphalt (HMA), concrete, crushed stone base, soil embankment and subgrade, pavement striping, and bridge painting. The Kentucky CPQC system has been in place for HMA longer than other pay items. Some other CPQC pay items were implemented on pilot projects. All correspondents had experience on CPQC projects of different types.

2.4.2 Evaluation of CPQC Program by Engineers and Contractors

Table 2.7 presents the evaluations of the current CPQC program by KyTC engineers from different districts, and the Division of Materials, in terms of project quality, overall project cost, project schedule, and project disputes on a 1-5 scale (1-very negative, 3-no effect, 5-very positive). Table 2.8 lists the same evaluation by contractors. The last row of the table shows the average value of each evaluation items. The district engineers' feedback shows that the influence of CPQC on project quality, project schedule and disputes is positive, and on overall project, cost is negative. But the average values are very close to neutral. The contractors' responses show that the influence of CPQC on project quality is positive, and on all the others is negative; however, only cost was a major concern. Because the survey did not receive many replies from the contractors, contractors with very strong opinions may bias the outcomes. So the average values do not necessarily reflect the opinions of all the highway contractors in Kentucky.

Respondent	Project Quality	Overall Project Cost	Project Schedule	Disputes in Project
District 2	5	3	4	2
District 2	3	3	3	2
District 2	4	3	2	4
District 3	3	3	3	3
District 4	4	3	3	3
District 4	2	1	3	3
District 4	3	2	4	3
District 4	4	2	3	3
District 6	4	2	3	3
District 6	4	3	5	5
District 7	3	4	3	5
District 7	4	3	3	4
District 7	4	4	3	3
District 7	4	2	3	3
District 7	4	3	3	3
District 8	4	2	3	3
District 9	3	3	4	3
District 9	3	2	3	3
District 9	4	4	4	4
District 10	4	3	3	4
District 11			3	
District 11	4	4	3	3
Division of Materials	4	3	3	4
Division of Materials	4	3	3	3
Division of Materials	3	4	4	3
Average	**3.67**	**2.88**	**3.24**	**3.29**

Table 2.7 Evaluation of CPQC Program by KyTC Engineers

Respondent	Project Quality	Overall Project Cost	Project Schedule	Disputes in Project
Contractor 1	5	2	3	4
Contractor 2	4	2	3	3
Contractor 3	5	5	5	5
Contractor 4	4	2	3	3
Contractor 5	3	1	3	1
Contractor 6	3	2	3	4
Contractor 7	0	0	0	0
Contractor 8	3	2	3	3
Average	**3.375**	**2**	**2.875**	**2.875**

Table 2.8 Evaluation of CPQC Program by Contractors

2.4.3 Advantages of the CPQC Program

The advantages of the CPQC program deemed by KyTC engineers and the contractors are shown in Table 2.9. Out of the 28 DOTs who responded, the major advantages of CPQC considered by them are: contractors are responsible for their own products, possible reduction of state personnel, and improved quality. Out of the 8 contractors who responded, the major advantages of CPQC are: contractor are responsible for their own products and improved quality.

District Engineers		Contractors	
Advantages	Percent of support	Advantages	Percent of support
Contractor responsible for their own products	46%	Contractor responsible for their own products	13%
Reduction of state personnel	32%	Reduction of state personnel	13%
Quality improvement	11%	Quality Improvement	25%
Increase of contractor's effort on QC	7%	Increase of contractor's effort on QC	13%
Gain of knowledge by contractors	7%	Gain of knowledge by contractors	
Increasing communication	11%		
Improve Safety	4%	Improving trust	13%
Increase productivity	4%		
Improving schedule		Improving schedule	13%
Better dispute resolution	4%	Better dispute resolution	13%

Table 2.9 Advantages of CPQC Program

2.4.4 Concerns of the CPQC Program

The major concerns of the CPQC program deemed by the district engineers, central material office, and the contractors are shown in Table 2.10. Out of the 28 KyTC engineers who responded, the major concerns of CPQC expressed by them are: validity of test data and QC documentation. Out of the 8 contractors who responded, the major concerns of CPQC are: inadequate QC personnel to recruit, lack of trust by KyTC, higher construction cost, and difficulty in controlling structural concrete variation.

DOTs		Contractors	
Concerns	**Percent of support**	**Concerns**	**Percent of support**
Validity of test data	46%	Inadequate QC personnel	13%
Bad QC documentation	18%	Lack of trust	13%
Inexperience QC personnel	7%	Cost of QC	13%
Aggregate and ready mix concrete producers do not share the incentives for QC	4%	Difficult to control concrete variation	13%
Not working good on small quantity	4%		
Incorrect sampling methods	4%		
Inadequate QC on soil embankment	4%		
Contractor operating at lower end of specification	4%		
DOT losing expertise	4%		
No correction following QC results	4%		
No QC personnel on the project	4%		
Incentives are over reward	7%		
Need a good verification program	4%		

Table 2.10 Concerns of CPQC Program

This survey also asked for special concerns of the contractors following new QC/QA specifications from the aspects of:

- Required quality control plans
- Availability of technicians and testing devices
- Coordination with material suppliers
- Quality control process
- Dispute resolution process
- Bonus and penalty schedules

On a 1-5 scale (1-serious concern, 2-concern, 3-neurtal, 4-satisfied, 5-very-satisfied), Table 2.11 and Table 2.12 presents the rating of these concerns from the engineers and the contractors. From the engineers' side, the average of ratings shows there are no big concerns. From the contractors' side, the average of ratings show their concerns are the dispute resolution process and bonus and penalty schedules. Again, because of the limited number of respondents, the contractors' ratings may not be very representative.

Respondents	Required Quality Control Plans	Availability of Technicians and Testing Devices	Coordination with Material Supplies	Quality Control Process	Dispute Resolution Process	Bonus and Penalty Schedules
District 2	4	4	4	5	3	4
District 2	2	1	3	2	4	2
District 2	4	3	4	4	4	4
District 3	2	3	3	2	3	3
District 3	2	3	3	3	3	3
District 3	4	2	4	2	2	4
District 3	2	2	2	3	3	2
District 4	3	4	3	4	3	3
District 4	4	2	3	3	3	2
District 4	3	2	1	3	2	3
District 4	4	4	4	3	3	2
District 6	2	3	3	3	3	1
District 6	5	5	3	5	5	3
District 7	3	3	3	3	4	4
District 7	3	3	3	3	4	3
District 7	4	4	4	4	3	2
District 7	3	4	4	3	2	2
District 7	2	2	4	3	4	2
District 8	3	3	3	4	3	2
District 9	4	4	4	4	3	2
District 9	3	3	3	3	3	2
District 9	4	5	3	4	3	4
District 10	4	4	4	4	3	3
District 11	4	2	2	4	3	4
District 11	3	4	3	2	2	2
Division of Materials	2	4	N/A	2	4	2
Division of Materials	4	2	2	2	4	4
Average	**3.22**	**3.15**	**3.15**	**3.22**	**3.19**	**2.74**

Table 2.11 KyTC Reviews of the CPQC Program

Respondents	Required Quality Control Plans	Availability of Technicians and Testing Devices	Coordination with Material Supplies	Quality Control Process	Dispute Resolution Process	Bonus and Penalty Schedules
Contractor 1	4	3	4	4	4	5
Contractor 2	4	4	4	4	4	4
Contractor 3	3	4	4	4	1	3
Contractor 4	5	5	5	5	5	N/A
Contractor 5	3	2	2	3	2	2
Contractor 6	5	4	5	5	2	1
Contractor 7	3	2	3	3	1	1
Average	3.86	3.43	3.86	4.00	2.71	2.67

Table 2.11 Contractor Reviews of the CPQC Program

2.4.5 Survey Recommendations

The engineers and contractors were asked to provide additional comments on the CPQC programs from the following aspects:

- Program requirements
- Dispute resolution process
- Acceptance and quality assurance procedures
- Incentive and disincentive schedules

A lot of recommendations were received; a summary of these recommendations are shown here. Some recommendations may be contradictory because different people have different opinions of on this program to date.

2.4.5.1 Survey Recommendations from Engineers

a. Program Requirement

- Provide resident engineers and contractors with some training.

- Clearly define responsibilities of all the parties involved in CPQC.
- Pay attention to project selection since not all projects are suitable for CPQC.
- Require more standardized statistical approaches across all areas of work pertaining to the application of randomness, lots, and incentive/disincentive aspects.
- Follow up adjustment and corrective actions in addition to testing.
- Do not give contractor random numbers until time to take the test.
- Improve the methods of filling out material forms.
- Set time restraints on receiving information from QC.
- Use a smaller lot size for the structural concrete should have smaller lot sizes.
- Use a separate and independent testing company.
- Improve the Department's verification philosophy.
- Ensure that those properties that are best related to performance are tested for acceptance.

b. Dispute Resolution Process

- Address the issue that the incentive/disincentive program may cause major disputes between contractors and ready mix suppliers. A 5% penalty may be 25-50% of the ready mix prices, and it also may equal the contractor's expected profit.
- Minimize arguments in the future by developing detailed guidelines prior to implementation of the CPQC program.

c. Acceptance and Quality Assurance Procedures

- Do not replace on-site inspection, sampling and testing with only statistical checking on Contractor's data.
- State personnel make final approval of all work performed.
- Tighten the tolerance for asphalt content and carrying more weight on it.
- Adjust the provisions of slump in the PWL calculation for concrete.
- Use surprise tests on verification.
- Increase the frequency of assurance testing.

d. Incentive and Disincentive Schedules

- Increase the requirements for getting incentives. The concrete should be within tighter tolerance in the PWL calculations.
- Remove the incentive schedules, because the contractor now looks at the bonus the same as 100% pay.
- Disincentives are sometimes not severe enough to force the contractor to take corrective action.

e. Other Recommendations

- Conduct an adequate evaluation of pilot program results before full implementation of contractor QC/QA.
- Make severe penalties for manipulating test results.
- Make a beneficial comparison between existing CPQC programs and "percent within limits" approach. Many contractors are vehemently opposed to " percent within limits".
- Require good information for reporting and managing system (computer database)

- Address the problem of small contractors because they are reluctant to pay for personnel training.
- Do not force engineers to give up their jobs and decrease the project quality due to the shift of inspection responsibility to the contractor.

2.4.5.2 Survey Recommendations from Contractors

a. Program Requirement

- Eliminate the incentive/disincentive part.
- The concept of percent within limits is a major concern.

b. Incentive and Disincentive Schedules

- There is a greater potential for penalty than for bonus, but overall it is a good program.

c. Acceptance and Quality Assurance Procedures

- Decrease the time of reporting back to contractors by the KyTC of the quality assurance results.
- Apply random checks by the KyTC to projects to back up what was turned in by the contractor.

2.4.6 Opinions on Training Program

The contractors and engineers were also asked if a training program on contractor quality control and DOT quality assurance would be helpful and what content was desired in this program. According to the responses, most engineers and contractors are in favor of a training program. The survey results and their recommendations will be shown in detail in Chapter 7.

Chapter III Highway Construction Quality Management System

3.1 Contractor's Quality Control and DOT's Quality Assurance

The quality management system currently implemented by highway agencies consists of two subsystems: the contractor's Quality Control (QC) and the State highway agency's (SHA) Quality Assurance (QA). Although every production process requires some kind of quality control and it has long been practiced by contractors, the new Contractor Performed Quality Control (CPQC) program standardizes this process and puts more emphasis on it. If the CPQC is clearly defined, implemented, and inspected, not only the material quality can be enhanced, quality assurance by agencies can also be more efficient.

QC and QA have different definitions. The following definitions are given by the FHWA (FHWA, 1995):

> Quality Assurance. All those planned and systematic actions necessary to provide confidence that a product or service will satisfy given requirements for quality.
>
> Quality Control. All contractor/vendor operational techniques and activities that are performed or conducted to fulfill the contract requirements.

In Kentucky, our definition of QC and QA are (KyTC, 2000):

> Quality Assurance. Quality Assurance consists of all planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy specified requirements for quality. QA serves to provide confidence in the contract requirements, which include materials handling and construction procedures, calibration and maintenance of equipment, production process control

and any sampling, testing and inspection which is performed by the Department for these purposes.

Quality Control. The sum total of activities performed by the Contractor to ensure the end product meets the contract requirements.

QC and QA share the final common goal of a quality management system -- enhancing the material production and construction quality. Many tasks in these two sub systems are complementary. However, QC and QA are conducted by different sides representing different interests. The difference between QC and QA may be reflected in the following aspects:

- Objectives
- Organizations
- Responsibilities
- Working process

A good CPQC program requires these elements to be clearly defined and properly implemented.

3.2 Objectives of CPQC

The contractor and the Department may have specific objectives on QC and QA. The primary objectives of the CPQC program, identified by DOTs, are:

1. Improve the quality of the materials and processes used in the construction of highway projects, and reduce the life cycle costs for the facilities involved.

2. Redirect the responsibility for quality control on projects to the contractor.

3. Reduce disputes between the DOT and its contractors.

4. Enhance the construction schedule and the Department's effort on quality management.

3.3 Quality Control Organization and Responsibilities for Contractors

Different states require different quality control and quality assurance personnel, sometimes with different names. In Kentucky, two positions are required for HMA CPQC, which are: a qualified Superpave Mix Design Technologist (SMDT) to be responsible for the submission and adjustment of the mix designs and a qualified Superpave Plant Technologist (SPT) to be present during production and to perform the daily inspection, process-control, and acceptance testing at the plant site (KyTC, 2000). According to the Special Notes on concrete CPQC, ACI Level-I Concrete Technicians are required.

Sometimes other positions are also required in the CPQC programs by other states and Corps of Engineers. This research found that the common positions required in CPQC program includes (shown in Figure 3.1):

- Quality Control Manager
- Quality Control Inspector
- Quality Control Laboratory Technicians
- Quality Control Sampler.

Comparing with the other DOTs, the CPQC program in Kentucky does not clearly specify the position of "Quality Control Manager", who is usually in charge of the contractor's overall CPQC program on a project.

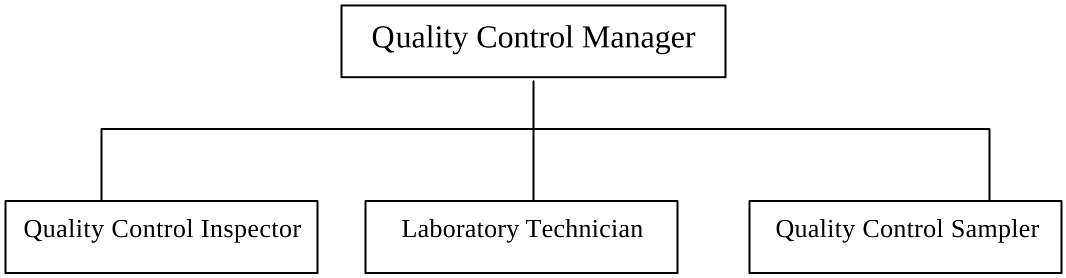


Figure 3.1 Contractor CPQC Personnel

Different positions in Figure 3.1 assume different responsibilities, which are shown in Figure 3.2.

Quality Control Manager

Responsibility:

- Direct program
- Provide and implement QC plan
- Review test results
- Review inspection reports, material certificates, and construction process records
- Coordinate QC activities
- Other responsibilities

Quality Control Inspector

Responsibility:

- Inspect source material
- Inspect plant operation
- Inspect onsite construction
- Record inspection results

Laboratory Technician

Responsibility:

- Calibrate testing equipment
- Perform QC testing
- Perform acceptance testing
- Report test results

Quality Control Sampler

Responsibility:

- Decide QC sampling place
- Take QC samples
- Take acceptance samples
- Record sampling places

Figure 3.2 Responsibilities of Contractor CPQC Personnel

In many states the laboratory technicians and quality control sampler need to be certified and all the personnel performing QC should go through a training program. It should be noted, however, one person is not necessarily only responsible for one position. For example, sometimes the quality control manager can also be a quality control inspector.

3.4 Quality Assurance Organization and Responsibilities for the KyTC

The responsibilities of Quality Assurance personnel are not as well defined in Kentucky as in other states. On HMA projects, the KyTC will use a qualified SMDT for approval of all mix designs and a qualified SPT for verification testing (KyTC, 2000).

