ASSESSMENT OF THE EFFECTIVENESS OF QUALITY ASSURANCE CONSTRUCTION SPECIFICATIONS FOR ASPHALTIC CONCRETE PAVEMENT

By

SUTHARIN PATHOMVANICH

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2000

The author dedicates this dissertation to her parents, Mana and Sukchai Pathomvanich, and her three sisters, Saluxsana, Sakara, and Anuttara.

ACKNOWLEDGMENTS

First, I would like to thank Dr. Fazil T. Najafi, my advisory committee chairman, for his continuing encouragement and support. Second, I am greatly indebted to Mr. Peter A. Kopac, Research Engineer for the Federal Highway Administration, who wisely advised me to contribute toward fulfilling some of the FHWA research needs and helped me in selecting a research topic based on the current needs. I would like to thank him for all of his invaluable assistance, advice, and critique throughout this research. Third, I would like to extend my sincere and heartfelt gratitude to Dr. Mang Tia, who generously gave his advice, help, kindness, and support throughout the research. Fourth, I would like to express my appreciation to Dr. Paul Y. Thompson for his kindness, concern, and encouragement. Fifth, I would like to thank Dr. Andre I. Khuri and Dr. Leon Wetherington for their interest, direction, and advice. Without their guidance, this dissertation would not have succeeded.

Further, I would like to thank the FDOT personnel--Mr. Gale C. Page, Mr. Tom Malerk, Mr. Bruce T. Dietrich, Mr. Winfred S. Langley, Mr. Patrick B. Upshaw, and Mr. Glenn Mans--for their assistance.

Also, I would like to thank my uncle and aunt, Mr. and Dr. Toochinda, for their love, generosity, and concern during my study in United States. This appreciation also extends to my boyfriend, Nitis Sthapitanonda, and all of my friends, especially Ratanaporn Awiphan.

Finally, I would like to thank my parents and my three sisters for providing me with love and good opportunities throughout my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

ASSESSMENT OF THE EFFECTIVENESS OF QUALITY ASSURANCE
CONSTRUCTION SPECIFICATIONS FOR ASPHALTIC CONCRETE PAVEMENT

By

Sutharin Pathomvanich

December 2000

Chairman: Dr. Fazil T. Najafi
Major Department: Civil and Coastal Engineering

A method to assess the effectiveness of highway construction specifications was developed in this research. Up to the present time, there was no truly objective method in existence that could assess the effectiveness of any state highway agency specifications. According to the proposed method, a specification is effective if the following levels of quality are the same: the quality the agency wants, the quality the agency specifies, and the quality delivered by the contractor. These three quality levels must be quantified in statistical terms (mean, standard deviation, offset from target, etc.).

The developed method was tested and demonstrated on Florida Department of Transportation's (FDOT) type S asphaltic concrete specifications for pavement density and asphalt content. The identification of quality level desired by the FDOT was attempted through a literature review, supplemented with a questionnaire survey. The FDOT's specifications, specifically the acceptance plans for density and asphalt content,

were analyzed to determine the quality level being ordered, with a computer program (AAD1_5) developed to assist in the analysis. The FDOT's Central Quality Reporting (CQR) database was analyzed to determine the quality level being delivered.

While the research failed to clearly identify the quality level desired, sufficient information was gathered to conclude there were several inconsistencies between what FDOT wants, what FDOT specifies, and what FDOT is getting. Therefore, FDOT's current density and asphalt content specifications are ineffective.

Recommendations were made to improve FDOT's specifications, increase their effectiveness, and improve the CQR database. At this time, FDOT is implementing new specifications, with features in line with the recommendations of this research. The statistical parameters determined here can be used by FDOT to evaluate how the new specifications will perform.

In addition to evaluating specification effectiveness, the method documented in this research can be used by any highway agency to monitor its specifications. For FDOT, the values of the statistical parameters presented in this research can provide a baseline quality level from which one can assess whether the quality delivered to FDOT in the future is improving. The quality should be improved when new specifications or new construction procedures and developments are in use.

CHAPTER 1
PROBLEM STATEMENT AND RESEARCH OBJECTIVES

1.1 Background

Different authors have used the term “quality assurance” in different ways. According to Willenbrock and Marcin, quality assurance, broadly interpreted, refers to the system of activities that is designed to ensure that the quality of the construction material is acceptable with respect to the specifications under which it was produced (TRB, 1979). It addresses the overall problem of obtaining the quality level of service, product, or facility in the most efficient, economical, and satisfactory manner possible. The scope of the total quality assurance system (regardless of the type of material specification used) encompasses portions of the activities of planning, design, development of plans and specifications, job advertising, awarding of contracts, construction, operation and maintenance.

LaHue defined a modern quality assurance system as “the overall process whereby the joint efforts of industry, state, and Federal officials are combined to develop or establish performance related quality criteria, exercise systematic process control, establish attainable specification criteria that recognize product variability and develop unbiased sampling and testing procedures” (TRB, 1979, p.7). To put this in the most simplistic terms, modern quality assurance for highway construction is a process to assure the development of better highway facilities through effective process control, product acceptance, product sampling and testing, and systematic feedback and evaluation (TRB, 1979).

According to Transportation Research Circular No.457, Glossary of Highway Quality Assurance Terms (TRB, 1996), quality assurance is defined as a process of systematic actions to provide confidence that a product or facility will perform satisfactorily in service. It addresses the overall problem of obtaining the quality of service, product, or facility in the most efficient, economical, and satisfactory manner possible. Quality assurance involves continued evaluation of the activities of planning, design, development of plans and specifications, job advertising and awarding contracts, construction, operation and maintenance, and the interactions of these activities.

Quality assurance in construction includes quality control, acceptance sampling and testing, and independent assurance. The acceptance sampling and testing are done to determine whether or not the quality of produced material or construction is acceptable in terms of the specifications. The independent assurance is a management tool that requires a third party to provide an independent assessment of the product and/or the reliability of test results obtained from process control and acceptance testing. The results of the independent assurance are not used for product acceptance (TRB, 1996).

Highway construction specifications that are generally used can be classified as either “recipe or method specifications” or “end-result specifications.”

Recipe or method specifications. These two terms are used interchangeably to mean those specifications that not only state what is wanted but also the manner by which it is to be attained. Limitation might also be placed on the hauling and lay down equipment and the types of rollers and patterns of rolling. This type of approach is traditional for many highway operations.