Besides these two responsibilities, some other states list the following additional responsibilities in their specifications:

- Participating in preparatory, initial control phase meetings
- Inspecting the effectiveness of the contractor's quality control
- Conducting pre-construction meetings
- Reviewing and making recommendations on the contractor's quality control plan
- Reviewing QC reports; noting and reporting deficiencies
- Making acceptance judgment based on acceptance test results and verification test results

3.5 CPQC Working Process

3.5.1 Quality Control Plan for Contractors

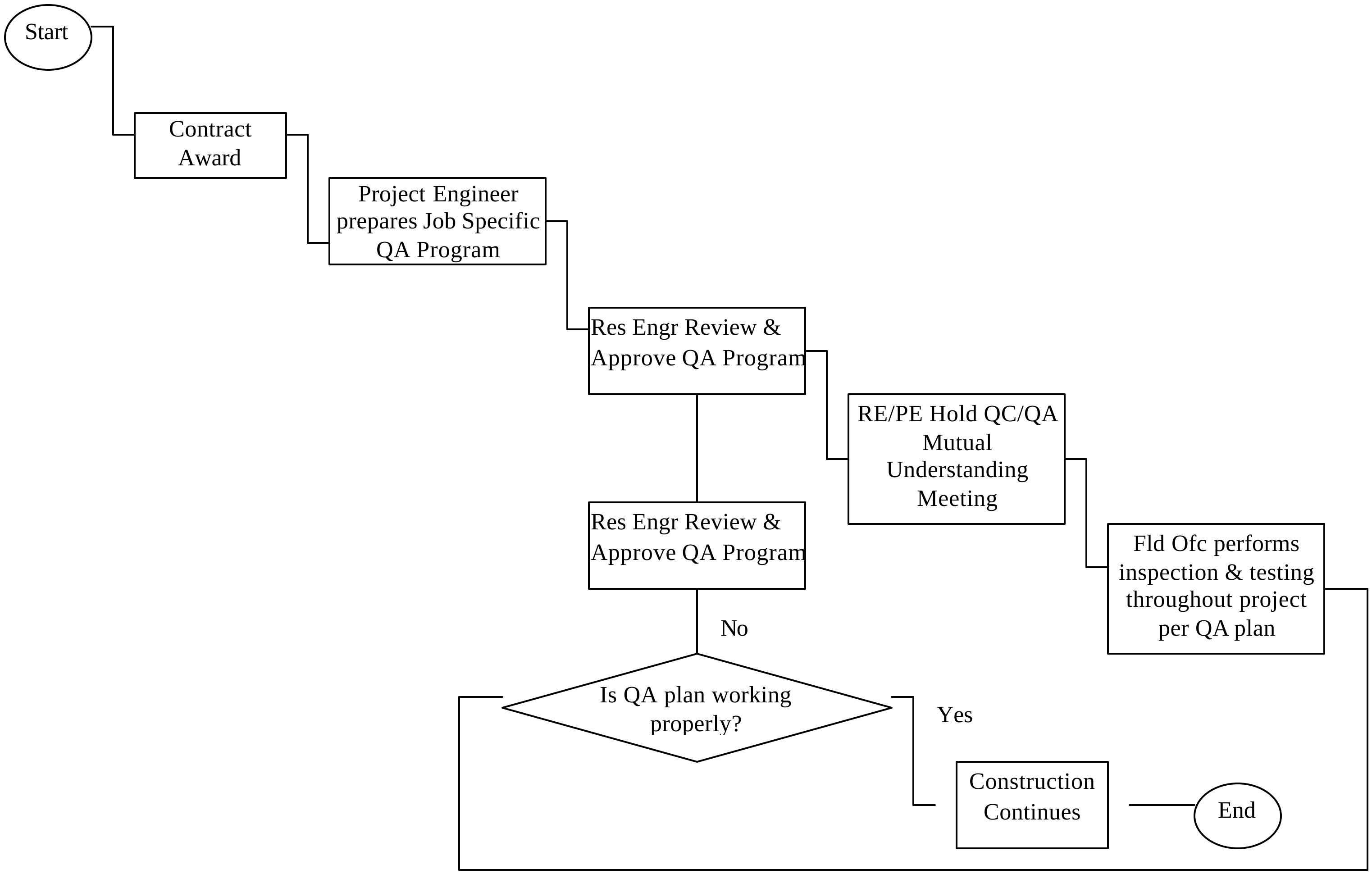
The need for and use of a Quality Control Plan cannot be overemphasized. Quality cannot be tested or inspected into a product; it must be "built in". It is imperative that the contractor has a functional, responsive QC Plan. The QC plan contains requirements which the contractor is expected to fulfill within his/her quality control system. The QC plan must be approved before a contractor can begin his/her work. The principle contents of a QCP usually include:

- Quality Control Organization
- Process Control
- Random Sampling Schemes
- Inspection Plan
- Control of Material Provider
- Correction Plan
- Documentation

3.5.2 Uniformity of CPQC and QA process

This research found that the uniformity of CPQC and QA is a common concern to the research committee members. A well-defined and streamlined CPQC and QA program will reduce the potential misunderstanding and improve its performance. For example, The U.S. Army Corps of Engineers has defined a common working process of QA for all of its CPQC projects (Figure 3.3) to standardize its process.

Beside the general working process, the requirement of uniformity should also be emphasized on specific QC and QA tasks, such as sampling methods, testing methods, verification test methods, and making decisions based on the test results. For example, some districts currently use the contractor's test equipment to perform the verification testing while other districts perform the testing independently.



http://www.spa.usace.army.mil/qmp/eqp6-02.htm

Figure 3 Example of QA Working Process (Corps of Engineers)

Chapter IV Contractor Performed Process Quality Control

A successful contractor performed quality control program should not only be deemed as the DOT transferring quality management responsibility to the contractors, it is also a requirement for the contractors to systematically incorporate quality control techniques into their production processes so that the final product quality can be improved. For highway materials, good quality usually means that material characteristics center around specification target values with acceptable variations. Therefore, a good quality control system should be able to detect the deviation from target values and allow for timely adjustment when the process goes wrong. *Real-time statistical process control*, required by many DOTs for the CPQC program, is one primary tool to assist a contractor with quality control.

4.1 Control Charts for Highway Material Production

The characteristics of all construction materials and products are subject to variations. This variability is caused by two sources: the chance cause and the assignable cause. While the first cause is unforeseen, the assignable cause is controllable. The objective of using control charts is to identify the process variability due to the assignable cause and not to be falsely alarmed by the chance cause. The benefits of control charts mentioned in literature include (FHWA, 1976, 16.4):

1. Providing early detection of trouble before rejections occurs.
2. Decreasing product variability.
3. Establishing the process capabilities.
4. Providing savings in terms of penalty and rework costs.

5. Decreasing the frequency of inspection for processes in control at a satisfactory level.
6. Providing a rational basis for establishing or altering specification requirements.
7. Providing a permanent record of quality.
8. Providing a basis for acceptance of a product by a purchaser.
9. Instilling a sense of "quality-awareness" in an organization.

In addition, good quality records can also help the DOTs' quality assurance by relieving their efforts on organizing and analyzing a contractor's data.

There are different types of control charts. Some examples are shown below:

- Control Chart for Fraction Nonconforming (p-chart)
- Control Chart for Attributes
- Control Chart for Nonconformities (c-chart)
- Control Chart for Nonconformities per Units (u-chart)
- Control Chart for Means ($\bar{x}$-chart)
- Control Chart for Range (R-chart)
- Control Chart for Standard Deviation (S-chart)
- Control Chart for Individual Units
- The Cumulative-Sum Control Chart
- The Moving Average Control Chart

All these control charts are used for different purposes in industrial production. However, because highway materials quality control has distinctive characteristics, not all these control charts are suitable for highway application.

Of all these control charts, this research found that the $\bar{x}$-Chart, R-Chart, S-Chart, the Control Chart for Individual Units, and the Moving Average Control Chart are most commonly used. The $\bar{x}$-Chart and the Moving Average Control Chart are used to control the mean value of a quality characteristic, for example, the asphalt content in hot mixed asphalt. The R-Chart and S-Chart are used to control the variations in the production process. The control of both the mean value and the variation are equally important to highway material production and construction. Some DOTs specify the required type of control chart, while others leave the decision to the contractor. However, whichever control chart is used, the contractor should know its application context and how to use it correctly. The following sections provide a brief overview of various quality control chart methodologies.

4.1.1 The $\bar{x}$-Chart and the R-Chart

The $\bar{x}$-Chart and R-Chart are the most commonly used techniques to control the production process means and variations. Because quality characteristics of most highway materials are either normally or approximately normally distributed, the $\bar{x}$-Chart and R-Chart have sound a statistical basis for usage. Suppose that we treat each lot as a sampling unit (here a lot refers to the quantity of materials defined in Kentucky specifications), which contains four observations taken from four sublots. We further suppose there are totally *m* lots in one project and $\bar{x}_1, \bar{x}_{2,} \ldots, \bar{x}_m$ is the average of each lot. Then the best estimator of the process average is the grand average, say

$$\bar{\bar{x}} = \frac{\bar{x}_1 + \bar{x}_2 + \ldots + \bar{x}_m}{m} \qquad (4.1)$$

The average range is

$$\overline{R} = \frac{R_1 + R_2 + ... + R_m}{m} \tag{4.2}$$

An estimate of the process standard deviation would be

$$\hat{s} = \frac{\overline{R}}{d_2} \tag{4.3}$$

(D.C. Montgomery, 1985, p174), where the value of d_2, listed in standard tables, is a factor solely depended on the sample size.

For sample size of four, d_2 is equal to 2.059. If the sample size is relatively small, the range method yields almost as good an estimator of the variance as does the sample variance S^2 (D.C. Montgomery, 1985, p174).

The grand mean can be used as the center line of the $\bar{x}$ control chart. For the upper and lower control limits, it is a standard practice in the United States to calculate it using a multiple of the standard deviation (p108, D.C. Montgomery, 1985). And the multiple usually chosen is 3. Such control limits are called 3-sigma limits. For normally distributed quality characteristics, the probability of a type-I error is 0.0027. That is, when we find something going beyond this control limit, there is only a 0.27% that it's a false alarm due to pure chance. If we use the $\bar{R}/d_2$ as an estimator of s and use 3-sigma limits, then the upper control limit (UCL) and the lower control limit (LCL) are, respectively:

$$UCL = \overline{\overline{x}} + \frac{3}{d_2\sqrt{n}}\overline{R} \tag{4.4}$$

$$LCL = \overline{\overline{x}} - \frac{3}{d_2\sqrt{n}}\overline{R} \tag{4.5}$$

If we designate

$$A_2 = \frac{3}{d_2\sqrt{n}} \quad (4.6)$$

The equation above can be written as

$$UCL = \bar{\bar{x}} + A_2\bar{R} \quad (4.7)$$

$$LCL = \bar{\bar{x}} - A_2\bar{R} \quad (4.8)$$

The R-chart is used to control the process variations. The center line of the R-chart is $\bar{R}$.

The 3-sigma limit of range's standard deviation can be used as the control limit for range.

The standard deviation of range can be estimated by multiplying the process standard deviation with a factor d_3.

$$s_r = d_3 s$$

Because the process standard deviation can be estimated from equation 4.3, the standard deviation of range can be written as:

$$s_r = d_3\bar{R}/d_2 \quad (4.9)$$

The upper and lower control limits for R-chart are:

$$UCL = \bar{R} + 3d_3\frac{\bar{R}}{d_2} \quad (4.10)$$

$$LCL = \bar{R} - 3d_3\frac{\bar{R}}{d_2} \quad (4.11)$$

Sometimes these two equations can be written as:

$$UCL = \bar{R}D_4 \quad (4.12)$$

$$LCL = \bar{R}D_3 \quad (4.13)$$

by letting

$$D_3 = 1 - 3\frac{d_3}{d_2} \quad (4.14)$$

$$D_4 = 1 + 3\frac{d_3}{d_2} \tag{4.15}$$

D3 and D4 can be found from standard tables (p510, D.C. Montgomery, 1985). Part of the table is presented in Table 4.1.

Observations in Sample, n	Factors				
	A2	d2	d3	D3	D4
2	1.880	1.128	0.853	0	3.267
3	1.023	1.693	0.888	0	2.574
4	0.729	2.059	0.880	0	2.282
5	0.577	2.326	0.864	0	2.114

Table 4.1 Factors for Control Chart Computation

4.1.2 Establishing an $\bar{x}$-Chart and a R-Chart

When a contractor is trying to establish a control chart, he/she needs to decide controlling parameters such as the process average $(\bar{x})$, range (R), and control limits. A common method to get these parameters is to select a given number of preliminary samples (*m*) when the process runs in control and then use them to calculate the parameters. If any of the preliminary samples are out of control against the trial control limits, these samples are discarded and revised control limits are obtained. This process is continued until an acceptable set of control limits is produced. Generally, we would prefer to have 20 to 25 preliminary samples to establish trial control limits (p203, D.C. Montgomery, 1985). Here is an example of establishing a control chart for hot mix asphalt (HMA) air voids. The data for this chart are obtained from a real project recorded in the Kentucky Material Information Management System (KMIMS) database, which contains extensive information related to material design, sampling and acceptance test results. However, this research only selected CPQC related data for analysis.

When setting up $\bar{x}$ and R control charts, we should begin with the R-chart. Because the control limits on the $\bar{x}$-chart depend on the process variability, unless the process variability is in control, these limits will not have much meaning (p203, D.C. Montgomery, 1985). The centerline of the R-chart is the average range. For sample size 4, from table 4.1, we can get D3 = 0 and D4 = 2.282. Using equation 4.12 and 4.13, we can get the control limits for range, as shown at the bottom of table 4.2.

The R-chart is plotted in Figure 4.1. From the R-chart we can see that the overall process variability is in control, although some points are close to control limits.

Lot Number	Sublot1	Sublot2	Sublot3	Sublot4	Average	Range
1	4.3	4.7	3.7	3.8	4.13	1
2	3.3	3	5.2	4.1	3.90	2.2
3	3.7	4.9	5.3	2.9	4.20	2.4
4	4.9	4.6	4.5	4.5	4.63	0.4
5	4.3	4.2	4.6	4.6	4.43	0.4
6	4	4.3	4.9	3.9	4.28	1
7	4.6	4	3.9	4.5	4.25	0.7
8	4.5	3.9	4.6	4.4	4.35	0.7
9	4.1	4.7	4.1	3.9	4.20	0.8
10	3.9	3.9	4.2	4.3	4.08	0.4
11	3.4	2.8	3.6	4.6	3.60	1.8
12	4.9	5.5	5.3	4.4	5.03	1.1
13	4.7	3.5	4.8	4.2	4.30	1.3
14	3.9	4.3	4.7	4.4	4.33	0.8
15	3.8	4.3	4.3	5.1	4.38	1.3
16	4.7	4.5	4.8	5.1	4.78	0.6
17	4.9	5.6	5.2	3.2	4.73	2.4
18	4.1	4.1	5.1	5	4.58	1
19	4.1	3.7	4.2	4.4	4.10	0.7

	Overall average:	4.33
	Average range:	1.11
D_3: 0	D_4: 2.282	
Lower Control Limit (R):		0
Upper Control Limit (R):		2.533

Table 4.2 Quality Control HMA Air Voids

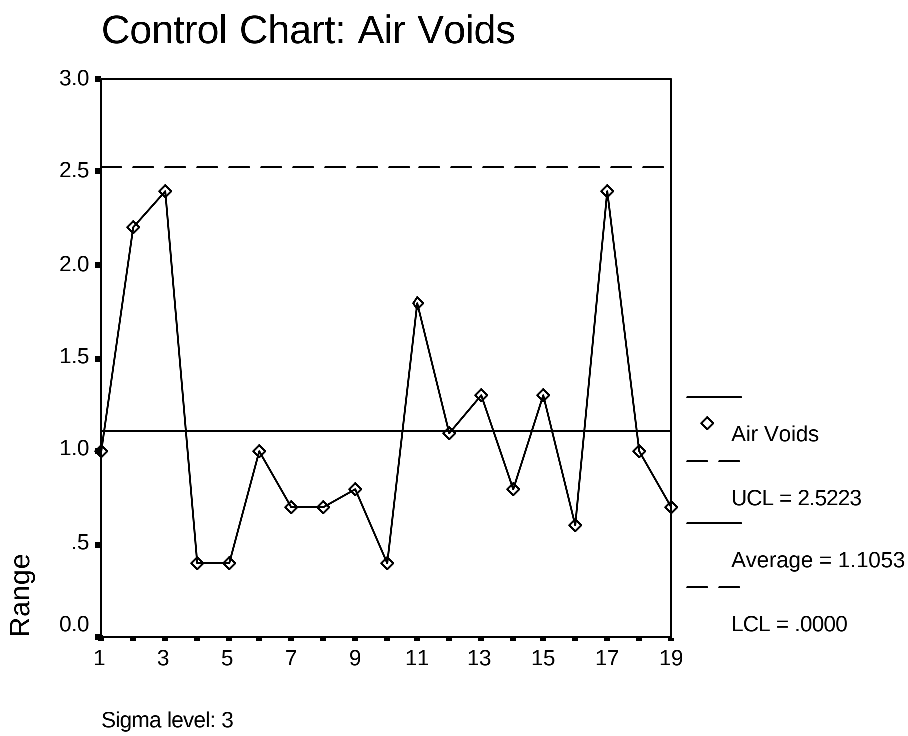


Figure 4.1 Establishing R-Chart for HMA Air Voids

Since the R-chart indicates that process variability is in control, we can construct the $\bar{x}$ chart. The centerline is the grand average. Equation 4.7, 4.8 can be used to construct the upper and lower control limit. For sample size 4, A2 equals to 0.729.

$$UCL = \bar{\bar{x}} + A_2\bar{R} = 4.33 + 0.729 \times 1.11 = 5.13$$
$$LCL = \bar{\bar{x}} - A_2\bar{R} = 4.33 - 0.729 \times 1.11 = 3.52$$

The $\bar{x}$-chart is shown in Figure 4.2. The established R-chart and $\bar{x}$-chart can be further used to control coming measurements.

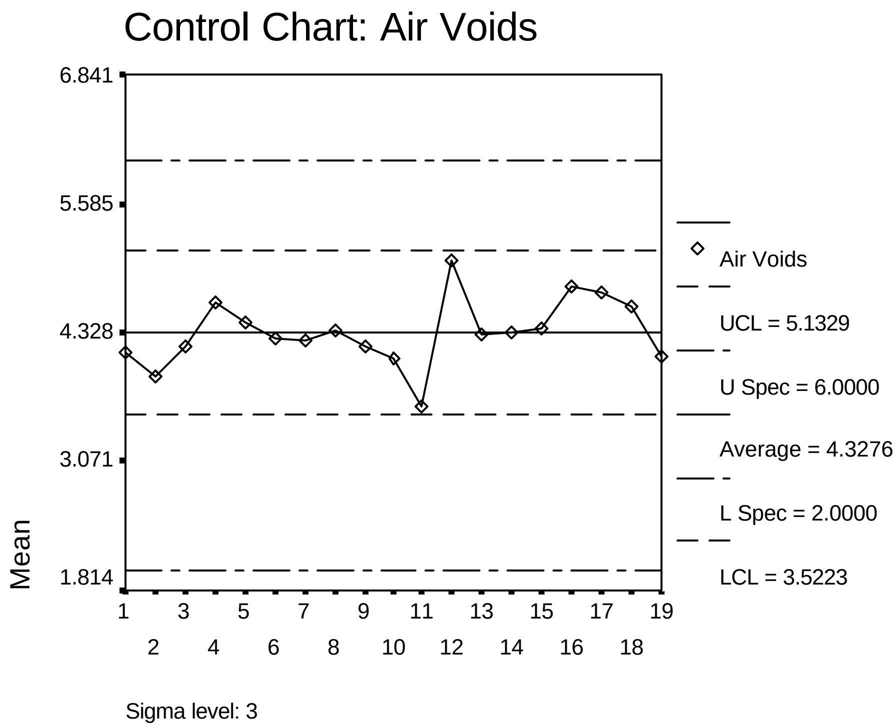


Figure 4.2 Establishing an $\bar{\mathbf{x}}$-Chart for HMA Air Voids

4.1.3 Individual Control Chart

If a contractor decides to use the results of the required acceptance testing as the quality control sample units, then he/she may not be able to obtain enough samples as necessary to construct an $\bar{x}$-Chart or R-Chart. As can be observed from the HMA and concrete projects in KMIMS, it is not unusual that the total samples do not exceed 20. The contractor's work may be almost done after he/she establishes the trial $\bar{x}$-Chart and R-Chart based on these samples. Therefore, the contractor may not get the control chart's "preventive" and "warning" benefits that the QC charts aim for. Another disadvantage of using the $\bar{x}$-Chart and R-Chart based on acceptance test results is that we cannot obtain enough samples at one specific time. For example, a sample with 4 units may require one or two days' production to get; and the process may have already gone off course for a while before it is recognized.

When replicate samples are difficult to produce, one can use the Control Chart for Individual Units. This control procedure uses the moving range of two successive observations to estimate the process variability (p200, D.C. Montgomery, 1985).

For the control chart for individual measurements, the controlling parameters are:

$$UCL = \bar{x} + \frac{3}{d_2}\bar{R} \quad (4.16)$$

$$LCL = \bar{x} - \frac{3}{d_2}\bar{R} \quad (4.17)$$

The centerline for this control chart is $\bar{x}$ (p201, D.C. Montgomery, 1985).

If a moving range of two observations is used, then D_3=0, D_4=3.267, and d_2 = 1.128. For the same HMA data shown in Table 4.2, the control chart for controlling moving range is shown in Figure 4.6 and controlling individual observations is shown in Figure 4.7.

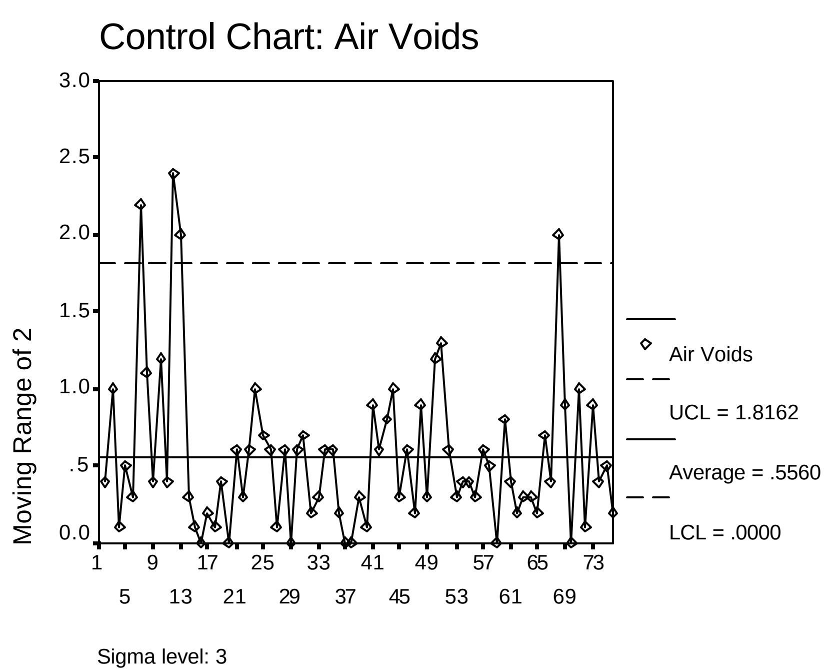


Figure 4.3 Individual Control Chart for HMA Air Voids: Moving Range

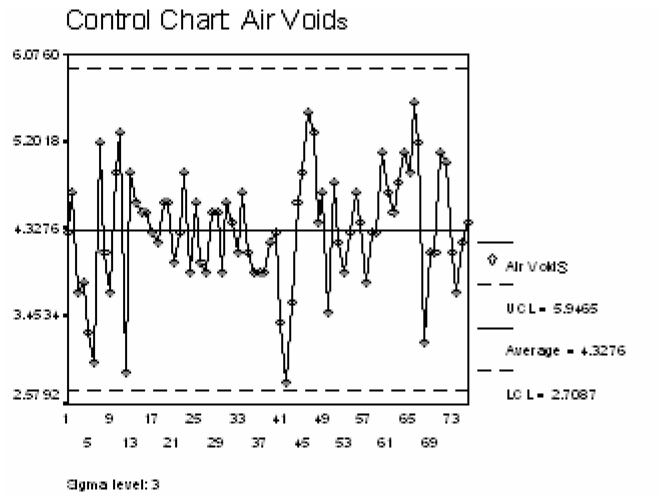


Figure 4.4 Individual Control Chart for HMA Air Voids: Individual Observations

"Out of control" signals are shown both from the moving range chart and the individual control chart. In general, there are more "warning" signals from the individual chart than from the $\bar{x}$-chart because the former is more sensitive in detecting small process shifts. The individual control chart may be likely to produce false "warning" when the production process is actually under control. However, because the data points falling beyond the control limits are distant from the average, it is worthwhile to investigate the reason. If the quality characteristics are normally distributed, the probability of false warning is small.

4.1.4 Moving Average Control Chart

Some DOTs (for example, Indiana) require the contractor to use a Moving Average Control Chart. The Moving Average Control Chart works in the following way: Suppose we want to treat 4 test measurements as a moving average. The first 4 measurements are averaged and its value is plotted on the control chart. When an additional test value is obtained, the first value is dropped, the fifth value is added, and the new group averaged. When a sixth value is obtained, the second value is dropped, and the new group averaged, and so on.

If we have only one measurement at each time point, we can establish the 3-sigma moving average control limits using the following equations:

$$UCL = \overline{\overline{X}} + \frac{3s}{\sqrt{W}} \tag{4.17}$$

and $$LCL = \overline{\overline{X}} - \frac{3s}{\sqrt{W}} \tag{4.18}$$

where $\overline{\overline{X}}$ is the grand mean, s is the standard deviation of the production process which can be obtained from historical records or approximated from sample standard deviation, and W is span of moving average which equals 4 in the example above. The equation 4.12 and 4.13 can be employed to calculate the control limit for range. Figure 4.4 and 4.5 show the moving average charts using the same air void data as before.

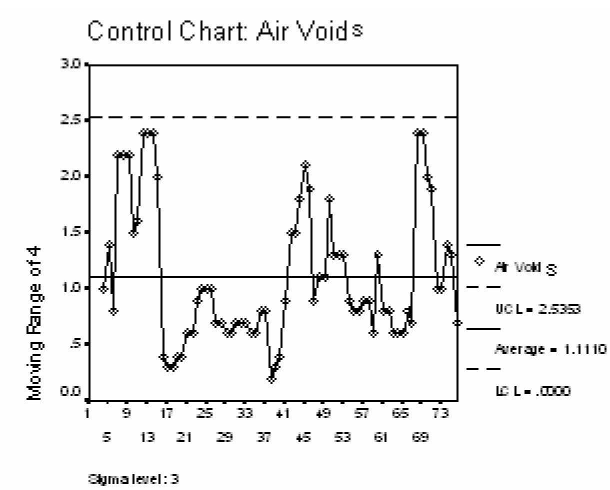


Figure 4.5 Moving Average Control Chart for HMA Air Voids: Moving Range

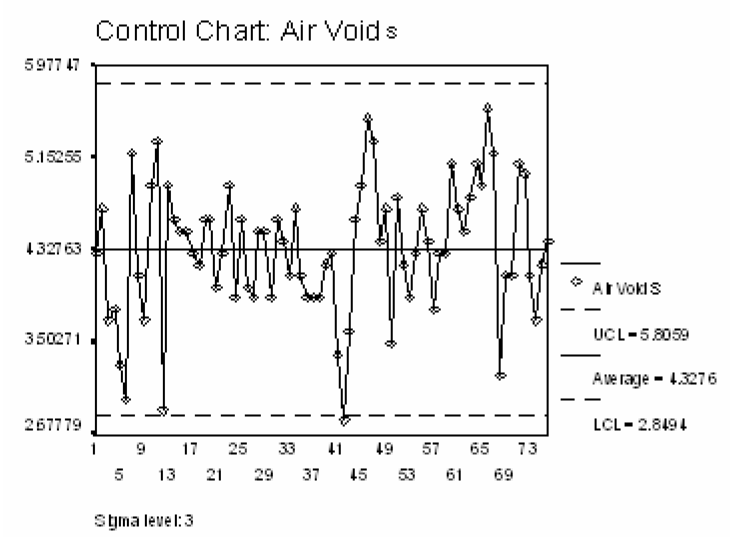


Figure 4.6 Moving Average Control Chart for HMA Air Voids: Moving Average

Comparing to the $\bar{x}$-chart, the moving average chart is more effective in detecting small process shifts. In fact, the individual control chart is a special moving average chart with $w = 2$.

4.2 Practical Use of Control Charts

4.2.1 Conditions of Using QC Charts

The statistical base of using a quality control chart is that the quality characteristics are normally distributed. Although this may not be true in other industries, it's widely accepted that the quality characteristics for highway materials are pretty well approximate a normal distribution. For example, Hudson (1971) illustrates that "The sources of variation (of construction materials) can be separated into two types. Some of these are chance sources which cause normal variations in materials, samples or measurements". For the individual control chart, the departure of normality will cause false warning (the control chart shows something wrong while in fact it is not) in the control charts. For the $\bar{x}$-Chart, even if the underlying distribution is not normal, the results should be robust according to the Central Limit Theorem. The resulting distributions of sample means for n = 4 has been proved to be very close to normal even if the underlying population is extremely non-normal. If a contractor is going to use a control chart for the volumetric characteristics and use the acceptance test results as controlling units, he/she may select to use the $\bar{x}$-Chart and R-Chart by combining two sublots or four sublots to compensate for possible deviation from normal distributions.

4.2.2 Quality Control Characteristics and Frequency

Although a contractor can use the required acceptance test data as input for tracking quality, a clear distinction should be made between quality control and quality acceptance.

Quality control usually requires different, sometimes more testing items, than quality acceptance does. For example, although Kentucky Standard Specification requires a HMA contractor to "monitor and evaluate the AC, air voids (AV), voids-in-mineral aggregate (VMA), density, and gradation" (section 402.03.02) , the density testing is actually conducted by engineers of KyTC, or no density testing is required on Option B materials. On the other hand, the contractor is required to conduct some testing or inspections that is not included in the acceptance testing. For example, Kentucky Method 64-426-02 requires performing the following tests and checks at the minimum frequencies listed below (Page 3, KM 64-426-02, 2001):

3.5.1. All Superpave mixtures	*Minimum frequencies*
Cold-feed checks (when using polish-resistant aggregate)	*Two daily (a. m./p. m.)*
Wet-sieve analysis	*One during first sublot (setup period); one per lot thereafter*
3.5.2. Specialty mixtures	*Minimum frequencies*
Open-Graded Friction Course (OGFC), Scratch Course, Sand Asphalt, Sand Seal Surface	
Cold-feed checks (when using polish-resistant aggregate)	*Two daily (a. m./p. m.)*
3.5.3. All Mixtures Minimum frequencies	
Temperature checks of asphalt mixture	*Hourly*
Temperature checks of performance-graded (PG) binder and aggregate	*Four daily (two in a. m./p. m.). Retain PG binder and aggregate charts for a one- year period for review by the Department.*

4.2. In addition to the acceptance tests required in Subsection 402.03.02 of the Department's Standard Specifications, the Department recommends, but does not require, the following minimum process-control tests and frequencies:

4.2.1. Perform one gradation determination, corresponding to the volumetric analysis for acceptance, per sublot.

4.2.2. Perform one density determination for every 1200 sq. yd. of surface area of mainline pavement.

Table 4.3 QC Requirement on HMA (Kentucky Method)

Although there is no required contractor performed quality acceptance testing during the placement of the HMA and PCC mixtures (density or layer thickness), the contractor may still want to do quality control if he wants to provide a better quality product and avoid penalties.

A contractor should at least perform acceptance testing at frequencies as required by the KyTC specifications and use these test results as the inputs for the quality control. In practice, some contractors do more tests than required, because they can monitor their production processes more timely and more accurately, thus can reduce the risk of making false judgments or producing unacceptable materials.

4.2.3 Deciding Control limits

The technique of the statistical process control is to distinguish the variability due to random causes from that due to assignable causes. Since we know that the chance of exceeding the control limits caused by pure stochastic variation is so small, a simple way to judge if a process is out of control would be observing points beyond the control limits. This is equivalent to statistically rejecting the hypothesis that a sample mean equals to the process mean (target value). Therefore, the control limits set up in the control chart have a statistical meaning, usually three times of the process standard deviation. The control limits are preset by the natural variability of a process.

The specification limits, on the other hand, do not consider a particular process's inherent quality characteristics. The specification limits are set by experiments or by management decisions for highway materials. It is usually a result of balancing between producing high-quality materials and reflecting the average performance of contractors. Therefore, there is no mathematical or statistical relationship between the control limits and specification limits (D.C. Montgomery, 1985). It is not uncommon that the specification limits do not coincide with the control limits. A contractor can plot the specification target value, upper and lower control limits on the control charts, but only the statistical control limits make sense.

However, this does not imply that the specification limits are not important to the contractors. After all, it's the specification limits that decide the acceptance of their materials. The contractor should compare the target values and variation of their materials under normal operation with those required by the specifications. If they cannot meet the specifications' requirement, a systematical correction should be conducted.

The constructing of control limits and using control charts are the contractor's responsibility. The sample data in KMIMS indicate some contractors are doing a good job by limiting their variation of their materials within the bonus level; and their control limits in the control chart are narrower than those required by specifications. This research recommends that the contractors establish their own control limits, while considering the specification limits at the same time.

4.2.4 Deciding Subgroups for Samples in Control Charts

For the $\bar{x}$-Chart and R-Chart, the criterion of deciding the number of observations for each sample (a subgroup) is to minimize the variation within groups and maximize the variation between the groups. An ideal way is to treat several observations obtained at the same time as a subgroup. If only one observation is obtained at one specific time point, we could use the individual control chart or we can group the observations logically close together, such as those from a lot, as a subgroup.

4.3 Lack of Control Analysis

After setting up the control charts, we need to use them to monitor the production process through detecting abnormities from the control charts, i.e., conducting lack of control analysis. The simplest lack of control analysis is to look at if there are one or more points outside of the control limits. Besides this, there are other criteria used in industrial production, which are (p114, D.C. Montgomery, 1985):

A run of at least seven of eight points, where the type of run could be either a run up or down, a run above or below the center line, or a run above or below the median.

Two of three consecutive points outside the 2-sigma warning limits, but still inside the control limits.

Four of five consecutive points beyond the 1-sigma limits.

An unusual or nonrandom pattern in the data.

One or more points near a warning or control limit.

Additional criteria can be found from statistical quality control references.

4.4 Trouble Shooting and Production Adjustment

After detecting problems from a quality control chart, the contractor needs to take corrective actions on the production process. This research finds it a good practice for the contractor to develop a trouble shooting and adjustment program, as required by the Indiana QC/QA procedures for HMA. The trouble shooting and adjustment program works as:

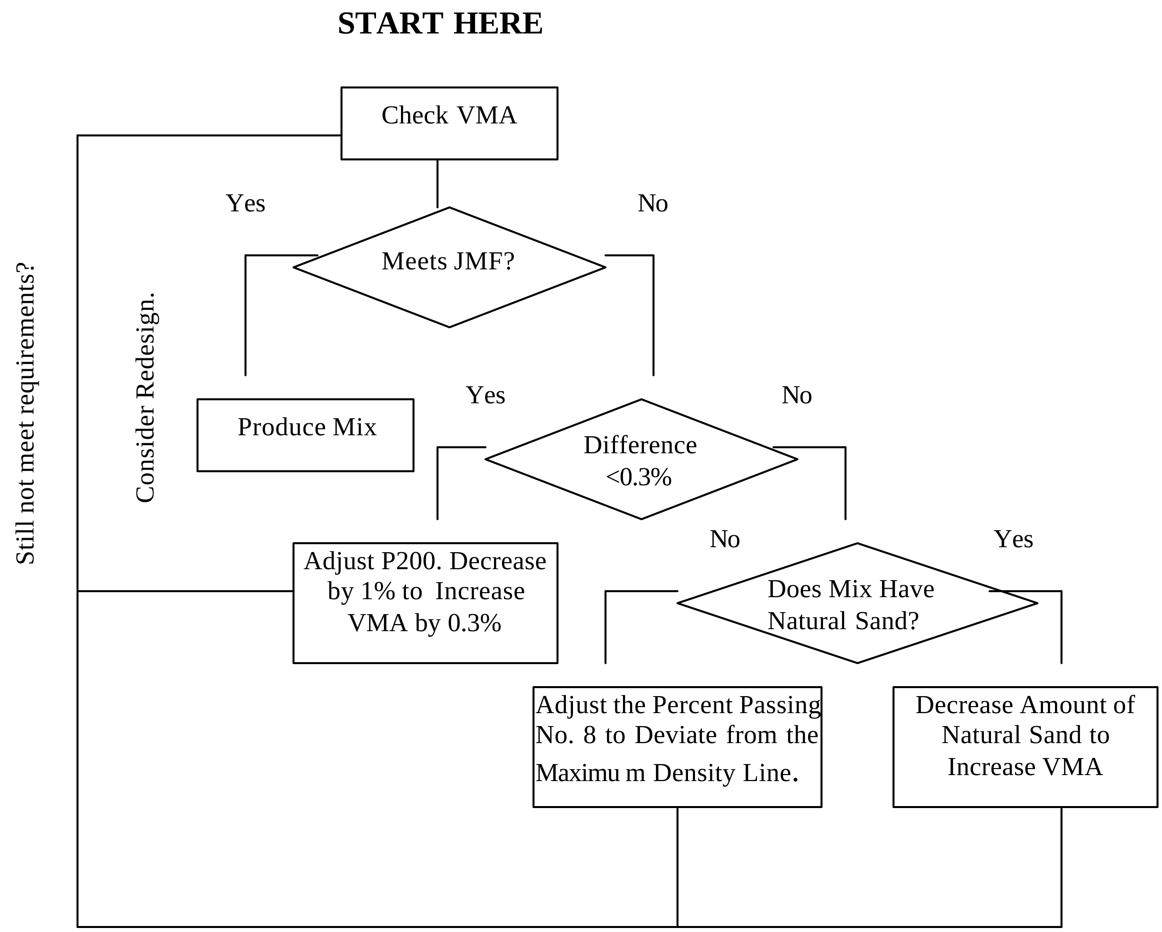
The contractor previously lists all of the possible causes for each abnormality found in the control chart. When the abnormality appears again, the contractor can easily identify the problem and take corrective actions. Corrective actions include, but are not limited to, investigation for assignable cause, correction of known assignable cause, or retesting (Indiana DOT, 2001).