End-result specifications. An end-result specification implies that the state or the consumer organization will define the product wanted and will examine only the final product to decide if it is acceptable or not. As yet, no state has adopted a true end-result specification under which a total project is to be built by the contractor and the final product in place is to be accepted or rejected by the state. Generally, advocates of end-result specifications for highway construction believe that detailed "how to" instructions should be eliminated as much as possible and that units of construction should be accepted or rejected on a lot-by-lot basis by measuring significant characteristics of the complete lot. Such an end-result specification places the entire responsibility for quality control on the contractor and is commonly referred to as a "quality assurance specification." It relies on statistical acceptance plans based on random sampling both to define the product wanted and to determine the acceptability of the lot.

Before 1970, a recipe system was frequently used. In more recent years, end-result quality assurance specifications have been emphasized. The advantage of quality assurance specifications to state agencies is the actual placing of responsibility for materials and construction quality on the contractor or producer. The contractors and producers can choose their own materials and equipment and design the most economical mixtures meeting the specified requirements (Dobrowolski and Bressette, 1998; Rilett, 1998; Schexnayder and Ohrn, 1997; TRB, 1979).

Although it is generally agreed that quality assurance specifications are an improvement over recipe specifications, no one has actually quantified the effectiveness of either type of specification, i.e., in terms of how well the specification serves its function. Since the primary function of a specification is to describe the quality level of the product desired, an effective specification is one for which the contractors correctly interpret the desired quality level and consistently provide that level.

There are many possible reasons why contractors might provide a consistently lower, or higher, quality level than that desired by the state agency. Additionally, either a lower quality level or an unnecessarily higher quality level than that desired can be a detriment to society and the travelling public. The lower quality level results in a highway that will exhibit premature distresses (potholes, roughness, cracking, etc.) and will need added maintenance or early rehabilitation, often increasing highway user delay costs and accident potential. The unnecessary higher quality level invariably results in higher initial construction costs.

1.2 Problem Statement

Specifications are the communication means that tell the contractor what level of construction quality is desired. However, it is not clear what quality level is being asked for in most highway construction specifications. In order to develop quality assurance specifications, the state agency needs to answer the following four questions:

1. What do we want?
2. How do we order it?
3. How do we evaluate the product?
4. What do we do if we did not get what we ordered?

For statistical specifications, the answers provided by the agency are couched in statistical terms and may be found in the acceptance plan portions of the developed specifications. To submit an informed bid, the prospective contractor must examine the acceptance plan and decide what his target quality level will be. The contractor's target quality level may or may not be the same as the quality level that the agency wants and/or believes it has ordered.

In this current time period with much national emphasis on continuous quality improvement, it would make sense for agencies to monitor how well their acceptance plans are working. Were the acceptance plans developed properly? Is there consistency between what the agency wants and what it is actually ordering? Are the specifications working properly? Are contractors providing the quality level the agency wants? Should the agency be specifying a higher, lower, or the same quality level? These and other similar questions can be answered by investigating the effectiveness of specifications.

When a specification is not effective, a good understanding of the problem (and the underlying reasons for the problem) is critical as a first step toward improving the specifications. (The word "specification" here is used to refer to a single property, for example, a density specification or a smoothness specification. The word "specifications" is used to refer to more than one property.) Up to now, no truly objective method existed that could assess the effectiveness of any state highway agency's specifications. This research created a method to assess the effectiveness of highway construction specifications. According to the method, a specification is effective if the following levels of quality are the same: the quality the highway agency wants, the quality the agency specifies, and the quality delivered to the agency. These three quality levels must be quantified in statistical terms (mean, standard deviation, offset from target, etc.).

The Florida Department of Transportation (FDOT) began using quality assurance specifications many years ago, and the effectiveness of FDOT's specifications has never been specifically investigated. Some specifications may be effective, but others may not be; all can probably be improved. Therefore, a statistical evaluation is necessary to do this investigation.

In this research, the method to assess the effectiveness of specifications was tested and demonstrated on FDOT's asphaltic concrete pavement construction specifications. The scope was limited to type S asphaltic concrete material and two quality characteristics--pavement density and asphalt content. Data were collected and analyzed to determine the specifications' effectiveness in providing appropriate quality levels. It is anticipated that the analyses would directly help FDOT make improvements to its asphaltic concrete pavement construction specifications. The approach taken in this research can also be used by FDOT or other highway agencies to improve other specifications (e.g., portland cement concrete) and other quality characteristics (e.g., gradation and thickness). Such specification improvements should result in sound, unambiguous, and realistic requirements that clearly communicate exactly what quality level the contractor is to provide. Highway agencies, contractors, and the traveling public all stand to benefit from the improved specifications.

1.3 Research Objectives

The objective of this research is to develop a method to assess the effectiveness of highway construction specifications. The method was tested and demonstrated on the existing FDOT asphaltic concrete pavement construction specifications. With the time limit and data availability, only two quality characteristics--density and asphalt content--

for type S asphalt mix were examined in this research. The data were analyzed to determine if the present test result variations are consistent with what FDOT wants and has ordered through its specifications. A computer program was developed to convert the statistical parameters that were used in data analysis to average absolute deviation (AAD), which is used as FDOT's measure of quality for asphalt content. Guidelines and recommendations are presented to improve the existing specifications for asphaltic concrete (Type S) pavement construction. Specific objectives for this study are summarized as follows:

1. To demonstrate how the construction quality assurance database can be analyzed to monitor the quality of construction and determine when changes are needed to specifications and/or to procedures.
2. To determine what quality levels FDOT wants the contractor to provide in terms of population parameters.
3. To determine what quality levels FDOT is specifying in highway construction specifications in terms of population parameters.
4. To evaluate and determine what quality levels the contractors are providing in terms of population parameters.
5. To develop a computer program that helps FDOT assess its AAD specifications. This computer program was used as a tool to convert the quality levels that the contractors are providing in terms of mean and standard deviation to the quality levels in terms of average absolute deviation that are specified in FDOT construction specifications for the asphalt content quality characteristic.

6. To investigate and evaluate the effectiveness of presently used FDOT construction specifications and to make some recommendations to improve their effectiveness.

Even though this research was specifically aimed towards implementation by the FDOT, other highway agencies will find it beneficial because the objectives are common to many highway agencies. Moreover, the same approach can be used to develop a similar technique which fits other kinds of materials, such as Superpave, Friction Course, Portland Cement Concrete, etc.

1.4 Research Approach

In order to achieve the research objectives, the development of the research methodology was organized into six tasks.