For example, Table 4-4 (Indiana QC procedure) lists the materials and properties that are verified at the HMA plant and the possible causes of problems with these materials. For each property, the potential problem areas are given a priority number with the number 1 being the highest priority.

		Agg. Stock-Piles	Blended Agg. Gradation	Mix Binder %	Rap Binder %	Air Voids	VMA
		Priority	**Priority**	**Priority**	**Priority**	**Priority**	**Priority**
01	Results / Sampling / Test Equipment: Verify	1	1	1	1	1	1
02	Stockpiles: Visually Check Segregation	2	2		2		
03	Loader Operations: Check	3	3		3		
04	Stockpiling & Trucking: Check	4	4				
05	CAPP Source: Discuss Findings	5	8				
06	Cold Feed-Loading		5				
07	Cold Feed-Contamination		6				
08	Cold Feed-Gates/Control System/Blend Percents		7				
09	Gradation vs. Binder%: Graph			3	5		
	A. Mix: Segregation?			3A	5A		
	B. Plant: Malfunction / Deterioration			3B	5B		
10	Plant Settings: Check			2			
11	Total Binder Consumption vs. Mix Production: Check			5			
12	RAP: Processes RAP / Uniformity / Binder Content			4	4		
13	Mix Gradation/ Check					3	2
14	Mix Agg. Blend of Components (Particle Shape Issues): Check					4	4
15	Mix Binder Content					2	3
16	Agg. Specific Gravity (Gse), (Gsb) and Absorption: Check						5
17	Adjust/ Respond As Appropriate & Per QCP (Don't over-react)	6	9	6	6	5	6
18	Verify Success of Changes & Check Impact on Other Control Factors	7	10	7	7	6	7
19	QCP Addendum: Submit if Applicable	8	11	8	8	7	8

Table 4.4 An Example of Trouble Shooting Schedule (Indiana DOT, 2001)

Figure 4.7 is an example of VMA correction plan provided by Indiana DOT QC/QA procedure (Indiana DOT, 2001). A loss of VMA is said to be a common problem affecting VMA; also, the amount of materials passing the 75 µm sieve and the relative proportions of coarse and fine aggregate can significantly affect the VMA (Indiana DOT, 2001).



VMA = Voids in Mineral Aggregate
AV = Air Voids
P200 = Percent Passing 0.075 mm (#200) sieve

Note: This flow chart is intended to provide guidance for adjustment of VMA. Due to differences in properties of specific mixes, the effect of the adjustments may be variable.

An Example of Correction Plan (Indiana DOT, 2001)

4.5 Summary

This chapter discussed some common quality control techniques to help contractor better control their production within the Contractor Performed Quality Control (CPQC) program. These techniques include quality control charts, diagnostic analysis of a quality control chart, trouble shooting, and production adjustment.

When replicate samples can be obtained from one time point, this research recommends using the $\bar{x}$-Chart and R-Chart; otherwise, the individual control chart or the moving average chart is more appropriate.

This research recommends that the contractors establish their own control limits for the control charts, while considering the specification limits at the same time.

This research finds it a good practice for the contractors to develop a trouble shooting and adjustment program when they detect abnormalities from the quality control charts.

Chapter V Quality Acceptance Sampling Plan

Each State DOT has a quality assurance program for highway construction projects. In Kentucky, the definition of the Quality Assurance is (KyTC, 2000):

QA consists of all planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy specified requirements for quality. QA serves to provide confidence in the Contract requirements, which include materials handling and construction procedures, calibration and maintenance of equipment, production process control and any sampling, testing and inspection which is performed by the Department for these purposes.

The Quality Assurance program includes quality acceptance, independent assurance sampling and testing, and other requirements. This research investigated the topics of the quality acceptance program and verification testing by the Department. This chapter discusses quality acceptance; verification will be covered in the next chapter.

Acceptance shall be the responsibility of the State DOTs. According to the definition of the *Federal Aid Policy Guide* (FHWA, 1995), the acceptance program should include:

All factors that comprise the State highway agency's (SHA) determination of the quality of the product as specified in the contract requirements. These factors include verification sampling, testing, and inspection and may include the results of quality control sampling and testing.

5.1 Introduction to a Quality Acceptance Plan

Acceptance sampling is one of the most important parts of the State DOT's quality assurance program. Although the contractor conducts quality control and quality acceptance testing on some material characteristics, the acceptance of the material is the sole responsibility of the Department. A typical application of the acceptance sampling is dividing materials of a highway project into a certain amount called a "lot", then randomly taking a few samples from this lot, testing the samples, and finally making acceptance decisions based on the testing results. However, the purpose of the acceptance sampling is to determine a course of action, not to estimate the true material quality of a lot (Duncan, 1986) (Montgomery, 1984). Therefore, it is possible that the DOT accepts materials with bad quality while sometimes rejects those with good quality.

Acceptance sampling procedures are usually specified in an acceptance sampling plan. Because acceptance sampling is used to make important decisions such as acceptance or rejection of materials, and payment adjustment, it is necessary for both the contractors and the DOTs to understand the relationship within the components in an acceptance sampling plan and the risk related to making these decisions. The primary topics addressed in an acceptance sampling plan usually include:

- Material characteristics being evaluated in an acceptance sampling plan
- Testing methods
- The size of a lot and the number of sublots per lot
- Methods of locating samples within individual sublots
- The number of samples or measurements per lot
- Evaluation methods based on testing results
- Specification limits
- Acceptance criteria
- Payment adjustments based on acceptance sampling results

All of these topics are related to the risk analysis of an acceptance sampling plan. For example, do the material characteristics we are testing truly determine the road performance? Are the testing methods reliable? Out of many questions, this research only investigated the effect of the lot size, the evaluation methods, the number of samples, and the acceptance criteria in an acceptance sampling plan.

5.2 Lot Size and Sampling Frequency

A “lot” is a quantity of certain highway materials upon which an acceptance/rejection decision is made. Different DOTs define the size of a lot differently: some treat the same materials in a whole project as a lot, some treat one day production as a lot, while others treat a predefined amount (tons or square yards) of materials as a lot (Table 5.1).

A large lot size has certain advantages. If the sampling frequency (one measurement out of a certain quantity of the materials) remains the same, large lot size will yield more measurements and statistically reduce the risk of making wrong acceptance/rejection decisions. If the large lot size results in fewer measurements, then the sampling is more economically efficient. However, a large lot with reduced measurements will decrease the representative power of the true materials and thus increase the possibility of making wrong decisions. Another advantage of a smaller lot size is that it can reduce the contractor’s risk by allowing him to adjust the material production process at the early stage of a project, stimulated by the Department’s acceptance decisions, before severe loss is incurred on a large amount of materials. The comparison of the KyTC’s acceptance lot size and sampling frequency shows that its sampling effort is moderate.

Although it is possible to review the feasibility of the lot size from investigating its statistically representative power, the selection, is usually a management decision. This research proposes using a moderate lot size, which gives the contractor time to make corrections based on the DOT’s acceptance/rejection decisions and yet contains enough measurements so that a statistically valid decision can be made.

DOT	HMA	Concrete
Alabama	700 tons each sublot.	
Arizona	Determined by Engineers and based on time period. E.g., During an 8-hour shift, a mix sample should be taken in each 2-hour period on a random basis within that period.	
Arkansas	3000 metric tons (3000 tons), with each standard lot divided into 4 sublots of 750 metric tons each.	3000 cubic meters or 4000 cubic yard (PCCP), 300 cubic meters or 400 cubic yards (structure concrete), with each standard lot divided into four sublots.
California	A lot represents the total quantity of asphalt concrete placed; More than one lot will occur if changes in the target values, material sources, or mix design. One sample per 450 tonnes or portion thereof. In all cases not less than one sample per day.	
Connecticut	1 lot/day, Min. 300 tons	
Illinois	AC by Nuclear Gauge, 1 sample per half day of production , Air Void, BSG, MSG, one per half day of production for first 2 days and 1 per day thereafter(Class I Mixture). 1 per day for non Class I Mixture.	
Indiana	4400 tons of base or intermediate, 2800 tons for surface mixture per lot. One lot is subdivided to 4 sublots.	A sublot will typically consist of 40 square meters and a lot will typically consist of 120 square meters.
Kansas	sublots of 750 tons (lot size 3 000 tons)	
Kentucky	A lot is 4,000 tons. A sublot is 1,000 tons.	4000 square yards/ lot, 1,000 square yards/sublot (PCCP)., 200 cubic yards/ lot, 50 cubic yards/sublot (Structure).
Louisiana	5,000 tons with five sublots. The lot size is adjustable. If historical records indicate that an acceptable and uniform hot mix is continuously being produced, the standard lot size may be increased when agreed upon by the engineer and contractor. And the lot size may decrease in some circumstances.	
Maryland	Plant control determined by contractor, initial verification shall consist of 4 samples with lot size of 1000 tons.	Slump, 1 per 50 cubic yards; Air Content: 1 per 50 cubic yards; Compression: 1 per 50 cubic yards; Split Tensile: 3 per day.
Michigan	One lot is made up of 3 sublots of approximately equal size up to a maximum of 2000 metric tons.	Material with the same required characteristics
Missouri	3000 tons of mixture and shall contain not less than 4 sublots	
Nebraska	A lot 3750 tons, a sublot 750 tons	
New Mexico	HMA: 1 per 1500 tons (QC); 10,000 tons with individual sublot size 2,000 tons (acceptance test)	PCCP 1 per 125 cubic yards (QC), 500 cubic yards (Acceptance)
North Dakota	1/1500 tons	
Oklahoma	4000 tons with equal four sublots.	Standard lot 10,000 with individual sublot 2500 square yards
Texas	The maximum sublot size shall be 1000 tons or 650 cubic yards, 4 sublots per lot	

Table 5.1 Lot size required by KyTC and other State DOTS.

5.3 Evaluation Methods and the Acceptance Sample Size

There are two types of acceptance sampling plans: the attribute acceptance plan and the variable acceptance plan. The attribute acceptance plan only grades the material as "conforming" and "nonconforming", without looking at the quantitative measurements. Major highway materials, however, are evaluated using the variable acceptance plan because it requires a smaller sample size and yields good performance. Therefore, the analysis of this research was concentrated on the variable acceptance plan. The approaches usually used in a variable acceptance plan include the average method ($\bar{x}$ method), k method, and m method.

The number of measurements required for acceptance testing, as well as the decision criteria, can be decided from a statistical risk analysis.

A detailed discussion of these evaluation methods, the number of measurements required, and the acceptance decision criteria with risk analysis can be found in Appendix IV. The analysis shows that the (Percent within Limits) PWL method has certain advantages over the average method, but the decision criteria should be carefully decided if one uses the PWL method. The analysis also shows that the acceptance sample size of 4 is the minimum requirement from a statistical point of view.

5.4 Comparison of Acceptance Methods and Acceptance Test Performers

Currently, the KyTC is applying the average method to hot mix asphalt (HMA) materials and the PWL method to concrete pavement for acceptance purposes. This research found both methods are used equally in the State DOTs (Table 5.4). Also, this research found that many DOTs make acceptance decisions based on the contractor's acceptance tests, provided that the contractor's test results are reliable (Table 5.4).

DOT	Acceptance Methods	Acceptance Test Performers
Alabama		Contractor
Arizona	PWL for HMA	Engineer
Arkansas	Average	Based on the average of the 5 tests (1 by contractor and 1 by DOT) performed on the lot.
California	PWL for HMA	Based on the average of the contractor's and the DOT's performed on the lot.
Connecticut	PWL for HMA	Contractor
Illinois		Contractor
Indiana	Individual and average value	Engineer
Kansas	PWL	Contractors. If the Department's verification test results do not show favorable comparison with the Contractors quality control test results then the Department's test results will be used for material acceptance.
Kentucky	Average for HMA, PWL for concrete	Contractor
Louisiana	PWL	Engineer
Maryland	Individual and average value	Engineer and Contractor
Michigan	PWL	Contractor
Missouri	PWL	Contractor
Nebraska	Average	Contractor
New Mexico	PWL	Contractor
North Dakota	Individual and average value	Contractor
Oklahoma	Average	Engineer use his own tests while comparing them with the contractors'
Texas		Engineer

Table 5.2 Comparison of Acceptance Methods and Acceptance Test Performers

5.5 Summary

This chapter discussed some major components of the highway materials acceptance plan: the effect of the lot size, the evaluation methods, the number of samples in a lot, and the acceptance criteria. The acceptance sampling plan can be categorized as the attribute sampling plan and the variable sampling plan, which include three acceptance methods: the average method, *k*-method, and *m*-method. These methods and the acceptance procedures under different circumstances are shown in Appendix IV.

A Lot should be treated as an acceptance/rejection unit. The effort of acceptance sampling is determined by the lot size and the sampling frequency. This research recommends carefully selecting the size of a lot so that the contractor has enough time to make corrections in a project and enough measurements can be obtained for making statistically valid acceptance decisions.

The number of measurements required, or the sample size *n*, can be calculated by using statistical methods from known acceptable quality level (AQL), rejectable quality level (RQL), the contractor's risk, and the KyTC's risk. Under the same AQL and RQL, increasing the sample size will decrease the risk of making wrong acceptance decisions. If the population standard deviation is known, a smaller sample size can be used without affecting the risk of making wrong decisions.

To increase the sample size without increasing the sampling effort, the KyTC can combine acceptance tests from two adjacent lots into one evaluation unit for the acceptance decision. The KyTC can also combine the contractor's acceptance test results (allowed in some States) with its own verification test results if the latter test is totally independent of the contactor's test.

Specification limits will affect the acceptance decisions. A reasonable acceptance plan requires that the specification limits are evidently performance related. Otherwise, the acceptance or rejection decision is unwarranted.

If the KyTC wants to use the statistical acceptance sampling plans described in Appendix IV, the normality distribution assumption of material characteristics should be checked, because all the formulas in Appendix IV are based on normal distribution assumptions.

Chapter VI Quality Assurance by Sample Verification

A quality assurance (QA) program is a comprehensive system to oversee all quality-related activities in an integrated fashion. As DOTs' personnel resources are reduced, more reliance is placed on the contractor-performed testing. Under this scenario, DOTs perform a supervisory role, and conduct a limited number of testing to verify the contractor-performed quality control data. For example, the KyTC uses the contractor's quality control test results for acceptance purposes, provided that the quality control (QC) data are reliable (Table 5.2). How to ensure that the contractor's QC test results are reliable remains a major concern for DOTs. This concern also reflects in our survey response from engineers. To alleviate this concern, some DOTs simply use their own acceptance test results, although they require the contractor to conduct quality control testing separately. However, if the QC test results are reliable, also using them for the acceptance purpose can avoid double efforts on sampling. The purpose of this chapter (with Appendix V) is to evaluate the KyTC's verification method by investigating the available test data in the Kentucky Material Information Management System (KMIMS) database, and introduces some useful statistical verification methods.

6.1 Introduction to Verification Testing

The verification testing is done by the DOTs to ensure the validity of the contractor's acceptance testing results. The frequency of the verification testing is often a compromise between the availability of the DOTs' resources versus the risk of not being able to catch abnormalities in the data reported by contractors. The rate of agency verification testing as compared to the acceptance testing ranges from 10% to 33% (25% for KyTC, see Table 6.1). More verification tests may provide the DOTs with more confidence on using the contractor's data, but it also comes with a cost.

State DOTs use various methods to judge the consistency between their data and the contractor's QC test data (Table 6.1). Some DOTs set a tolerance limit between the contractors' data and the DOT's test result on split, or paired samples. If the discrepancy exceeds this limit, dispute resolution clauses take over. Another approach is to compare the statistical characteristics of the two sets of data. If the two sets of data demonstrate similar statistical parameters (mean and variance), they accept the contractor's data. Both methods have advantages and disadvantages. Checking tolerance limits is simple and does not require any sophisticated statistical analyses. However, this method does not establish any trends and precludes any meaningful statistical tracking.

DOT	Verification Frequency (HMA)	Verification Method
Alabama	1 per lot	
Arkansas	1 per lot	compare difference
California	not less than 10 percent of the minimum quality control sampling and testing frequency required of the Contractor	T-test and F-test
Connecticut	min. 1 lot/project	T-test and F-test
Illinois	>=10% for gradation; >= 20% for asphalt content, bulk specific gravity, maximum specific gravity, and field density	Split Sample, compare difference
Kansas		T-test and F-test
Kentucky	1 per lot	compare difference
Michigan	a minimum of one set per grade of concrete daily, 33% of contractor's test for HMA	compare difference
Missouri	1 per day	compare difference
Nebraska	1 per lot	compare difference
New Mexico		T-test and F-test
North Dakota		compare difference

Table 6.1 Comparing of Verification Test Frequency and Test Methods

6.2 Review of QC/QA Data in the KMIMS Database

This research evaluated the effectiveness of the current verification methods employed by the KyTC. This process included an investigation of the QC/QA data from the KMIMS database. All the materials and construction information is contained in this database in the form of tables. For example, part of the HMA sampling information can be found in Table amix7_I in the KMIMS database. Comparisons were made between the contractor-performed and the KyTC-performed data. The reviewed pay items include hot mix asphalt (HMA) and concrete from CPQC projects. 34, 421 HMA sample records were selected from the KMIMS data: Table amix7_I, (contains both the acceptance test information reported by contractors, and the verification test information reported by KyTC). Because of the limited number of the concrete CPQC data (trial projects only), this research selected 2,900 records on 15 CPQC concrete projects from KMIMS data: Table sam_res and conc2_I. It is important to note that KMIMS database suffers from incomplete data entries and inconsistent records. Therefore, several data files were rendered useless in this analysis.

6.2.1 Analysis of Hot Mix Asphalt QC/QA Data

The HMA material characteristics reviewed in this research include air voids, asphalt content, and voids in mineral aggregate. Different characteristics have different specification requirements (Table 6.2): for superpave, the target value of air voids (AV) is 4.0; for asphalt content, different job mix formula (JMF) have different target asphalt content values; and for voids in mineral aggregates (VMA), there is a minimum VMA requirement for each JMF.

AV	
Pay Value	**Test Result (%)**
1.05	3.5-4.5
1.00	3.0-5.0
0.95	2.5-5.5
0.90	2.0-6.0
(1)	<2.0 or >6.0

(a) Payment Schedule for Air Voids

AC	
Pay Value	**Deviation From JMF (%)**
1.00	$\leq \pm 0.5$
0.95	± 0.6
0.90	± 0.7
(1)	$\geq \pm 0.8$

(b) Payment Schedule for Asphalt Content

VMA	
Pay Value	**Deviation From Minimum**
1.00	$\geq$ min. VMA
0.95	0.1-0.5 below min.
0.90	0.6-1.0 below min.
(1)	> 1.0 below min.

(c) Payment Schedule for Voids in Mineral Aggregate

Table 6.2 HMA Payment Schedules (KyTC, 2000)

Because of these different requirements, the research uses different methods to review.

Air Voids for HMA Projects

After discarding the incomplete data, 1818 verification sample records and 1827 acceptance sample records were obtained. These data were analyzed to test the equality of means and variances using statistical methods. The analysis results are reported in Table 6.3.

	Test Type	Number of Records	Mean	Std. Deviation	Std. Error Mean
Air Voids	Acceptance	1818	4.086	.8526	.0200
	Verification	1827	4.063	.9778	.0229

(a) General Statistics of Air Voids Acceptance and Verification Data

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	P Value	t	Degree of Freedom	P Value	Mean Difference	Std. Error Difference	95% Confidence	
								Lower	Upper
Equal variances assumed	18.984	<0.001	.736	3643	.462	.022	.0304	-.0372	.0820
Equal variances not assumed			.736	3581	.462	.022	.0304	-.0372	.0819

(b) Comparison of Means and Variances of Air Voids Acceptance and Verification Data

Table 6.3 Analysis of Air Void Acceptance and Verification Test Results

According to the test results, the means of both sets of samples are consistent and close to the target value 4.0. But the Variances are not the same. The verification test results reveal more variation than the acceptance tests.

Asphalt Content for HMA Projects

After the discarding incomplete data, 3082 verification and acceptance sample records were obtained. The required asphalt content in the job mix formula for each mix may be different; therefore, the job mix asphalt content should be treated as the reference point. By taking the difference between the required asphalt content and the acceptance test data one can determine how closely the specifications are met (Delta #1). Similarly, one can determine the closeness of the verification results by taking the difference between the verification data and the required asphalt content (Delta #2). These two differences serve as two new variables which are compared statistically and the results are reported below.

Test Type	Number of Records	Mean*	Std. Deviation	Std. Error Mean
Delta #1 = Acceptance – JMF AC	3082	-.0066	.1518	.00273
Delta #2 = Verification – JMF AC	3082	-.0074	.20970	.00378

* - Note:
\+ means above the JMF asphalt content
\- means below the JMF asphalt content

(a) General Statistics of Asphalt Content Acceptance and Verification Data

	Levene's Test for Equality of Variances		t-test for Equality of Means					
	F	P-Value	t	Degree of freedom	P-Value	Mean Difference	95% Confidence Interval of the Difference	
							Lower	Upper
Delta #1 Vs. Delta #2(Equal variances assumed)	250.679	<0.001	.188	6162	.851	.0009	-.00827	.01002
Delta #1 Vs. Delta #2(Equal variances not assumed)			.188	5615	.851	.0009	-.00827	.01002

(b) Comparison of Means and Variances of Asphalt Content Acceptance and Verification Data

Table 6.4 Analysis of Asphalt Content Acceptance and Verification Test Results

According to the test results, the means of both sets of samples are consistent and close to 0. This means that the average asphalt content data reported by the contractor and the KyTC are similar. But the Variances are not the same. The verification test results show more variations in the KyTC data as compared to contractor performed acceptance test data.

Voids in Mineral Aggregates for HMA Projects

After discarding the incomplete data, only 422 verification and acceptance sample records were obtained. The required minimum VMA in the job mix formula for each mix may be different; therefore, the job mix VMA should be treated as the reference point. By taking the difference between the acceptance test data and the required minimum VMA one can determine how good the specifications are met (Delta #1). Similarly, one can determine the closeness of the verification results by taking the difference between the verification data and the minimum VMA (Delta #2). These two differences serve as two new variables which are compared statistically and the results are reported below.

Test Type	Number of Records	Mean	Std. Deviation	Std. Error Mean
Delta 1 = Acceptance – JMF VMA	422	1.267	.9404	.0458
Delta 2 = Verification – JMF VMA	422	1.255	1.0368	.0505

(a) General Statistics of VMA Acceptance and Verification Data

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	P-Value	t	Degree of Freedom	P-Value	Mean Difference	Std. Error Difference	95% Confidence Interval of the	
								Lower	Upper
Delta1Vs. Delta2 (Equal variances assumed)	3.008	.083	.184	842	.854	.013	.0681	-.1212	.1463
Delta1Vs. Delta2 (Equal variances not assumed)			.184	834.107	.854	.013	.0681	-.1212	.1463

(b) Comparison of Means and Variances of VMA Acceptance and Verification Data

Table 6.5 Analysis of VMA Acceptance and Verification Test Results

According to the test results, the means and the variances of both sets of samples are consistent. This means not only the averages, but also the variations, of the contractor's and the KyTC's VMA data (after taking the difference with the reference VMA) are similar.

6.2.2 Analysis of Concrete QC/QA Data

The concrete material characteristics reviewed in this research include air content, slump, and 28 days compressive strength. Different classes of concrete have different specification requirements; therefore, the analysis must be conducted on each type of concrete separately. Out of the 2700 useable concrete records, the concrete samples with the following material codes: 4745, 4700, and 4744 contributes to most of the selected observations (Figure 6.1). But there is no clear indication of acceptance or verification samples for material 4744 in the KMMIS database. Therefore, the analysis was conducted on the data with the following codes: 4745 and 4700, which are PCCP with Class C fly ash and Class A concrete, respectively.

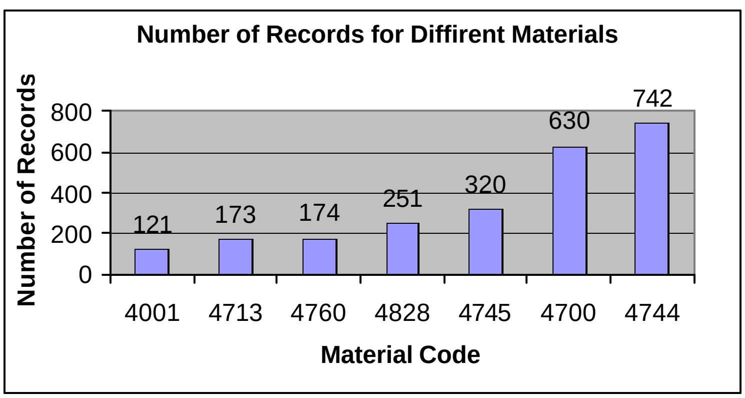


Figure 6.1 Number of Records of Different Type of Concrete

Analysis of Portland Cement Concrete Pavement (PCCP) with Fly Ash

The analysis results of PCCP with Fly Ash are shown in Table 6.6. According to the analysis results, the verification test results and the acceptance test results are different in variance of air content, variance of slump, mean of slump, and mean of 28 day strength.

	Test Type	Number of Observations	Mean	Std. Deviation	Std. Error Mean
Air Content	Acceptance	428	5.50	.92	4.44E-02
	Verification	92	5.53	.71	7.35E-02
Slump (in.)	Acceptance	428	2.699	1.399	6.761E-02
	Verification	92	3.407	.836	8.712E-02
Strength (mpa)	Acceptance	421	37.0227	6.1335	.2989
	Verification	92	39.1660	6.0441	.6301

Table 6.6 (a) General Statistics of Acceptance and Verification Test of PCCP Concrete Data

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	P Value	t	Degree of Freedom	P Value	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Air Content	Equal variances assumed	8.462	.004	-.224	518	.823	-2.27E-02	.10	-.22	.18
	Equal variances not assumed			-.265	164.655	.792	-2.27E-02	8.59E-02	-.19	.15
Slum (in.)	Equal variances assumed	50.618	.000	-4.682	518	.000	-.709	.151	-1.006	-.411
	Equal variances not assumed			-6.427	216.854	.000	-.709	.110	-.926	-.491
Strength	Equal variances assumed	.034	.854	-3.044	511	.002	-2.1433	.7041	-3.5265	-.7601
	Equal variances not assumed			-3.073	135.083	.003	-2.1433	.6975	-3.5226	-.7639

Table 6.6 (a) Comparison of Means and Variances of PCCP Concrete Acceptance and Verification Data

Table 6.6 Analyses of PCCP Concrete Acceptance and Verification Data

Analysis of Class A Concrete

The analysis results of Class A Concrete are reported in Table 6.7. According to the analysis results, the verification test and the acceptance test results are consistent in all quality characteristics.

	Test Type	Number of Observations	Mean	Std. Deviation	Std. Error Mean
Strength (psi)	Acceptance	242	6032.05	622.00	39.98
	Verification	67	5926.18	623.81	76.21
Slump (in.)	Acceptance	245	1.8289	.5887	3.761E-02
	Verification	67	1.7948	.5417	6.618E-02
Air Content	Acceptance	245	5.591	.815	5.204E-02
	Verification	67	5.727	.788	9.633E-02

Table 6.6 (a) General Statistics of Acceptance and Verification Test of Class A Concrete Data

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	P Value	t	Degree of Freedom	P Value	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Strength	Equal variances assumed	.089	.766	1.232	307	.219	105.87	85.92	-63.20	274.94
	Equal variances not assumed			1.230	105.152	.221	105.87	86.06	-64.77	276.51
Slump	Equal variances assumed	.171	.680	.428	310	.669	3.416E-02	7.983E-02	-.1229	.1912
	Equal variances not assumed			.449	112.356	.655	3.416E-02	7.612E-02	-.1167	.1850
Air Content	Equal variances assumed	.501	.480	-1.222	310	.223	-.136	.112	-.356	8.322E-02
	Equal variances not assumed			-1.244	107.665	.216	-.136	.109	-.353	8.077E-02

Table 6.6 (a) Comparison of Means and Variances of Class A Concrete Acceptance and Verification Test Data

Table 6.6 Analysis of Class A Concrete Acceptance and Verification Test Data

6.2.3 Summary Remarks

The HMA data show different variations between the KyTC's data and the contractor's data, although the overall difference is not large. The KyTC's verification data usually have more variations than the contractor performed acceptance data. The concrete data also show some discrepancies, but in general it is very consistent.

6.3 Statistical Verification Approaches

To reduce the discrepancies in the verification tests and acceptance tests, a closer monitoring of the contractor's data is required. Because many projects, as shown in the KMIMS database, are relatively small and lead to only a few verification samples, the statistical tests cannot reveal more information than individual comparisons. However, for large projects that contain many observations, it is possible to use statistical methods for verification test. It is also possible to conduct an annual evaluation of a contractor's acceptance test performance by adding all samples of the same materials in different projects together to conduct a statistical test. This research deems it necessary to discuss the available statistical comparison methods and how to use them correctly.

6.3.1 Independent Samples Vs. Paired Samples

Verification testing is required when the DOT decides to use the contractor's data for acceptance purposes. In fact, construction projects that are partially funded through the federal government must conform to the regulations of the FHWA Quality Assurance Program detailed in Title 23 CFR 637 b. According to this document, "the verification sampling shall be performed on samples that are taken independently of the quality control samples". In Kentucky, the KyTC will obtain an independent sample at the same time when the contractor is obtaining the random sample. Although this procedure is not the same as the split sample, it is not totally independent either. In statistical analysis, we can treat it as paired sample with the contractor's test to get a more accurate result.

There are two reasons why we need to treat independent samples and paired samples separately:

The first reason is that the sources of variability are different. Totally independent samples contain the following sources of variability: material, sampling, test method, operators, etc. The paired samples, because they are taken at the same place and the same time, should have the same variability in material and sampling. The paired samples still reflect variability in test methods (if the test is conducted on the contractor's machine such variability may also be omitted) and operators. Therefore, which method to use depends on what the KyTC wants to verify.

The second reason is that the statistical test procedure to detect the difference between the acceptance test and verification test is not the same. Because the acceptance tests by the contractor and verification tests by the KyTC are conducted on the same population, they should have the same distribution or statistical parameters, i.e., the mean and the variance. Therefore, we should test the equality of both the mean and standard deviation between the contractor's data and the KyTC's data. The test methods for dependent and independent samples are different. The following combinations of the intended statistical test and its condition are discussed in Appendix V:

- Independent Sample; Test for Equality of Means
- Independent Sample; Test for Equality of Variances
- Dependent Sample; Test for Equality of Means
- Dependent Sample; Test for Equality of Variances

6.3.2 Advantages and Concerns of the Statistical Tests

Advantages

The statistical tests provide us consistent and systematic methods with a well-established theoretical basis. From these tests we can know the probability of "correctness" when we make decisions.

Another advantage is that the statistical test can detect smaller variations in the data. In the report "Followup to the 1999 Process Review of Hot Mix Asphalt Acceptance" by the Kentucky office of the FHWA, although the general HMA quality is very acceptable, there are some concerns about the too much variability in the samples. For example,

The tolerance (SS 402-7) of 1% for the same equipment and 1.5% for different equipment, even though in accordance with AASHTO, makes the State's checking within tolerance almost automatic. The large tolerances lay the ground work for the acceptance of other sublots, that the Department does not test, at even higher tolerances. The large tolerances result in lost opportunity to improve the consistency of the mix.

If we can use the statistical methods to detect and control the difference, we may improve the material quality by decreasing the variability.

Concerns

In many KyTC projects, there are not sufficient data to run an effective statistical analysis. The possible non-normal distribution of the KMIMS data is also a problem because most statistical tests take a normality assumption. Usually, one can safely use the independent t test or paired t test to compare for means, but one needs to be very careful when comparing variances.

Another disadvantage is that some equations, especially those used to compare variances, are very complicated. These tests are not suitable for manual calculation; a computer program is required.

6.4 Summary

After comparing the specifications of the KyTC with those of other state DOTs, this research found that the KyTC's sampling effort is typical and reasonable.

The research team conducted data analyses on the acceptance test records and the verification test records stored in the KMIMS database. The HMA data showed some minor differences between the KyTC's data and contractor's data, although the overall difference is not large. The verification test data show more variations than the acceptance test data. The concrete data between acceptance tests and verification tests also have some minor difference, but overall they are very consistent. However, the data analysis may not be very comprehensive because of the incomplete and inconsistent data entry in the KMIMS database. This research recommends improving the KMIMS database so that the sample records can be used more effectively later.

Because many KyTC projects result in only a small number of samples, the current acceptance-verification comparison method is appropriate. For larger projects, statistical testing is a better way to check the difference between acceptance test results and the verification tests. If annually evaluating the validity of the contractor's acceptance tests is wanted, the KyTC could employ statistical tests on all the samples of the same materials in different projects for that contractor. If any abnormality is found through the statistical tests, further investigation is required or the verification testing rate should be increased. Testing for the equality of means is robust and reliable because the data from KMIMS shows that the distribution of sample data is very close to a normal distribution. However, we need to take caution when using the statistical methods to test the difference between variances because they are influenced by the distribution.

From the analysis of Appendix IV this research concludes that increasing the acceptance tests from 4 to 5 will significantly reduce the risk of making wrong acceptance decisions. One way to do this without increasing the cost of sampling, as the California DOT does, is to combine the verification tests and the acceptance tests for acceptance purpose. However, we need to change the sampling method from paired sampling to totally independent sampling.

This research proposes that further investigation is necessary when the contractor's acceptance test and the KyTC's verification test will result in a different payment schedule. The KyTC can either take more samples or, as some other DOTs, use their own test results for payment purposes.

Chapter VII Current Status of Contractor Quality Control Program

The Kentucky Highway Department has been involved in Contractor Performed Quality Control (CPQC) for over 5 years and is one of the more experienced agencies in this field. This chapter will briefly summarize the current status of the CPQC program in Kentucky.

7.1 Current Status of Each Pay Item Used for Contractor Quality Control

The pay items that employ the CPQC program include asphalt and concrete pavements, pavement striping, embankment, crushed stone base, and bridge painting. The predominant focus of this program has been on hot mix asphalt projects. The Department has also extended it to the other pay items on a trial basis or pilot projects. This section will discuss the current status of each pay item.

7.1.1 Asphalt

The CPQC program started in 1994 and was formally implemented in 1996. The program in general works very well. A special program, the Asphalt Mixture Acceptance Workbook (AMAW), has been developed to help the State-Qualified Superpave Plant Technologists (SPT) to record test results and calculate pay values for asphalt mixtures. A technologist training and qualification program has also been established to help the contractors develop and maintain a pool of well-trained specialists for designing and managing of hot mix asphalt (HMA) projects. According to our survey, engineers and contractors gave high marks to this training program.