Task 1--Literature search. Find and review the following:

1. Previous research reports.
2. Past and current Florida asphaltic construction specifications, including existing Florida Superpave construction specifications.
3. Other asphaltic construction specifications (e.g. AASHTO, other states, etc.)

Task 2--Data collection.

1. Collect the results of any experimental research projects that may have been conducted by FDOT that could be used to answer the following question: What quality level (in terms of mean, standard deviation, offset from target, etc.) existed prior to implementation of specifications?

2. Interview selected FDOT officials and Florida contractors to obtain information that can be used to supplement data collection in Subtask 2-1, above, to answer the following question: What quality level does FDOT want?
3. Collect quality control/acceptance data from FDOT projects after implementation of current FDOT quality assurance specifications. Because of the availability of information, the data that were observed started from year 1991 to the present. These data were used to answer the following question: What quality level are contractors actually providing under the current specifications?

Task 3--Data analysis.

1. Analyze collected data in Subtasks 2-1 and 2-2 to provide answers to each question posed in those subtasks.
2. Analyze the current FDOT specifications to answer the following question: What quality level is actually being ordered?
3. Analyze collected data collected in Subtask 2-3 to provide an answer to the question posed in that subtask.

Note: Data analysis primarily consisted of determining statistical parameters from data based on small sample sizes (n = 1 through 7). In addition, data analysis included several instances of hypothesis testing (e.g., test hypothesis that the mean and/or standard deviation of two or more data sets are equal) and testing to determine whether data are normally distributed.

Task 4--Computer program development.

1. Develop a computer program to help evaluate the effectiveness of the existing FDOT construction specifications. This software was used as a tool to relate the quality

levels in terms of mean and standard deviation to the average absolute deviation in order to compare the contractors' provided quality levels with those being specified. The results in subtask 3-3 were used as inputs. The computer program simulates the test results and generates the value of average absolute deviation, which is used to determine the pay factor that the contractors will get.

Task 5--Interpretation.

1. Determine effectiveness of FDOT specifications. For example, is the FDOT actually ordering the quality level it wants, and are contractors providing that quality level?
2. Depending on findings from Subtask 5-1, present reasons for the effectiveness (or lack of effectiveness) of FDOT's current specifications.
3. Make any recommendations for improvement of FDOT's current specifications.

Task 6--Final dissertation.

1. Write draft and final dissertation.
2. Make a presentation.

Task 1--Literature search. Find and review the following:

1. Previous research reports.
2. Past and current Florida asphaltic construction specifications
3. Other asphaltic construction specifications (e.g., AASHTO, other states, etc.)

Task 2--Data collection.

1. Collect the results of any experimental research projects that may have been conducted by FDOT prior to implementation of current FDOT asphaltic concrete pavement construction specifications.
2. Interview selected FDOT officials and Florida contractors to obtain information that can be used to supplement data collection in Subtask 2-1.
3. Collect quality control/ acceptance data from FDOT projects after implementation of current FDOT quality assurance specifications.

Task 3--Data analysis.

1. Analyze collected data in Subtasks 2-1 and 2-2 to provide answers to each question posed in the subtasks (see pp.8-9).
2. Analyze the current FDOT specifications.
3. Analyze collected data collected in Subtask 2-3 to provide an answer to the question posed in that subtask.

Task 4--Computer program development.

1. Develop a computer program to use as a tool to evaluate the effectiveness of the existing FDOT construction specifications.

Figure 1-1. Research Approach Flow Chart

Task 5--Interpretation.

1. Determine effectiveness of FDOT specifications.
2. Depending on findings from Subtask 5-1, present reasons for the effectiveness (or lack of effectiveness) of FDOT's current specifications.
3. Make any recommendations for improvement of FDOT's current specifications.

Task 6--Final dissertation.

1. Write draft and final dissertation.
2. Make a presentation.

Figure 1-1--continue

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

There are several reasons for ensuring the quality of a product; however, the main reason is money. In highway quality assurance, the contractors earn more money when producing a good quality product while the highway agencies save more money in future maintenance costs if the quality is built into the pavement. There are two main steps in ensuring good quality of the pavement. The first step is preparation of good specifications for the project. The second step is ensuring the specifications are met during mix design and construction.

2.2 Highway Specifications

Specifications are one of the most important tools to be concerned with in producing a good quality pavement. Specifications are used to describe the materials, workmanship, and other general requirements for the project that the highway agencies expect from the contractors. Good specifications should be easy to understand for both the contractors and the highway agencies in describing what quality is expected from the contractors. Unclear specifications often result in increased cost to the contractor, resulting in claims that have to be evaluated by the owner and that, in many cases, end up in court (Roberts et al., 1996). According to a survey conducted by the American Society of Civil Engineers, the contractors estimated that owners could save about 7.8% on construction costs if specification quality were upgraded. Assuming the annual cost of new construction (excluding homebuilding) to be $100 billion, $7.8 billion could be saved (Engineering News Record, 1979).

2.2.1 History

Before the 1970s, recipe or method specifications were used in most highway projects to define the quality that the highway agencies expected from contractors. When using recipe specifications, the highway agency spells out in detail what is to be built and how it is to be done. As was mentioned in the AASHO Road Test, the use of recipe specifications does not insure that the pavement would perform and last as expected (TRB, 1976; Rilett, 1998b). Moreover, the acceptance procedure is based on engineering judgement. Engineering judgement is strongly based on past experience, and if variables unknown to the specification writer change under new conditions, the end result may not be satisfactory (Miller-Warden Associates, 1965; Rilett, 1998a). It is difficult to define quality in legal or contractual terms when engineering judgement is used. The degree of acceptable variation will differ from engineer to engineer and from job to job.

In more recent years, quality assurance specifications have been emphasized. The advantage of quality assurance specifications to state agencies is the actual placing of responsibility for materials and construction quality on the contractor or producer. The specifications place few restrictions on the materials and methods to be used in order to obtain a completed product. The contractors and producers can generally choose their own materials and equipment and design the most economical mixtures meeting the specified requirements. Quality assurance specifications rely on statistical acceptance plans based on random sampling both to define the product wanted and to determine its acceptability (McMahon and Halstead, 1969; Miller-Warden Associates, 1965; TRB, 1976; Rilett, 1998b).