There are also some concerns with this program. Our survey showed that some engineers were worried about the validity of the contractors' data. After reviewing the KMIMS database, we found in general the contractor's data agree with the verification data, but there were also some differences between the two data sets in which the verification data showed more variations. Increasing the communication between the engineer and the contractor, enhancing a contractor's quality control data documentation and presentation, increasing the randomness of the verification testing, and using additional statistical methods for verification, would increase the engineers' confidence in contractor performed quality control data. Although the KyTC allows its inspectors to use contractor's equipment to conduct HMA verification testing, there are some concerns on the frequency of contractor's testing equipment calibration and uniformity of practices between different districts.

7.1.2 Concrete

The CPQC program for concrete pavement is still in the experiment stage; and full implementation will start in 2003. At present, the structural concrete pilot projects have been stopped because of disputes over various program specifications.

There is no penalty for concrete pavement through 2002 because the CPQC is still considered to be experimental on concrete projects. After that, the contractor will incur a penalty on concrete below the minimum quality requirements.

The acceptance of concrete pavement will still use the Percent Within Limits (PWL) method, but it is not clear how the structural concrete specifications will be developed.

Like asphalt, concrete specifications came with a computer program which is designed for recording project data, and performing pay calculations. The concrete information in the KMIMS database should be improved. Based on part of the concrete CPQC data in the KMIMS database, this research found that the data for contractors and the KyTC are very consistent.

There are some concerns expressed by engineers on concrete quality control documentation. The contractor should improve their paperwork and reduce the time of processing it.

7.1.3 Pavement Striping

The first pavement striping CPQC project was initiated in 2000 in District 2. The pavement striping special note requires the contractor to designate a Quality Control Coordinator for the project who will be the contact person for any questions or concerns regarding the quality of the work performed. This requirement facilitates the coordination between the contractor and the department. On pavement striping CPQC projects, the department performs verification testing on (at least) 20% of the test data submitted by the contractor and on a totally random basis, while on the other pay items the department usually requires a 25% verification testing rate on a side-by-side basis. Incentives are used for pavement marking, but there is no disincentive payment. If the result fails, the contractor is required to perform restriping until it is done properly.

The CPQC program for pavement striping is quite successful according to the feedback from the parties involved.

7.1.4 Soil Embankment

The special note for soil embankment CPQC has been used for some pilot projects. At present, the special note only addresses soil. If the quantity of coarse materials (+ No.4 sieve) is greater than 60%, then acceptance is based on visual inspection and the department will perform the testing. Rock embankment may be included in the special note later.

The soil characteristics tested by QC and QA include density and moisture content. For rock embankment, the state tests lift thickness and gradation. Currently, the state is running assurance testing at a 25% rate, side by side with contractor personnel. On embankment, no incentive, or penalty is used.

Soil embankment CPQC does relieve state inspectors on projects to do other evaluation work. However, there have only been limited experiments in this field to date.

7.1.5 Crushed Stone Base

The CPQC program has been implemented on several crushed stone base projects. It worked well on large projects. However, it is a challenge for small contractors to establish testing laboratories. Basically, the pilot program on crushed stone base has been put on hold because of difficulties in providing adequate statistical assurances and the development of a field permeability testing device.

7.1.6 Bridge Painting

On bridge painting projects, lots are controlled areas. There are no incentives and disincentives. If paint test fails, the contractor must redo his/her work. The researchers do not have much experience in bridge painting CPQC to date. Training for coating inspectors is required now.

7.2 General Issues of the CPQC Program

Some general issues have been raised during this research. One of them is the consistency of QC/QA practices across the KyTC districts. This research recommends uniform CPQC practices across all districts, which includes sampling methods, testing methods, calibrating of testing equipment, and testing frequencies. To promote uniform practices, all district quality personnel may need to meet and set a standard for all testing practices.

The research committee also discussed the possibility of outsourcing CPQC testing. By doing so, contractors do not need to establish additional testing laboratories and hire related technicians. Hence, the KyTC engineers may have more confidence in the data if they are generated by a third-party. However, it is not clear that enough qualified testing labs are currently available in Kentucky to fulfill the third party independent testing. Testing by a third-party company may also cost more than testing by a contractor or the department.

Quality control is not a separate bid item for hot mix asphalt, but is a separate bid item for several other pay items. Because CPQC on these items are still in the experimental phase, this reminds contractors to incorporate quality control in their project bids. However, this should be a transitory measure and should be part of the total cost later.

The verification testing (or QA testing) on CPQC pavement striping projects is totally independent of the contractor's testing. On some CPQC pay items, the verification testing is a side by side testing with the contractor's quality control testing or sometimes the KyTC engineer and the contractor share the same equipment.

The responsibility of the quality control manager may need to be better defined. The contractor should get better coordination of QC activities, show more details in quality control, and present more organized QC documents. A good coordinated QC program may also partially alleviate the engineers' concern on the accuracy of QC data.

Some CPQC pay items are using incentive/disincentive payment schedules. Some concerns have been expressed by the KyTC engineers on the incentive part. They think the contractors find it very easy to get incentives, and now expect incentives as normal payments. A review of the whole incentive/disincentive process is proposed to make sure that incentives are only paid for outstanding quality.

Hot mix asphalt and concrete pavement contractors are basically supplier companies, so they can control their whole production process. But for structural concrete and aggregates some coordination issues between contractors and suppliers exist. The department can encourage sharing of incentives between contractors and suppliers, but not require it. However, this has been a source of contention where additional effort without certain reward has been evidenced.

Some KyTC engineers worry about the future decrease of staffing of state personnel due to CPQC. The purpose of CPQC, however, should be an approach that encourages the contractor to formally incorporate quality control in their production processes and take the corresponding responsibility. The new CPQC process does not mean a corresponding reduction in state staff; however, it should allow KyTC project personnel to spend more time on overall project management.

Chapter VIII CPQC Training Program

Since the contractor quality control process is new, a training program may help the contractors and the KyTC engineers better understand the program requirements and the proper working procedures. Such a program was proposed by KyTC engineers and contractors in our survey. This type of training is mandatory for some agencies such as the Florida DOT, Texas DOT, and the Corps of Engineers.

8.1 Survey Responses on the CPQC Training Program

In a recent survey the research team asked the KyTC engineers and some contractors if they thought a training program on contractor performed quality control and DOT quality assurance would be helpful. Out of 27 responses this research received from the engineers and Central Materials Office, 3 respondents did not support a training program while 24 supported it. Out of 8 responses this research received from contractors, 2 respondents did not support a training program, and one no opinion, while 5 supported it.

Another question asked in the survey was what content should be included in the training program. According to the survey results, the training program would include the following topics:

- An agenda that clearly defines participant roles including expectations and accountability.
- The contractor's and inspector's responsibility.
- Procedures of work and handling the results of CPQC paperwork.

- Program requirements, acceptance and quality assurance procedures, and incentive and disincentive schedules.
- A statistical approach that can differentiate each party's duties better.
- The statistical basis of the sampling method.
- How to enter data into the spreadsheets and keep records.
- Various types of QC testing.
- Extensive consideration of CPQC program details.
- Emphasis on testing procedure details.
- Understanding of consequences of unsatisfactory material quality.
- Techniques for improving material quality.
- Emphasis on good construction monitoring and inspecting activities.

8.2 Training Contents of the CPQC Program

To meet the mission of the contractor quality control program and to help the change from the old system to a new system, this research proposes implementing a training program for QC/QA participants. This training program may not cover detailed technical requirements, which already have been addressed in several technical training modules. Instead, this training should help the QC/QA participants understand the philosophy of this program and the overall working procedures. This training may also increase the uniformity of implementing CPQC specifications in different districts. The research team proposed the following main contents for a potential training program:

- Background and Overview of Quality Management System.
- Background and Overview of CPQC Program and its objectives and benefits.
- QC participant requirements and their responsibilities.
- QA participant requirements and their responsibilities.
- Contents of Quality Control Plan.
- Working procedures for QC Activities.
- Working procedures for QA Activities.
- Understanding statistical basis of random sampling, acceptance testing, verification testing, and incentive/disincentive schedules.
- QC/QA paperwork and documentation.

Chapter IX Summary and Recommendations

9.1 Summary

Many DOTs, including the KyTC, have transferred the responsibility for quality control of some major construction work to the contractor, with the agencies only performing quality assurance checks. This research found that most DOTs are implementing Contractor Performed Quality Control (CPQC) on hot mix asphalt (HMA) and concrete projects. The KyTC is implementing CPQC on more experimental pay items than most of the other States surveyed. This research also found that existing research and specifications on CPQC mainly focused on the following areas: quality control and quality assurance organization, quality control methods and procedures, quality acceptance, quality verification by DOTs, and training programs for CPQC.

This research found that the overall evaluation of the CPQC program, by both the KyTC engineers and contractors, was positive. The major benefits of this program identified by the contractors and DOTs are: the contractor is responsible for their own products, possible reduction of state personnel, enhanced knowledge of the quality improvement process, improved quality of finished products, and improvement of schedules.

There are also some concerns on the CPQC program by both the DOTs and the contractors. The major concerns of the DOTs are: validity of contractor test data, QC documentation, insufficient certified technicians (of contractors), and insufficient quality assurance by DOTs. The major concerns of the contractors are: capability of technicians and facilities, higher construction cost, lack of quality improvement training, and lack of trust by State's personnel.

The contractor's quality control and DOTs' quality assurance are two sub systems of the quality management system. This research compared the CPQC and QA organizations, responsibilities, and working processes of the KyTC with what are required in other States.

Many DOTs do not view CPQC just as a method of the Department transferring quality management responsibility to the contractor, but a requirement for the contractor to systematically incorporate quality process control techniques into their production processes to improve the material quality. Since many contractors may be new to CPQC, this research summarized and discussed in detail some common quality control techniques, in the context of the KyTC CPQC program. The quality control techniques discussed in this report are concentrated on quality control charts for highway material production. Also discussed are lack of control analysis based on control charts, trouble shooting and production adjustment.

This research summarized the quality acceptance methods used by different DOTs. This research also analyzed the effect of the lot size, the evaluation methods, the number of samples, and the acceptance criteria on acceptance decisions. The current acceptance sampling effort by the KyTC is typical as compared to other DOTs. According to statistical risk analysis theory, this effort is the minimum requirement, and although acceptable, some improvements have been suggested.

In addition to quality acceptance, verification sampling is an important aspect of the CPQC program. This research summarized the verification methods and compared the verification sampling effort of the KyTC with other states. The current verification sampling effort of the KyTC is typical as compared to other DOTs. This research also reviewed the performance of current KyTC verification approaches by conducting an analysis on the KMIMS QC/QA data. The research recommends paying some attention to the differences between quality acceptance data and quality verification data on HMA projects. This research also discussed how to use statistical verification methods and their benefits and concerns.

This research also summarized the current status of the KyTC CPQC pay items and the general issues related to this program. The pay items that are employing the CPQC program include asphalt, concrete, pavement striping, embankment, crushed stone base, and bridge painting. This program works well on some pay items such as asphalt and pavement striping, while improvements are required on the other pay items.

Since the CPQC is new, a training program may help the contractors and engineers better understand the program requirements and the proper working procedures. Such a program is recommended by many KyTC district engineers and contractors, and is even mandatory for some other DOTs. This research proposes the major contents of a possible CPQC training program.

9.2 Recommendations

The following recommendations on CPQC (not in the order of priority) are offered by the researchers:

1. The KyTC should not initiate additional Contractor Performed Quality Control (CPQC) pay items until fully satisfied with the results obtained for the existing pay items.
2. Uniform practices for CPQC should be employed by all KyTC districts.
3. A CPQC training program should be developed for quality managers in construction companies and appropriate KyTC personnel.
4. The existing CPQC system should be reviewed periodically and modified as needed.
5. The CPQC information in the current KMIMS database needs to be enhanced to make it more consistent and user-friendly for quality control/assurance data collection, storage and retrieval.
6. Contractor data submitted to the CPQC process must not only be accurate and comprehensive, but also submitted in a timely manner.
7. The KyTC needs to better communicate with contractors the objectives of CPQC and the potential benefits that can be achieved.

8. The collection and testing of samples for verification purposes should be conducted more independently by the highway department, exclusive of the contractor's tests.
9. As CPQC matures for certain pay items, incentives should be paid only for outstanding quality, and disincentives should be charged for subpar quality.
10. When projects are built in remote areas with limited suppliers, some flexibility is appropriate for evaluating the final products. However, this should not lower the standards.
11. Quality control has been treated as a separate bid item for most experimental pay items. After the process has matured, the QC bid prices should be eliminated as a separate bid item and included in the pay item's base price by the contractor.

APPENDICES

APPENDIX I

The National Survey Form on CPQC Practices (for DOTs)

APPENDIX II

The National Survey Form on CPQC Practices (for Contractors)

APPENDIX III

The Kentucky Survey Form on CPQC Practices (for KyTC)

APPENDIX IV

Statistical Quality Acceptance Procedures with Risk Analysis

APPENDIX V

Statistical Sampling Verification Techniques for KyTC

APPENDIX I

The National Survey Form on CPQC Practices (for DOTs)

KYSPR-01-222

Contractor Quality Control on KyTC Projects

STATE DOT QUESTIONNAIRE

PURPOSE OF THIS SURVEY

The quality of the constructed project is a major issue in highway construction. For years the inspection responsibility for quality, or quality control, was performed by DOT personnel. Agencies also performed quality assurance checks to be sure that their own quality control activities were in compliance with desired standards. Contractors simply did the work and the DOT decided if the work was in compliance, and if full payment should be made. However, in recent years, many DOTs have considered transferring the responsibility for quality control of construction work to the contractor, with the agencies only performing quality assurance checks. The KyTC is considering this transfer of responsibility and more research is needed to help determine if, when and how the implementation of this major change to contractor performed quality control should occur.

Please complete the following request for information to aid in the processing of this survey:

State DOT: ______________________________

Address: ______________________________

____

____

City: ____________ State: ______ Zip: ____________

Questionnaire Completed By: ______________________________

Position/Title: ____________________ Date: ____________

Telephone: ____________________ Fax: ____________________

PLEASE RETURN QUESTIONNAIRE AND SUPPORTING INFORMATION BY: **11/22/99**

TO: Dr. Donn E. Hancher
C151B Raymond Building
University of Kentucky
Lexington, KY 40506-0281

TEL: (606) 257-4857
FAX: (606) 257-4404
email: hancher@engr.uky.edu

THANK YOU FOR YOUR VALUABLE ASSISTANCE ON THIS PROJECT!!

1. Do you apply Contractor Quality Control to highway construction projects?

____ Yes ____No

2. If so, in what kind of project do you use this method?

__ Grading
__ Portland Cement Concrete Pavement
__ Plant Mix Asphaltic Concrete Pavement
__ Concrete Bridge Floor
__ Painting
__ Sign Placement
__ Traffic Control Systems

Others:

____

____

____

____

____

3. What do you feel are the major advantages of using Contractor Quality Control?

____

____

____

4. What do you feel are the major concerns of using Contractor Quality Control?

____

____

____

5. In the past 12 months, how many projects involving Contractor Quality Control has your state conducted? _______

What is the approximate total dollar value of these projects? _________________

6. Are there any specification changes in your department to accommodate the Contractor Quality Control?

____ Yes ____No

7. If so, could you give us the name of specifications changed?

____

____

____

8. On a 1-5 scale (1-very negative, 3-no effect, 5-very positive), how has Contractor Quality Control affected:

Project Quality:	1	2	3	4	5
Overall Project Cost:	1	2	3	4	5
Project Schedule:	1	2	3	4	5

9. Are there many statistical techniques used for agency's Quality Assurance?

____ Yes ____No

10. If so, what do you think are the most important factors for using statistical techniques properly in Contractor Quality Control projects?

____ Sampling Method
____ Sample Size
____ Defining Controlling Statistics
____ Determination of Acceptance and Rejection Level
____ Selecting Inference Methods

Others:

____

____

____

11. Are there any new technologies used to improve the efficiency of Quality Assurance process in the Contractor Quality Control Projects?

____

12. Are there any additional comments that you would like to make?

9. Are you willing to discuss further issues related to Contractor Quality Control with the researcher?

__ Yes __ No

10. If YES, please specify the person(s) in your department to contact:

Name: ______________________________

Position/Title: ______________________________

Address: ______________________________

____

____

City: ____________ State: ______ Zip: ____________

Telephone: ____________ Fax: ____________

E-mail Address: ______________________________

Thank you for your cooperation. Please return this questionnaire by____________ to

Dr. Donn E. Hancher
C151B Raymond Building
University of Kentucky
Lexington, KY 40506-0281

TEL: (606) 257-4857
FAX: (606) 257-4404
Email: hancher@engr.uky.edu

PLEASE FAX IF POSSIBLE

APPENDIX II

The National Survey Form on CPQC Practices (for Contractors)

University of Kentucky Transportation Research Center

Contractor Quality Control on Kentucky DOT Projects

CONTRACTOR QUESTIONNAIRE

PURPOSE OF THIS SURVEY

The quality of the constructed project is a major issue in highway construction. For years the inspection responsibility for quality, or quality control, was performed by DOT personnel. Agencies also performed quality assurance checks to be sure that overall quality control activities were in compliance with desired standards. Contractors simply did the work and the DOT decided if the work was in compliance, and if full payment should be made. However, in recent years, many DOTs have considered transferring the responsibility for quality control of construction work to the contractor, with the agencies only performing quality assurance checks. The Kentucky DOT is considering this transfer of responsibility and more research is needed to help determine if, when and how the implementation of this major change to contractor performed quality control should occur.

Please complete the following request for information to aid in the processing of this survey:

Company: ____

Address: ____

____

____

City: ____________ State: ______ Zip: ____________

Questionnaire Completed By: ______________________________

Position/Title: ____________________ Date: ____________

Telephone: ____________________ Fax: ____________________

PLEASE RETURN QUESTIONNAIRE AND SUPPORTING INFORMATION BY: **9/30/00**

TO: Dr. Donn E. Hancher
Civil Engineering Dept.
151B Raymond Building
University of Kentucky
Lexington, KY 40506-0281

TEL: (606) 257-4857
FAX: (606) 257-4404
email: hancher@engr.uky.edu

THANK YOU FOR YOUR VALUABLE ASSISTANCE ON THIS PROJECT!!

1. Are you aware that some DOTS are transferring the responsibility for quality control on their construction projects to the contractor?

____ Yes ____No

2. Are you in favor of contractors assuming the responsibility for quality control on KyTC highway projects?

____ Yes ____No ____Uncertain

3. Do you currently have any quality control programs in your company for your operations (i.e. quality control plans, material testing, product sampling, etc.)?

____ Yes ____No

If so, please identify below:

____

____

____

____

____

____

____

____

____

4. Do you currently have in-house capabilities to perform quality control on your construction projects?

____ Yes ____No

5. If required to perform quality control on your projects for the Kentucky Transportation Cabinet, will you:

* Use your own employees? ____ Yes ____No ____Uncertain
* Use consultants or testing firms? ____ Yes ____No ____Uncertain
* Do a combination of both in-house/out-house? ____ Yes ____No ____Uncertain

6. What do you feel are the major advantages of Contractor (performed) Quality Control? (More efficiency, time saving, promotion of trust, etc.)

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7. What do you feel are the major concerns of Contractor (performed) Quality Control? (Availability of capable technicians, availability of testing facilities, etc.)

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8. On a 1-5 scale (1-very negative, 3-no effect, 5-very positive), how will Contractor Quality Control affect the following factors according to your prediction:

Project Quality:	1	2	3	4	5
Overall Project Cost:	1	2	3	4	5
Project Schedule:	1	2	3	4	5
Project Disputes:	1	2	3	4	5

Additional Comments:

____

____

____

9. Are there any additional comments that you would like to make?

____

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____

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____

10. Are you willing to discuss further issues related to Contractor Quality Control with the researchers?

__ Yes   __ No

If YES, please specify the person(s) in your company to contact:

Name: ____

Position/Title:____

Address: ____

____

____

City: ________________ State: _____ Zip: ________________

Telephone: __________________ Fax: __________________

E-mail Address: ________________________________

Thank you for your cooperation. Please return this questionnaire by 9/30/00 to

Dr. Donn E. Hancher
Civil Engineering Dept.
151B Raymond Building
University of Kentucky
Lexington, KY 40506-0281

TEL: (606) 257-4857
FAX: (606) 257-4404
Email: hancher@engr.uky.edu

PLEASE FAX IF POSSIBLE

APPENDIX III

The Kentucky Survey Form on CPQC Practices (for KyTC)

University of Kentucky Transportation Research Center

Contractor Quality Control on KyTC Projects

KYTC QUESTIONNAIRE

PURPOSE OF THIS SURVEY

Kentucky is currently applying Contractor Performed Quality Control (CQC) and DOT Quality Assurance to asphalt pavement construction and experimenting on more pay items such as concrete, soil embankment & subgrade, crushed stone base, painting & striping, etc. We conducted a national wide Contractor Performed Quality Control survey one and a half years ago. In order to further evaluate the program, we are seeking additional input on current activities on KyTC construction projects.

Please comp lete the following request for information to aid in the processing of this survey:

District: ______________________________

Address: ______________________________

____

____

City: ______________ State: ______ Zip: ______________

Questionnaire Completed By: ______________________________

Position/Title: ______________________ Date: ______________

Telephone: ______________________ Fax: ______________________

PLEASE RETURN QUESTIONNAIRE AND SUPPORTING INFORMATION BY: **Feb. 8, 2002**

TO: Dr. Donn E. Hancher
C151B Raymond Building
University of Kentucky
Lexington, KY 40506-0281

TEL: (606) 257-4857
FAX: (606) 257-4404
email: hancher@engr.uky.edu

THANK YOU FOR YOUR VALUABLE ASSISTANCE ON THIS PROJECT!!

PLEASE WRITE ON THE BACK OF ANY PAGES IF YOU NEED MORE SPACE FOR YOUR RESPONSES.

1. Please identify the types of projects you have experienced with contractor quality control and the approximate number of each type.

Category of CQC Items	**Number of Projects for Each Category**
☐ Asphalt Pavement	
☐ Concrete	
☐ Crushed Stone Base	
☐ Soil Embankment & Subgrade	
☐ Pavement Striping	
Others:	

2. On a 1-5 scale (1-very negative, 3-no effect, 5-very positive), how has CQC affected:

Project Quality:	1	2	3	4	5
Overall Project Cost:	1	2	3	4	5
Project Schedule:	1	2	3	4	5
Disputes in Project:	1	2	3	4	5

3. What do you think are the major advantages of using CQC?

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4. What do you think are the major disadvantages of using CQC?

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5. On a 1-5 scale, do you have any special concerns of the contractor following the specifications? The following are some examples, and you can add more concerns at the bottom. (1-serious concern, 2-concern, 3-neurtal, 4-satisfied, 5-very-satisfied)

Required quality control plans:	1	2	3	4	5
Availability of technicians and testing devices:	1	2	3	4	5
Coordination with material suppliers:	1	2	3	4	5
Quality control process:	1	2	3	4	5
Dispute resolution process:	1	2	3	4	5
Bonus and penalty schedules:	1	2	3	4	5

Other concerns: ____

____

____

____

____

____

6. Do you have any recommendations on the following aspects of the program?

Program requirements

____

____

____

____

____

Dispute resolution process

____

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____

____

____

Acceptance and quality assurance procedures

____

____

____

____

Incentive and disincentive schedules

Any other recommendations?

7. Do you think a training program on contractor quality control and DOT quality assurance would be helpful? ☐ Yes ☐ No

If yes, what content is desired?

8. Are there any additional comments that you would like to make?

____

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____

____

9. Are you willing to discuss further issues related to contractor quality control with the researchers?

__ Yes __ No

If YES, please specify the person(s) in your department to contact:

Name: ____

Position/Title:____

Address: ____

____

____

City: ______________________ State: _______ Zip: ______________________

Telephone: ________________________ Fax: ____________________________

E-mail Address: ____

Thank you for your cooperation. Please return this questionnaire by Feb. 8, 2002 to

Dr. Donn E. Hancher
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University of Kentucky
Lexington, KY 40506-0281

TEL: (859) 257-4857
FAX: (859) 257-4404
Email: hancher@engr.uky.edu

PLEASE FAX IF POSSIBLE

APPENDIX IV

Statistical Quality Acceptance Procedures with Risk Analysis

Basic Terminologies

The following terms used in this part are defined for clarification:

The *specification limit* is a specified value for a certain material characteristic, for example, the asphalt content or the air void, for which experiments show or people think if the material characteristics exceed the limits the performance will adversely affected.

The *acceptable quality level* (AQL) is a percent defective below which the products should mostly be accepted, while the *rejectable quality level* (RQL) is a percent defective above which the products should mostly be rejected. Both AQL and RQL are expressed in terms of percentage of the poor material. Here the "poor" means it exceeds the specification limit.

Even when the true percent defective of a lot is below the AQL, due to the variation within the materials and the limited number of samples taken, it may still be rejected. We may feel sorry for the contractor but there is another side of story: the DOT may accept some materials of which the true percent defective is above the rejection quality level. The probability of non-acceptance of a lot that has a defect level equal to or below the AQL is called the Producer's Risk (here we call it the contractor's risk). The probability of acceptance of a lot with a defect level equal to or higher than the RQL is called the Consumer's Risk (here we call it the DOT's risk). This is demonstrated in Figure A4.1.

		Decisions Based on Sampling	
		Accept the Lot	**Reject the Lot**
True Lot Quality	**Less than AQL**	Right Decision	Contractor's Risk Type I Error
	More than RQL	DOT's Risk Type II Error	Right Decision

Figure A1.1 The Contractor's risk and the DOT's risk.

It should be noted that the *Acceptable quality level* (AQL) *or rejectable quality level* (RQL) are not used directly to accept or reject materials, but are selected by the DOT to calculate the number of acceptance sample required and a sole critical value for acceptance, which can be a single number of percent defective or percent within limits.

Types of Acceptance Sampling Plans

There are two types of acceptance sampling plans: the attribute acceptance plan and the variable acceptance plan. The attribute acceptance plan only grades the material as "conforming" and "nonconforming", without looking at the quantitative measurements. Major highway materials, however, are evaluated using the variable acceptance plan because it requires a smaller sample size and yields good performance. Therefore, the analysis of this research was concentrated on the variable acceptance plan. The approaches usually used in the variable acceptance plan are the average method ($\bar{x}$ method), k method, and m method.

The Average Method ($\bar{x}$ Method)

For the materials to be accepted, the average value of the acceptance sampling data must be greater (or smaller) than a certain value when there is only one single specification limit, or within a certain range when there are double specification limits. For example, if there is only a lower specification limit L (as concrete compressive strength), the procedure for the average method is to:

1. Take a random sample of size n and find the average $\overline{X}$.
2. Using $A = L + k\sigma$, accept the lot if $\overline{X} \geq A$, otherwise reject it.

Where A is called a quality level parameter. L is the lower specification limit and σ is the population standard deviation of the material. k is a parameter that works in combination with s in a manner similar to a safety factor.

In the case of an upper specification limit, A is set as $U - ks$ and the acceptance criterion is reversed as $\overline{X} \leq A$. In the case of double specification limits, A should be within the two end points of an acceptance interval: $L + ks$ and $U - k\sigma$.

It must be noted that the material usually should not be accepted when the average value of acceptance samples falls right on the specification limit. The reason is that even if the average value meets the specification limit, statistically there would be one half of the total materials within the specification requirements and another half outside it. Fifty percent of defective materials are usually unacceptable. Thus, the tolerance quality limits, the quality level "*A*", are set in such a way to provide the agency more confidence.

This method requires a previously known (or estimated) standard deviation σ and a predetermined number of measurement n and a critical value k. The procedure of deducting n and k, which can be estimated by using the DOT's risk, the contractor's risk, AQL, and RQL, will be addressed later. In practice, many DOTs just specify "L + kσ" or "L - kσ" as a single number and assume the standard deviation is the same for all contractors. The disadvantage for this practice is that the materials with larger variation are paid the same as those with smaller variation, if their means are the same.

The k-Method

The *k*-method is basically the same as the $\bar{x}$ method. The only difference is that for highway materials, the average method is thought to have a fixed standard deviation. Under the *k*-method, *k* is a critical value in a normal curve that corresponds to a specified proportion *m*. If there is a lower specification limit, the procedure for the *k*-method is to:

1. Estimate $Z = (\bar{X} - L) / \sigma$ or $Z = (\bar{X} - L) / S$ when the population standard deviation (σ) is unknown.

2. Accept the lot if $Z \geq k$, otherwise, reject it.

In the case of an upper specification limit, *Z* is computed as

$Z = (\bar{X} - L) / \sigma$ or $Z = (\bar{X} - L) / S$ when the population standard deviation is unknown.

The acceptance criterion remains the same as $Z \geq k$. The parameters that need to be determined are the number of required acceptance sample *n* and the critical value *k*.

The m-Method

Instead of using the *Z* (calculated above) to estimate the percent of nonconformance, the *m*-method uses an unbiased estimation $\frac{\bar{X} - L}{s}\sqrt{\frac{n}{n-1}}$ (designated as Q_L) as a normal deviate and uses this number to get the estimation of percent defectives *p'* (Duncan, 1986). In case of a lower specification limit, the quantity

$\hat{p}_L = \int_{Q_L}^{\infty} \frac{1}{\sqrt{2p}} e^{-0.5t^2}\, dt$ where $Q_L = \frac{\bar{X} - L}{S}\sqrt{\frac{n}{n-1}}$, ($s$ is unknown) is the minimum variance unbiased estimate of *p'*. The estimate $\hat{p}_L$ is compared with the maximum allowable percent defectives *m* and the lot is accepted if $\hat{p}_L \leq m$.

In case of an upper specification limit, the standard normal deviate

$$Q_u = \frac{U - \overline{X}}{S}\sqrt{\frac{n}{n-1}} \text{ or } Z_M = k\sqrt{\frac{n}{n-1}}$$

is used and the acceptance criterion remains the same.

According to the Department of Defense standard for sampling inspection of variables, the *k*-method is called procedure 1 and the *m*-method is called procedure 2. Because the average method is equivalent to the *k*-method when the standard deviation is known, the following discussion only uses the *k*-method and the *m*-method.

Determining Sample Sizes and Acceptance Critical Values with Risk Analysis

The primary task in designing a statistical sampling plan is to find the sample size *n* and the acceptance criterion – the *k* or the *m* – that will yield the characteristics (acceptance quality level, reject quality level, DOT' risk, and contractor's risk) specified for the plan (Duncan, 1986). On the other hand, given *n*, *k* or *m*, we can evaluate the contractor's risk and the DOT's risk by back calculation.

The procedures of getting these numbers are different, depending on which of the following situations exist:

- Standard deviation known, a single specification limit
- Standard deviation known, double specification limits
- Standard deviation unknown, a single specification limit
- Standard deviation unknown, double specification limits

Standard deviation known, single specification limits sampling plan

In this situation, the samples are assumed to be normally distributed with a known σ from the past values and a lower specification limit *L* or upper specification limit *U*. For example, this lower specification limit can be 28-day concrete compressive strength. The first step of making an acceptance plan for the DOT is to determine an Acceptable

Quality Level (AQL, p_1) and the Rejectable Quality Level (RQL, p_2) in percent defectives, as well as the contractor's risk *a* and the DOT's risk *ß* associated with the first two parameters. These numbers are management decisions upon which the required samples *n* and critical value *k* can be calculated. It is the critical value that will be eventually used to make acceptance or rejection decision by engineers. The equations for calculating the number of samples and the critical value are:

$$n = \left(\frac{Z_a + Z_b}{Z_{p1} - Z_{p2}} \right)^2 \quad , \quad k = \frac{Z_{p2} Z_a + Z_{p1} Z_b}{Z_a + Z_b}$$

where Z_ε (ε designates α, β, p_1, p_2) is the standard normal Z score with (upper) tail area ε (K. Govindaraju, 2000) .

For example, suppose we know the standard deviation of the 28-days compressive strength of a certain amount of concrete pavement and decide to use AQL = 10%, α = 5%, RQL = 25% , and β = 5%, the variables plan parameters are found to be:

$$k = \left(\frac{0.675 \times 1.6449 + 1.282 \times 1.6449}{1.6449 + 1.6449} \right) = 0.98$$

$$n = \left(\frac{1.6449 + 1.6449}{1.282 - 0.675} \right)^2 = 29.4 = 30 \, .$$

For this sampling plan, we need to take 30 samples. This is too many for a lot, and thus not very feasible for our application. Let us change the AQL, α, RQL and β as, AQL = 5%, α = 10%, RQL = 25% and β = 10%, the plan parameters are found to be:

$$k = \left(\frac{0.675 \times 1.17 + 1.555 \times 1.17}{1.17 + 1.17} \right) = 1.115$$

$$n = \left(\frac{1.282 + 1.282}{1.6449 - 0.675} \right)^2 = 7.07 = 7 \, .$$

Let us change the AQL, α, RQL and β as, AQL = 4%, α = 15%, RQL = 25% and β = 15%, the plan parameters are found to be:

$$k = \left(\frac{0.675 \times 1.037 + 1.7505 \times 1.037}{1.037 + 1.037} \right) = 1.21$$

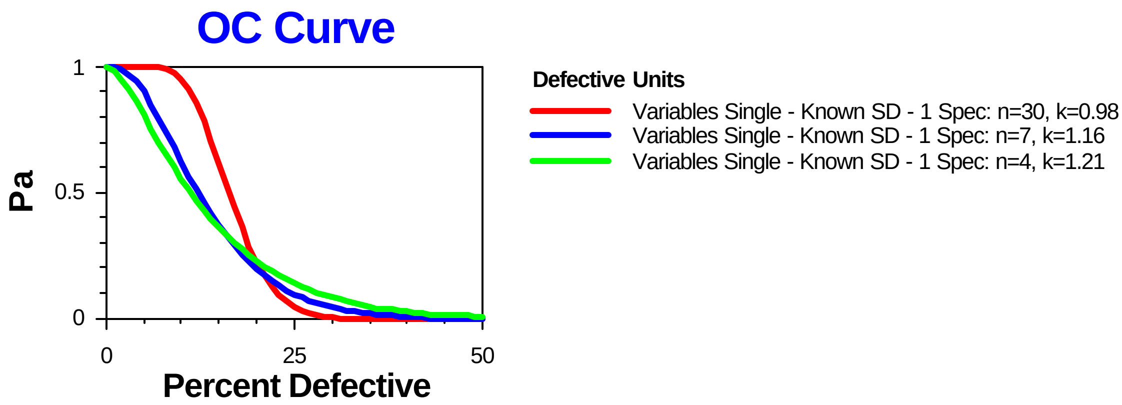
$$n = \left(\frac{1.037 + 1.037}{1.7505 - 0.675} \right)^2 = 3.7 = 4 .$$

The following table lists some possible combinations of n, k, a, and ß, calculated from the above equations, where *m* is the maximum allowable percent defective.

Sample Size	**Critical Value**	**AQL**	**RQL**	**Contractor's Risk**	**DOT's Risk**
n=30	k=0.98 m=16%	10%	25%	5%	5%
n=8	k=1.12 m=12%	6%	25%	10%	10%
n=7	k=1.12 m=12%	6%	25%	12%	12%
n=6	k=1.16 m=10%	5%	25%	15%	15%
n=5	k=1.12 m=11%	5%	25%	15%	16%
n=4	k=1.21 m=8%	4%	25%	15%	15%

Table A4.1 Possible Combinations of n, k, m, The Contractor's Risk and The DOT's Risk (σ known)

As we can see, the discriminating power of the sampling plan will deteriorate as we decrease the number of samples. For the sample size of four, even if the strength of the concrete of a lot is 96% percent above the specification limits, it still has a 15% chance of being rejected. On the other hand, even if the strength of the concrete of a lot is 25% below the specification limits, it also has 15% possibility being accepted. The Operating Characteristic (OC) Curves can reveal the discriminating power of different acceptance plans in a visual friendly way (Figure A4.2). The steeper the OC curve, the lower the DOT's risk and the contractor's risk will be.