The Florida Department of Transportation began to develop the groundwork for the quality assurance specifications in 1965. By 1971, the preliminary specifications for asphalt pavement construction were developed. In 1976, FDOT made a decision to adopt the quality assurance specifications with pay adjustment for all asphalt concrete construction effective with contracts awarded after January 1, 1977. The acceptance plans contained in the specifications have undergone some changes. For example, the minimum limit of pavement density for type S asphaltic concrete was initially defined as 98 percent of control strip, and the control strip density had to be at least 95 percent of Laboratory Density (Office of Materials and Research, 1977). In 1991, the minimum limit of the control strip density was changed to 96 percent of Laboratory Density (FDOT, 1991). In 1977, the allowable tolerance of the asphalt content was +/-0.5 percent from the job mix formula (Office of Materials and Research, 1977). From 1982 to 1991, the deviation of the arithmetic average of the lot acceptance test from the job mix formula was used to define limits of asphalt content for type S asphaltic concrete (FDOT, 1982). In 1991, the specifications were changed to an average of accumulated absolute deviations of the acceptance tests from the job mix formula (FDOT, 1991). The limits instituted in 1991 are still in use today (FDOT, 1999).

2.2.2 Purposes of Highway Specifications

Highway specifications are used as follows:

1. To provide contractor a definite basis for preparing bid.

2. To inform all buyer representatives as to what the contractor is obligated to do.
3. To describe procedures that are required by the highway agencies.
4. To state the basis for sampling and testing methods, including acceptance or rejection of the completed work (Miller-Warden Associates, 1965).

2.2.3 Function of the Specifications

Practical and realistic specifications are an important consideration in any quality system. A practical specification is designed to ensure the highest overall value of the resulting construction. A realistic specification acknowledges the cost associated with specification limits and the presence of variability in all products, processes, and construction. The quality level of any product should be associated with the degree of variability. Statistically developed specifications are both practical and realistic because they provide a rational means for achieving the highest overall quality of the material or construction, while recognizing and providing for the variability of the process and product (Willenbrock, 1975).

2.3 Quality Assurance

2.3.1 Definitions

2.3.1.1 Quality Assurance

According to the Transportation Research Board's Glossary of Highway Quality Assurance Terms (TRB, 1996), quality assurance is defined as a process of planned and systematic actions to provide confidence that a product or facility will perform satisfactorily in service. It addresses the overall problem of obtaining the quality of service, product, or facility in the most efficient, economical, and satisfactory manner possible. Quality assurance involves continued evaluation of the activities of planning, design, development of plans and specifications, advertising and awarding contracts, construction, maintenance, and the interactions of these activities. Quality assurance in construction includes quality control, acceptance sampling and testing process, and independent assurance. The acceptance sampling and testing is done to determine whether or not the quality of produced material or construction is acceptable in terms of the specifications. The independent assurance is a management tool that requires a third party to provide an independent assessment of the product and/or the reliability of test results obtained from process control and acceptance testing. The results of the independent assurance are not used for product acceptance (TRB, 1996).

The current regulations on sampling and testing of materials and construction appear in the Federal Register (FHWA, 1995). According to these regulations, contractor testing results may be used in an acceptance program. An acceptance program is defined as the process of determining whether the materials and workmanship are in reasonably close conformity with the requirements of the approved plans and specifications. The rule provides flexibility to the states in designing their acceptance programs. Acceptance of materials and construction is not necessarily based solely on any one set of information; i.e. it may or may not include the contractor's test results. The quality of the product will be insured by each state's verification sampling and testing. In addition, the data from the contractors' quality control sampling are allowed to be used if the results from the states' verification sampling and testing programs confirm the quality of the material. The samples used for the verification sampling and testing must be obtained independently by the states or a designated agent. A dispute resolution system must be established to resolve discrepancies between results from a state's verification sampling and testing program and those of the contractor (FHWA, 1995).

Quality assurance of highway construction requires proper answers to the following four questions (McMahon and Halstead, 1969; TRB, 1979):

1. What do we want?
2. How do we order it?
3. Did we get what we ordered?
4. What do we do if we do not get what we ordered?

What do we want? (planning and design stage). Answers to this question encompass research, development, engineering technology, and experience. When the proper materials are specified, the design is correct, good construction practices are followed, and gross deficiencies are eliminated from the beginning. The quality level of the finished project is judged by how well it serves society--physically, functionally, emotionally, environmentally, and economically.

How do we order it? (plans and specifications). The second question relates to how the details are spelled out in specifications. One factor that affects the attained quality is how well the requirements of the plan and specifications define the needed characteristics of the finished project.

Did we get what we ordered? (inspection, testing, and acceptance procedures). In order to answer this question, the inspection, testing, and acceptance procedures need to be done. The accuracy of the answer depends on both the skills of the engineer or inspector and on the results of a system of sampling and testing. How the samples are taken and how the results are interpreted depend on the type of specifications. Under the recipe approach, the highway agency's inspector observes the procedures and makes necessary tests as construction proceeds. Thus, acceptance depends on the ability of the inspector to detect improper procedures or inferior materials. For the statistical quality assurance technique approach, a specific number of samples need to be taken on a random basis. The following are a number of problems regarding sampling and testing that affect the efficacy of quality assurance system:

1. The total of materials use in construction cannot be tested. The sample test results are only the characteristic estimation.
2. There is some testing variability. Different answers may be obtained even when the materials are the same.
3. It may take a long period of time to get the test results.
4. Often acceptance is based on indirect or empirical measurements to estimate the characteristic desired.

Although there are some problems with testing time and performance-related results, as mentioned above, these aspects are beyond the scope of this research.

What do we do when we do not get what we ordered? It is legally possible to insist that the failing material be replaced; however, the replacement uses more time and costs more money. Therefore, the principle of reasonable conformity and partial payments has been established. When using statistical probabilities, a system of preset partial payments for different percentages of materials within definite ranges of characteristics is provided. The payment system appears in the contract; therefore, the contractor knows in advance what the reduction or increase in payment will be for specific levels of test results and variability. There is no guarantee that the variability always will be exact as estimated by statistical probabilities; however, if sampling and testing have been properly done, a high level of confidence can be assumed.

2.3.1.2 Quality Control

Quality control is defined as the process that the contractor or producer performs to assure that the materials or construction conforms to the specifications. This concept of quality control includes sampling and testing to monitor the process; however, it does not include acceptance sampling and testing (TRB, 1996).

2.3.2 Objectives of Quality Assurance Specifications

The following objectives need to be considered for a successful quality assurance plan (Weed, 1996a):

1. Communicate to the contractor in a clear and unambiguous manner exactly what is wanted. Various statistical measures are used to describe the desired end result.
2. Sufficient incentive should be provided for the contractor to produce the desired quality or better. This can be accomplished by means of adjusted pay schedules. Pay reduction will be imposed on the contractor for deficient quality. A bonus will be given for superior quality when appropriate.
3. The specification should specify 100 percent payment for acceptable work, and it should be fair and equitable in assigning pay factors for work that differs from the desired quality level.
4. The specification should define an acceptable quality level (AQL) and rejectable quality level (RQL) realistically for each quality characteristic. The

AQL should be set high enough to satisfy design requirements; however, it should not be so high that extraordinary methods or materials will be required. The RQL should be set low enough that the option to require removal and replacement is truly justified when it occurs.

5. The appropriate target level of quality for obtaining 100 percent payment should be clear to the contractor.

2.3.3 Advantages and Disadvantages of Quality Assurance Specifications

2.3.3.1 Advantages of Quality Assurance Specifications

The biggest advantage to the state highway agencies is by placing the responsibility for materials and construction quality on the contractor or producer. The benefit to contractors and producers is the freedom to choose their own materials and equipment and to design the most economical mixtures meeting the specified requirements. The benefits of quality assurance specifications are primarily due to the lot-by-lot acceptance procedures. When lots are immediately accepted, conditionally accepted with a reduction in payment, or rejected, contractors or producers know their position. A price reduction motivates the contractor to take corrective action before large quantities of non-specification material or construction are produced. Moreover, it avoids tie-up of capital when payment is held up due to failing tests (Hughes, 1996; TRB, 1976, 1979).

The quality assurance specifications are easier to write and to interpret what is expected from a highway agency by describing the desired end result in statistical terms rather than in a vague term like "reasonably close conformance." The acceptance criteria and random sampling procedures are clearly defined. The risks to both the contractor and the highway agency can be controlled and known in advance. Quality assurance specifications are easier to enforce because of a clear separation of responsibilities for control and acceptance. Moreover, they are easier to apply because pay adjustment for defective work is predetermined; thus, no negotiations are required. Under the earlier method-type specifications, a contractor's bid was often influenced by the reputation of the engineer who was in charge of the project acceptance.

An additional benefit of quality assurance specifications is the produced data. Whereas historical data collected in conjunction with method specifications have been notoriously unreliable, the quality assurance specifications produce useful data obtained with valid random sampling procedures. These data can be analyzed at a later date to develop better specifications (Weed, 1996a).

2.3.3.2 Disadvantages of Quality Assurance Specifications

Agencies performing the contractor quality control activities as well as their own quality assurance sampling and testing may experience an increase in workload because the number of tests may increase. Small contractors may not be able to hire a full-time quality control technician when the prospect of successful bidding contracts was uncertain. These organizations would have to arrange with a testing laboratory to do the work (TRB, 1976).

2.3.4 Types of Acceptance Plans

There are two general types of acceptance plans in quality assurance. One is an attribute sampling plan, and the other is the variable sampling plan.

2.3.4.1 Attribute Sampling Plan

An attribute sampling plan is used when the samples are inspected with a go/no go gauge. When attribute sampling is used, each lot is assumed to consist of a collection of N units. A random sample containing n units is chosen from the lot, and each of them is checked. The attribute sampling plan is useful when it is not practical to measure the characteristic, but each unit can be classified as acceptable or defective by visual inspection (Chang and Hsie, 1995; Vaughn, 1990; Wadsworth et al., 1986).

An attribute sampling plan does not require complicated computation. Generally, the inspection process is to subject each item in the sample to a rapid visual examination or to use a simple gage to determine whether or not a certain dimension meets specifications. Elaborate testing or measuring equipment is not needed. The time that is required for inspecting a large number of items is minimal.

The great disadvantage of attribute sampling is that not much information is obtained. The purpose of attribute sampling is to classify an item as accepted or rejected; the inspection does not provide the average level and the variability of a characteristic. Therefore, there is no clue in regard to the type of corrective action that should be taken (Hudson, 1971; Wadsworth et al., 1986; Vardeman and Jobe, 1999).

2.3.4.2 Variable Sampling Plan

Sampling by variables makes use of all the relevant information (number of tests, means, standard deviation, etc.) computed from the sample to estimate the quality. Sampling by variables provides greater discriminating power for any given sample size. Moreover, this type of sampling produces a continuous result which is more suitable for developing adjusted pay schedules to deal with the intermediate levels of quality that are often encountered. The continuous measure of percent defective is a more appropriate parameter upon which to base a system of adjusted payments (Chang and Hsie, 1995; Hudson, 1971; Wadsworth et al., 1986; Vardeman and Jobe, 1999).

In general, attribute sampling is much less efficient than variable sampling. To obtain a certain buyer's risk or seller's risk, the number of samples needed for sampling by attribute may be 30 percent greater than the number needed for the variable sampling (Weed, 1989).

There are two cases in variable sampling--one where the standard deviation is known and the other where it is not. In most highway construction situations, the true standard deviation, σ, is not known. However, the standard deviation can be estimated from random measurements taken from the population. There are three forms of specification limits in any type of variable acceptance plan. The limits of the measured characteristic may be an upper limit, a lower limit, or both an upper and a lower limit. The acceptance plan may be designed in several ways. It may specify a minimum percentage of material or construction having a value of the measured characteristic within the limit(s), or a maximum or minimum value of the measured characteristic may be specified (TRB, 1976).

For density and asphalt content, variable sampling plans are used in current Florida standard specifications for road construction. The minimum value of the lot mean is defined for density, while the average absolute deviation from the job mix formula is used for asphalt content (FDOT, 1999).

2.4 Acceptance Using Lot-by-Lot Method

In lot-by-lot acceptance plan, one or more samples are chosen at random from the lot. The decision of acceptance or rejection is based on the test results of the samples.

The lot-by-lot sampling inspection improves quality in at least two ways. First, inspection by lots lowers the number of defective items per accepted lot when compared with the number of defectives in the lots taken as a whole. Second, because a large number of rejected lots is costly to the supplier, the supplier will try very hard to submit better quality lots in the future (Bowker and Goode, 1952).

A lot in highway quality control can be applied to a very large group of units, to a large quantity of material, or to an infinite number of locations. However, a lot is generally a definite amount of similar material (Chang and Hsie, 1995; Hudson, 1971a). Different lots of the same kind of material can differ in quality, as indicated by variations in the measured values of some characteristic of material. The lot size needs to be defined for sampling and testing purposes. Only after establishing the size of the lot can the sampling locations and frequencies for quality control and assurance be determined.