*Pa: probability of acceptance

Figure A4.2 The Characteristic Curves of The Three Sampling Plans

The discussion above is based on the *k*-method. In the *m*-method, *k* is replaced by a maximum allowable percentage defective number *m*, which is the area under the normal curve beyond $k\sqrt{\frac{n}{n-1}}$. In the last example, one can get n = 4 and k = 1.21, the maximum percent defective *m* will be the proportion of the area under the normal curve beyond $1.21\times\sqrt{\frac{4}{3}} = 1.397$, which equals to 8.1%. The other values of *m* that correspond to the different sample size *n* and critical value *k* are reported in the Table A4.1 as well.

After deciding on the m-parameter, one can determine whether to accept the lot or not by the following criterion: taking a random sample of size 4 for each lot, then computing the $Q_L = \frac{\overline{X} - L}{s'}\sqrt{\frac{4}{3}}$ and using this as a normal deviate, obtaining the area (*p*') in excess of Q_L in a standard normal distribution table. If $p' \leq 8.1\%$, accept the lot; otherwise reject it.

When this is only an upper specification limit, the acceptance procedure can be done in a similar way.

Standard deviation known, double sampling plan

In the case of double specification limits (with both an upper and a lower specification limit), the evaluation of the acceptance sampling plan is more complicated. One needs to review the following situations separately:

1. The upper and lower limits are close together;
2. The upper and lower limits are widely spread;
3. The upper and lower limits are moderately close.

1. The upper and lower limits are close together

When the material characteristic is normally distributed and s' is known, the first step is to note whether the area under a standard normal curve beyond $z = \pm \frac{U - L}{2s'}$ is greater than an acceptable percent defective (Duncan, 1986). If it is, the acceptance samples will always be rejected. Because even the average of the acceptance samples falls equally between the upper and the lower specification limit (the best possible value), the percent defective will be larger than required. Therefore, if the DOT made the specification too tight, the contractor's material would be under the risk of being rejected at all the time.

2. The upper and lower limits are widely spread

If the upper and the lower specification limits are widely spread, i.e., $\frac{U - L}{2} \geq 3s'$, two single plans can be used, one for application at the lower specification limit, the other for application at the upper specification limit (Duncan, 1986).

The procedure for deducting the size of sample *n* and the critical value *k* under preset Acceptable Quality Level (AQL), Rejectable Quality Level (RQL), the contractor's risk, and the DOT's risk is the same as a single limit sampling plan. If one is going to use the

k-method, then he/she can accept a lot if $\frac{\overline{X}-L}{s'} \geq k$ and $\frac{U-\overline{X}}{s'} \geq k$, otherwise the lot must be rejected (Duncan, 1986). If one is going to use the m-method, he/she needs to first calculate the maximum allowable defective proportion using $m = k\sqrt{\frac{n}{n-1}}$. Then one needs to compute $Q_L = \frac{\overline{X}-L}{s'}\sqrt{\frac{n}{n-1}}$ or $Q_U = \frac{U-\overline{X}}{s'}\sqrt{\frac{n}{n-1}}$, and find the percent defectives (p_L' or p_U') corresponding to Q_L or Q_U. If either p_L' or p_U' exceeds the maximum allowable percent defective m, reject the lot; otherwise the lot must be accepted.

3. The upper and lower limits are relatively close

When the upper and the lower specification limits are not widely spread, yet not so close that no sampling is required, the procedure to get *n*, *k*, *m* will be different. The sample size *n* and the maximum allowable percent defective *m* will be influenced by the upper and lower specification limits. The computation of these parameters should be performed on a case-by-case basis. However, the general trend is that when the upper and the lower specification limits move together, under the same contractor's risk and the DOT's risk, the sample size and the maximum allowable percent defective will decrease. Ideally, specification limits should be performance driven. Because the change of specification limits will influence risk components, the KyTC needs to review the previous acceptance sampling plan whenever they want to adjust the specification limits.

The analysis above assumes a previously known population standard deviation. In highway construction projects, because the KyTC deals with different contractors, sources of materials, and production processes, it is more appropriate to assume the population standard deviation is unknown. The following two scenarios of the highway material acceptance sampling plan are based on an unknown standard deviation assumption.

Standard deviation unknown, a single specification limit

In the case of having no previous knowledge about the standard deviation of a material characteristic, the KyTC has to estimate it using the sample standard deviation *S*. For given AQL (p_1), RQL (p_2), the contractor's risk (α), and the DOT's risk (β), the equations for calculating *n* and *k* become:

$$k = \frac{Z_{p2}Z_a + Z_{p1}Z_b}{Z_a + Z_b}$$

$$n = \left(\frac{Z_a + Z_b}{Z_{p1} - Z_{p2}}\right)^2 \left(1 + \frac{k^2}{2}\right), \ (\sigma \text{ unknown})$$

where the Zs are the standard normal Z score with (upper) tail area corresponding to p_1, p_2, α, and β(E. G. Schilling, 1982, A. J. Duncan, 1986, K. Govindaraju, 2000) .

Because the sample size here is $1 + \frac{k^2}{2}$ times of that required in the standard deviation known case, one can see that a larger sample is required to compensate for the uncertainty of material variation to get the same discriminating power.

When AQL = 4 %, α = 15%, RQL = 25% and β = 15%, the *k* and *n* will become:

$$k = \left(\frac{0.675 \times 1.037 + 1.7505 \times 1.037}{1.037 + 1.037}\right) = 1.21$$

$$n = \left(\frac{1.037 + 1.037}{0.675 - 1.7505}\right)^2 \left(1 + \frac{1.21^2}{2}\right) = 6.4 = 6$$

Using the same AQL, RQL, the contractor's risk level, and the DOT's risk level in the Table A4.1, the sample size will increase, as shown in Table A4.2.

Sample Size	**Critical Value**	**AQL**	**RQL**	**Contractor's Risk**	**DOT's Risk**
n=43	K=0.98 m=13%*	10%	25%	5%	5%
n=14	K=1.12 m=11%	6%	25%	10%	10%
n=11	K=1.12 m=12%	6%	25%	12%	12%
n=10	K=1.16 m=12%	5%	25%	15%	15%
n=8	K=1.12 m=11%	5%	25%	15%	16%
n=6	K=1.21 m=11%	4%	25%	15%	15%

*m is obtained from a standard chart developed by A.J. Duncan (page 281, A.J. Duncan, 1986).

Table A4.2 Possible Combinations of *n, k, m*, The Contractor's Risk and The DOT's Risk (σ unknown)

The *k* acceptance method remains the same as the standard deviation known case, but the *m*-method is different. The *m*-method seems to be similar to the widely used Percent Within Limits (PWL) acceptance method in the highway construction industry. The difference is that *m* is the percent outside the limit while the PWL is the percent within limit (PWL = 100%-*m*).

Using the *m*-method, we need to estimate a proportion of nonconforming ($\hat{p}$) from

$$Z_L = \frac{\overline{X} - L}{S} \text{ or } Z_U = \frac{U - \overline{X}}{S}.$$

If $\hat{p} < m$, accept the lot; otherwise reject it.

When the standard deviation is unknown, the estimation of $\hat{p}$ and *m* is complicated. The minimum-variance method of Lieberman and Resnikoff requires special tables and a special procedure for determining $\hat{p}$ and *m* (Duncan, 1986). Fortunately, the estimate of $\hat{p}$ can be easily obtained because many DOTs, like KyTC, provide these tables. However, the maximum allowable percent defective, *m*, is not always available. A chart developed by A.J. Duncan can be used to find the value of *m* by inputting the previous calculated *n* and *k* (page 281, A.J. Duncan, 1986).

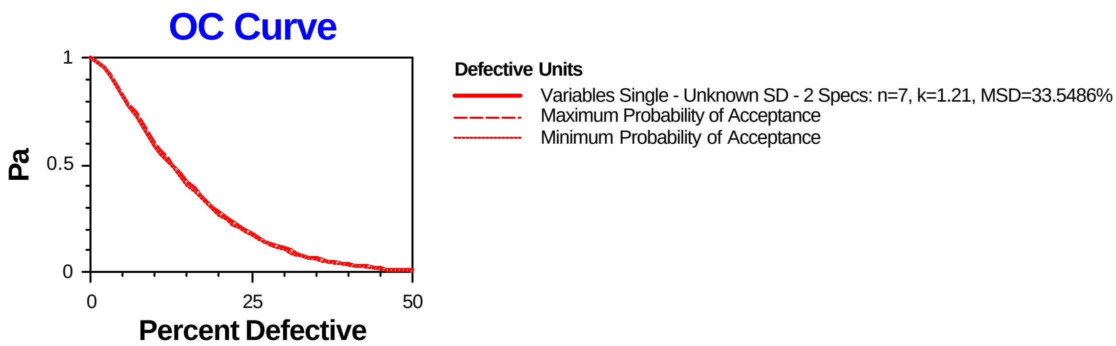
From example, suppose the lower specification limit for pavement concrete compressive strength is 26.54 Mpa (3,850 psi) and the sample test shows that the average strength is 28.96 Mpa (4,200 psi) and standard deviation is 1.03 Mpa (150 psi). Based on the AQL, RQL, a and ß, one can get k = 1.21 and n = 6.

$$Z_L = \frac{\overline{X} - L}{S} = \frac{4200 - 3850}{150} = 2.33$$

From a PWL estimation table one can find the percent defective to be equal to 2%. Using the chart provided by A.J. Duncan, one can get the maximum allowable percent defective 11%. Therefore, we accept this lot because the percent defective is less than 11%, or in other words, percent within limits above 89%.

Standard deviation unknown, double specification limits

Many acceptance sampling plans for highway materials are based on double specification limits. When the previous population standard deviation is unknown, one can no longer find a one to one correspondence between a finite number of z's and a given fraction nonconforming (Duncan, 1986). In other words, if the AQL (p_1), RQL (p_2), producer's risk (α) and consumer's risk (β) are given, previously there is only one Operating Characteristics curve (the curve describing the consumer's risk and producer's risk at different quality level), but now there will be a band of OC curves. For example, for AQL = 96%, α = 15%, RQL = 25% and β = 15%, one can calculate that the *k* and *n* will be 1.21 and 7, respectively. The band of OC curves is shown below.



*Pa: probability of acceptance

Figure A4.3 The OC Curves of an Acceptance Sampling Plan

(σ' Unknown, Double Specification Limits)

A corrected *k*-method and *m*-method are recommended in this situation (Duncan, 1986).

1. The Corrected *k*-Method

The criteria for acceptance under the corrected *k* method should be:

$$\frac{\overline{X} - L}{S} \geq k$$

$$\frac{U - \overline{X}}{S} \geq k \text{ and}$$

$$s \leq \text{the MSD}$$

where MSD stands for Maximum Standard Deviation. The procedure of getting MSD is not reported here because the DOTs normally do not use this method.

2. The Corrected *m*-Method

The corrected *m*-method for the double specification limit, unknown standard deviation, is almost like the single specification limit. The difference is that the percent defective becoming the combination of percent defectives regarding to both the upper specification limit and the lower specification limit. $\hat{p}_L$ can be estimated by using $Z_L = \frac{\overline{X} - L}{S}$ and $\hat{p}_U$ by using $Z_U = \frac{U - \overline{X}}{S}$. A lot is accepted if $\hat{p}_L + \hat{p}_U \leq m$, where *m* is the same *m* that would be derived for a single-limit plan.

For example, Suppose KyTC is treating the air void as an acceptance material characteristic for the Hot Mixed Asphalt (HMA), and the specification limit requires air void between 3% and 5% according to the Superpave Ndes (Number of Design).

Eight tests (a combination of two lots) are performed and the test results are 4.3% , 4.7% , 3.7%, 3.8%, 3.3%, 3% , 5.2%, 4.1%, which yield the average value of 4.01% and the standard deviation of 0.72%.

Using the chart developed by A.J. Duncan, one get the maximum allowable percent defective *m* = 14%.

Then one can calculate the quality level and find the estimated percent defective,

$$Z_U = \frac{U - \overline{X}}{S} = \frac{5 - 4.0125}{0.722} = 1.3677, \text{ The corresponding } \hat{p}_U = 7.73\%.$$

$$Z_L = \frac{\overline{X} - L}{S} = \frac{4.0125 - 3}{0.722} = 1.4024, \text{ The corresponding } \hat{p}_L = 7.19\%.$$

Total percent defectives: 7.73% + 7.19% = 14.92% > 14%.

Because the total percent defective is larger than the allowed maximum percent defective, one should reject this lot. However, if only the average of the air voids is considered, one may give the contractor bonus because the average of 4.01% is almost on target.

The specification limit discussed above is based on the Superpave recommended range of design air void 3% to 5%. Because the specification limit seriously influences the acceptance decision, knowledge of the real relationship between the air void and the performance should be developed before applying this percent within limit acceptance plan. For example, if the air void range between 2% - 6% is allowed, then the lot should be accepted.

APPENDIX V

Statistical Sampling Verification Techniques for KyTC

Because samples taken for the acceptance testing and verification testing come from the same population, they should have the same distribution or statistical parameters if the testing equipment, testing methods, and recording employed by the Contractors and the KyTC are the same. Two parameters are used to test this equality: mean and variances. Depending on the verification sampling methods, we can treat the verification samples as dependent or independent from the acceptance samples, which result in different statistical test procedures. Therefore, the following combinations of the intended statistical test and its condition should be discussed:

- Independent Sample; Test for Equality of Means
- Independent Sample; Test for Equality of Variances
- Dependent Sample; Test for Equality of Means
- Dependent Sample; Test for Equality of Variances

Independent Sample, Test for Equality of Means

The sample size of the material verification test, as reported in the KMIMS database, is generally less than 20. Because of the limited size, we need to use a two-sample T-test to test if a difference exits between the acceptance test data and the verification test data.

If the variances of the two sets of data are the same, we need to test the hypotheses that:

- Null Hypothesis: the mean values of the verification data and the acceptance data are equal.

- Alternative Hypothesis: the mean values of the verification data and the acceptance data are not equal.

The following procedure can be applied to this test:

At first, we compute a pooled estimate of the variance from the two independent samples:

$$s_p^2 = \frac{[(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2]}{n_1 + n_2 - 2}$$

Then we compute a t-statistic:

$t = \dfrac{\overline{X}_1 - \overline{X}_2}{\sqrt{\dfrac{s_p^2}{n_1} + \dfrac{s_p^2}{n_2}}}$, where $\overline{X}_1$ and $\overline{X}_2$ are the mean of the acceptance test results and the mean of the verification test results, respectively.

Finally, we need to look for a T value, $t_{a(2),?}$, in a standard table where a is the significance level we want to use and v= $n_1 + n_2 - 2$, and compare the t statistic we get above with this $t_{a(2),?}$. If $|t|= t_{a(2),?}$, the mean of the verification data and that of the acceptance data are different. Otherwise, we cannot conclude they are different.

Like all the other statistical test methods, this test requires some assumptions. The assumption for this test is that both acceptance and verification data come at random from normal populations with equal variances. When the variances are unequal, we can use a reliable procedure that is attributed to Smith (1936) and also know as “Welch’s approximate t”. The test statistic is

$$t' = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}.$$

And the critical value is the Student's t with degrees of freedom of

$$n = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}}$$

The procedure is more complicated when the variances of the two samples a show big difference.

Independent Sample, Test for Equality of Variances

One of the purposes of the quality control is to reduce the variability of the materials and construction. So there should be a way to compare the variances of the acceptance data reported by the contractor with that of verification data performed by the KyTC. The null hypothesis for this test is that the variance of the contractor's data is the same with the KyTC's. The procedure usually used is called the variance ratio test, for which one calculates (Zar, J. H., 1996)

$F = \frac{s_1^2}{s_2^2}$ or $F = \frac{s_2^2}{s_1^2}$, whichever is larger.

Then we find the critical value F' in a standard table that corresponds to a certain significance level and degree of freedom. If F>F', the null hypothesis and conclude the pair of variances are different.

However, the variance ratio test is severely and adversely affected by sampling non-normal populations (Markowski and Markowski, 1990, p139). Therefore, we must be very careful when using this method. Our analysis showed that the KMIMS data do not always conform to a normal distribution. The Levene test is a homogeneity-of-variance test that is less dependent on the assumption of normality, but it may tend to give false rejection thus increasing the contractor's risk. The research team does not recommend making decisions based on comparing the variances between the acceptance test and verification test. However, if the pair of variances are very different, say several multiples of variance, then further investigation may be necessary.

Dependent Sample, Test for Equality of Means

The verification samples used currently are not totally independent. In the QC/QA specification we require that the one verification test should be taken at the same place and the same time along with one of the contractor's acceptance test per lot. The contractor takes 4 samples per lot that equally divided into four sublots. The verification test is closely related to one of the contractor performed acceptance tests. Although they are not split samples, they are paired samples from the statistical point of view. For the paired sample, another method, which is more appropriate in this situation, can be used to test if the means of the acceptance tests and verification tests are different.

The paired-sample t-test does not have the normality and equality of variances assumptions of the two-sample t test, but assumes instead that the differences, d_j, come from a normally distributed population of differences (Zar, J.H., 1996). The equation for the paired-sample t test is:

$$t = \frac{\overline{D}}{s_D / \sqrt{n}} \text{ where}$$

$$s_D = \sqrt{\frac{\sum \left(Di - \overline{D}\right)^2}{n-1}}$$

D_i is the difference of each pair of samples and $\overline{D}$ is the average of the differences.

Similarly, we look for a t value with a significance level a in a standard table, using df = n-1. If |t|= $t_{a(2),n-1}$, the mean of the verification data and that of the acceptance data are different.

Dependent Sample, Test for Equality of Variances

The equation for testing the difference between variances of two correlated samples is complicated. A *t* statistics can be computed using the following equation (Zar, J.H., 1996):

$$t = \frac{(F-1)\sqrt{n-2}}{2\sqrt{F(1-r^2)}}$$

F is variance ratio as described before, *n* is the sample size common to both samples, and *r* is the correlation coefficient. The degrees of freedom associated with this t are $n - 2$ (Zar, J. H., 1996).

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