Under lot-by-lot testing for acceptance, the process of constructing a highway may be thought of as the production of a succession of lots. These lots are individually considered by highway agencies for acceptance or rejection. When estimating the size of lots and sublots, the subject of risk is raised. The acceptance plan becomes burdened with an excessive amount of costly testing when the lot size is too small. When the lot size is large, it is a disadvantage for the contractor because of the large quantity of material that can be rejected when the quality is not acceptable (Anglade, 1998).

2.5 Random Sampling

If a sample is to provide us with useful information about the population, it must be representative, i.e., the sample must be made up of typical members. A representative sample for quality assurance is generally obtained by random sampling. Random sampling is often defined as a manner of sampling which allows every member of the population (lot) to have an equal opportunity of being selected as a sample. Most state highway agencies use stratified random sampling, where the lot is divided into equal sublots and the sample is obtained by random sampling from each sublot (Drain, 1996; Hughes, 1996).

The more fundamental method of random sampling, which can be called pure random sampling, allows the samples to be selected with an unbiased manner, based entirely on chance. However, this method has some practical drawbacks that will be discussed shortly.

2.5.1 Pure Random Sampling

A drawback of pure random sampling is that the samples occasionally tend to be clustered in the same location. Although this method of sampling is valid from a statistical point of view, neither the highway agency nor the contractor would feel that it adequately represents the lot. Sampling locations that tend to be spread more uniformly throughout the work are believed to represent the lot better. Therefore, most highway agencies use stratified random sampling for acceptance.

2.5.2 Stratified Random Sampling

The stratified sampling method for highway material and construction items is designed to eliminate the clustering problem and tend to be quite similar. (Weed, 1989) Each lot is considered to be made up of sublots. Sublots are defined as an equal size subdivision of lot. Random sampling is done within the boundaries of each sublot.

Stratified random sampling is used in the current Florida road specifications for type S asphaltic concrete material. For the density quality characteristic, the standard size of a lot is 1500m of any pass made by the paving train regardless of the width of the pass or the thickness of the course. A sublot is 300m or less. At the end of a production day, when the completion of the lot is less than 1500m, it is considered as a partial lot. If the partial lot length is 600m or less, and a full-size lot from the same day is available, then the previous full-size lot is redefined to include this partial lot. The number of tests required is shown in Table 2-1.

For asphalt content, a standard size lot for acceptance at the asphalt plant consists of 3600 metric tons with four equal sublots of 900 metric tons each. If the partial lot contains one or two sublots, this partial lot is included to the previous full-size lot from the same day (if available), and the evaluation is based on either five or six sublot determinations. When the total quantity of the mix is less than 2700 metric tons, the engineer will evaluate the partial lot for the appropriate number of sublots from n=1 to n=3 (FDOT, 1999).

2.6 Variability in Highway Construction

The quality of highways has always been a concern of highway engineers and contractors. The variability of materials and construction processes is used as one of the measures to assess quality in the American Association of State Highway and Transportation Officials (AASHTO) Guide for Highway Construction (AASHTO, 1996).

In connection with the inspection of highway materials or construction, various kinds of measurements are made. For example, it is necessary to measure the density of pavement to ensure its quality. It is time consuming and costly to measure every small portion of pavement. Therefore, decisions must be based on measured density in a few

Table 2-1. Density Testing Requirements

Lot Size	Number of Tests
Less than 900 m	3
901 to 1200 m	4
1201 to 1500 m	5
1501 to 1800 m	6
1801 to 2100 m	7
Greater than 2100 m	Two lots

Source: FDOT Standard Specifications for Road and Bridge Construction 1999 (FDOT, 1999).

suitable locations. The samples and locations should be so chosen that the measured values can be considered as representative of the density of the entire pavement. For these reasons, statistics need to be used to determine the variability with respect to each material or construction characteristic.

No matter what kinds of measurements are made, it is unlikely that all measured values will be exactly the same. Relatively small variations in the measured values of a property of a material may be caused by the fact that the measurements cannot be made exactly enough. However, fairly large variations usually occur because of the nature of the materials and the fact that no two samples of the material will be alike. Therefore, increasing the precision of a test method, or the care with which the measurements are made, beyond a certain limit would not make the measured values more reliable.

Factors that greatly affect the variation are called “Assignable Causes”. The assignable causes are actual errors and usually produce much larger variations than random causes. An example of assignable causes is the intentional departure from specified proportions or methods or a malfunction of equipment. Assignable causes can be detected and eliminated by thorough inspection. Assuming no assignable causes are operating, there are three sources of variations involved in highway construction (Hudson, 1971; Hughes, 1996):

The actual variation. The actual variation is the unavoidable variation in material or a combination of materials that are tested.

The sampling variation. The variation due to differences in the samples selected for testing such as segregation, etc. Segregation is a major source of variation in most property measure values of a sample used in highway construction. Segregation separates a material into unlike parts. Most of the highway materials tend to segregate to some degree. If we could get perfectly mixed material in which the particles are arranged in the manner indicated in Figure 2-1a, the accuracy of the measured values made on samples taken from any part of the area would depend only on the precision with which the measurements were made. In contrast, if the material is completely segregated as indicated in Figure 2-1b, samples taken from different areas would be widely different. The actual construction materials are neither mixed with complete uniformity nor completely segregated. They are most likely as indicated in Figure 2-1c. As a result of segregation, the density test results at two locations may differ greatly (Miller-Warden Associates, 1965; Hudson, 1971). Random sampling is mostly used in highway quality assurance to reduce the effect of segregation. The locations or units from which the samples are obtained must be entirely random, which means that the locations of the samples are determined without bias, such as by using a table of random numbers.

The testing variation. The testing variation is the variation due to the lack of uniformity in the testing procedure and includes the effect of differences in the preparation of portions of a sample for testing. The testing variation would be measurable if the test did not destroy the material. The same sample could be used to repeat the test.

The relation between the total standard deviation and its three components is usually represented by the following equation:

$$S_T = \sqrt{S_a^2 + S_s^2 + S_t^2} \tag{2.1}$$

S_T = Total standard deviation

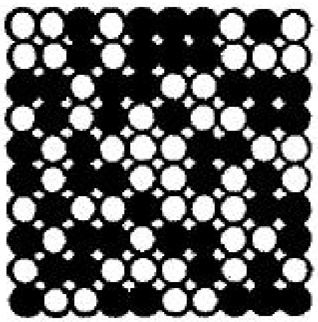
S_a = Actual variation

S_s = Sampling variation (also called sampling error)

S_t = Testing variation (also called testing error)

2.7 Acceptance Tolerance

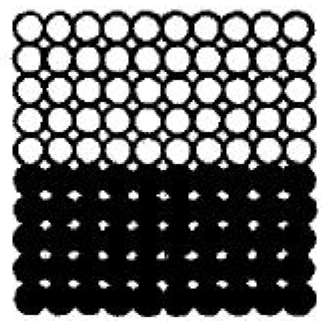
Under most current practices, one periodic sample is taken by stratified random sampling. This sample is tested, and the testing results are used to determine if the material is accepted or rejected. If the measured test results are within the tolerance specified in the specification book, the material or construction lot is accepted. If the test results are not within the tolerance stated in the specifications, the material or construction lot is rejected.

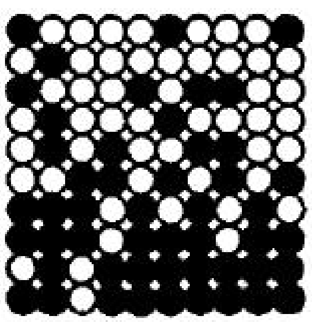


a) Completely random arrangement of types of particles produced by perfect mixing.

Complete segregation of types of particles.

b)





c) Arrangement of particles intermediate between completely random and completely segregated. The type of mixture commonly found in practice.

Figure 2-1. Degrees of Segregation

Reasonable specification limits should allow for normal testing variability and process variability. According to a FHWA report, a considerable gap exists in highway work between the quality of work specified and the quality of work received (Quality here refers to quality of compliance to specifications limits and not quality of performance) (FHWA, 1977).

Although the AASHTO Guide Specifications are a noteworthy milestone toward standardization, they are not necessarily the best engineering or the most economic specifications for some states (Miller-Warden Associates, 1965). Willenbrock (1975) suggested that every highway agency should have their own specifications to describe realistic standards, which more accurately reflect the inherent variability of a given material type or construction characteristic. The realistic specifications would enable a contractor who is normally applying good control processes to run a minimum risk of having acceptable material rejected. Hughes (1996) stated that the state highway agencies use their experience, engineering judgement, tolerances from other agencies, and standard precision statements more often than they use variability data from studies and projects. Moreover, many specification limits are still being set the same way as the ones used in the AASHO Road Test almost 40 years ago.

2.8 Pay Factor

A common feature of most statistical end-result specifications is the pay adjustment. When a construction item falls just short of the specified level, it may not warrant replacement or removal but neither does it deserve 100 percent payment. Therefore, the pay factor in the specifications is used to adjust the contractor's pay according to the level of quality actually achieved. The pavement has more chance to fail prematurely if the construction is deficient. It may not be capable of withstanding the design loading. The necessity of repairing this pavement early results in an additional expense to the highway agency. The highway agency is normally responsible for this expense because such repairs typically occur long after any contractual obligations have expired. A main objective of the pay adjustment is to withhold sufficient payment at the time of construction to cover the extra cost anticipated in the future repair that was caused by the deficient quality work.

The FHWA initially supported the incentive pay concept as an experimental feature. After several years of satisfactory experience, it is now used as a standard feature in many highway construction specifications (Weed, 1996b). Under the incentive pay concept, a contractor receives a bonus as a reward for providing superior quality product. That means the quality levels exceed the specification in areas where additional value is provided in terms of performance of the finished product. The incentive not only tends to soften the punitive perception the construction industry originally had of statistical end-result specifications, it provides an increased incentive to produce high-quality work believed to be in the best interest of all concerned. A specification with incentive pay adjustment is intended to give conscientious contractors with good quality control a bidding advantage over contractors with poor quality control. In a competitive environment, incentives provided in the contract documents will normally result in very little if any additional project costs. A good contractor will be confident of achieving the incentives and will bid accordingly in order to increase his chances of getting the work. Absolutely, this assumption relies on the premise that it does not cost any more to do quality work. The good quality-conscious contractors have proven this premise over and over (Wegman, 1996).

Pay adjustment with maximum pay factor of 100 percent is used in current Florida Road Construction Specifications. For density property, partial payment is given when the lot has an average density less than 98 percent of the control strip density. For asphalt content, the limits depend on the sample size of each lot (FDOT, 1999).

There are factors that must be taken into account in pay adjustment for deficient quality pavement:

1. The cost of earlier repair because the poor quality pavement was constructed,
2. The administrative costs involved in preparing for the premature pavement repair,
3. The motoring public costs for the earlier disruption of traffic to make the necessary repairs, and
4. For practical reasons, a small area of poor quality pavement may make it necessary to overlay a larger area of pavement (Weed, 1989).

CHAPTER 3
MATHEMATICAL AND STATISTICAL PRINCIPLES UNDERLYING VARIABILITY IN QUALITY ASSURANCE SPECIFICATIONS

The purpose of this chapter is to present an overview of the mathematical and statistical concepts related to an acceptance plan of quality assurance specifications.

3.1 Statistical Modeling

Shapiro and Gross (1981) stated that a statistical model is a mathematical formulation that expresses in terms of probabilities the various outputs of a system. A statistical model is mostly useful in situations where the output cannot be expressed as a fixed function of the input variables. For example, consider the measurement of the pavement density. Assuming several measurements are taken, it will not be surprising to find a different reading for each measurement. These measurements can be considered as the output of the system. It can be further assumed that the actual pavement density is fixed and that this variability in the reading is due to errors in measurement. Thus, a model is selected to represent this variability.

$$y_i = m + e_i \tag{3.1}$$

y_i = The output (i.e. the ith measurement)

m = The true mean of the population

e_i = Measurement error for the ith trial

Equation 3.1 can be considered as a statistical model when a probability distribution is selected to represent the variability e_i, which is sometimes positive and sometimes negative. When taking a large number of observations, the average of e_i will be zero; therefore, the net result is μ. However, in a real problem there is only a limited number of data points, and because of this fact, only an approximation of μ is obtained. Therefore, an estimate of the variability of the measuring error is required. In statistics, this estimate of the variability is called a standard deviation and is represented by the symbol σ.

3.2 Reliability of Measurement

The terms precision, accuracy, and bias are often used when comparing the reliability of estimated values that are based on tests of samples. If the measurement values are spaced closely together near one spot, these values provide good precision. If the mean of the measurement values tend to coincide with the true mean of the population, these values provide good accuracy. Bias is a measure of inaccuracy and is the degree to which the mean of a distribution of measurements tends to be displaced from the true population value. A common way to explain these terms is by imagining a marksman shooting at a target, as shown in Figure 3-1 (Hudson, 1972; Hughes, 1996; Weed, 1996a).

3.3 Quality and Variability Concepts

Quality in this dissertation refers to the quality of conformance with the specifications. The greater the compliance is, the more effective the specifications are.

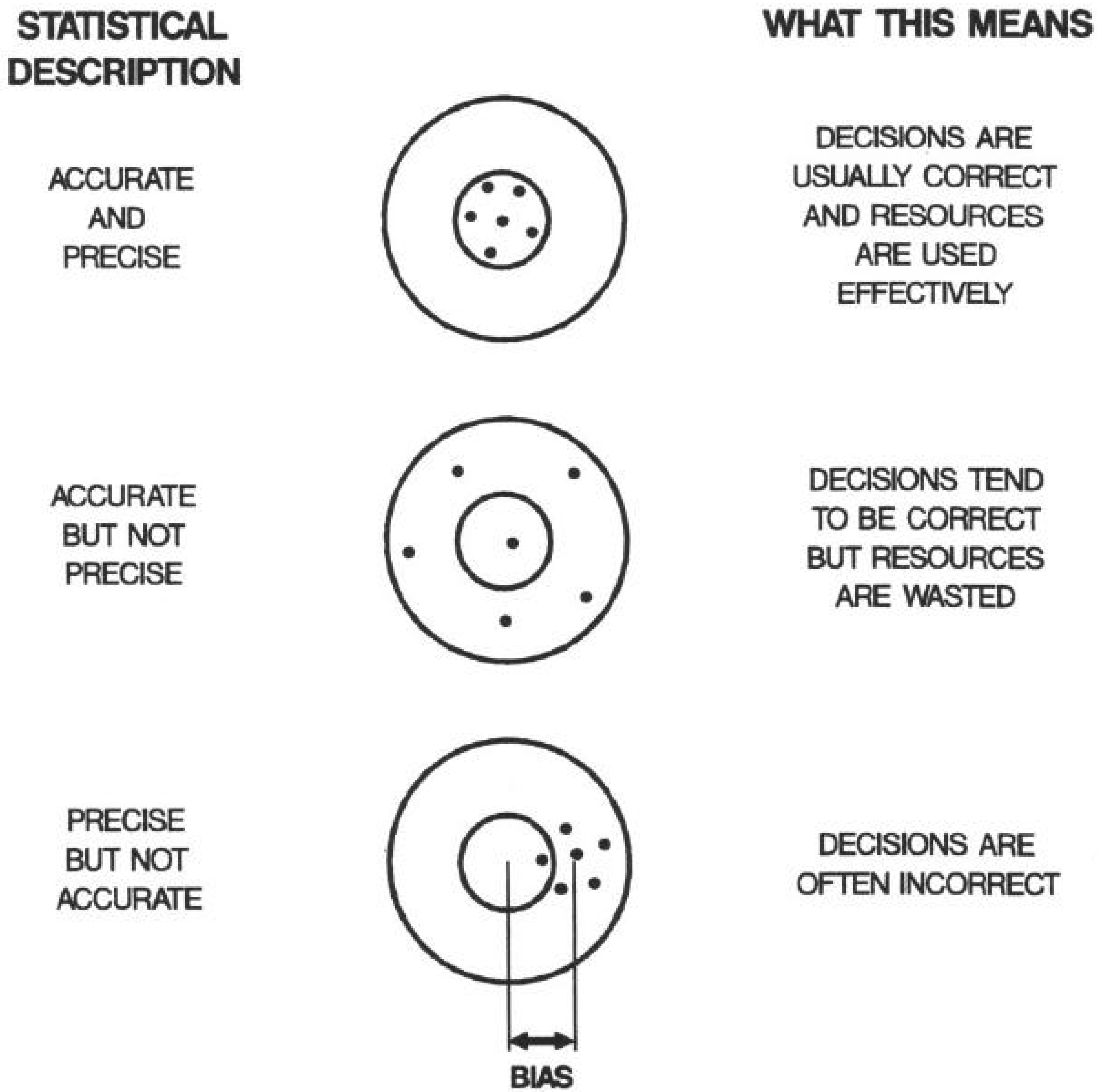


Figure 3-1. Concept of Accuracy, Precision, and Bias

The concept of variability comes from the fact that all materials and construction are not exactly the same and subject to some variations. The variations could be natural and occur randomly, which most specifications allow. However, variations resulting from errors (design, equipment, materials, or construction errors) will penalize the producer by deducting a percentage of his payment depending on the amount of variation.

The variability can be defined by using the sampling data to compute two important properties. The first one is the central tendency of all the measurements, known as the average value or mean. The other is a measure of variation from the mean that is known as the standard deviation (Adam and Shah, 1966).

The central tendency is the central position on a scale of measurement, the value about which the observations have a tendency to center. The most common measure of the central tendency is the average value. The average can be determined by adding all the measurements or values in the data set and dividing the sum obtained by the number of measurements that make up the data set. The equation is as follows:

$$\bar{x} = \frac{\sum_i x_i}{n} \qquad (3.2)$$

This characteristic is not enough to describe the distribution adequately. Even though the central tendencies of two sets of data are the same, the distributions may be different. Therefore, at least a second characteristic called the dispersion is required.

The dispersion or a measure of variation describes the degree of scatter shown by the observations. There is not much variability if the measurements are closely clustered about the mean. The variability is greater when the measurements spread far from the mean on both sides. The dispersion can be measured by the use of statistical parameters such as the range (R) or the standard deviation (σ). The range is the difference between the largest (x_{max}) and the smallest (x_{min}) values in a set of data as shown in the following equation:

$$R = x_{\max} - x_{\min} \tag{3.3}$$

The major drawback of the range is that it uses only two extreme values in the calculation. It shows that the other values lie between the extremes; however, the range does not provide any measure of the dispersion of the other values. The standard deviation is the most satisfactory and most commonly used parameter to measure the variation. Since the standard deviation is the square root of the average of the squares of the numerical differences of each observation (*x*) from the arithmetic mean (μ), it takes into account the effect of all of the individual observations (*n*) (Willenbrock, 1975). The population standard deviation (σ) can be determined by the following equation:

$$s = \sqrt{\frac{\sum_i (x_i - m)^2}{n}} \tag{3.4}$$

The sample standard deviation (*S*) can be estimated from the following equation:

$$S = \sqrt{\frac{\sum_i (x_i - \overline{x})^2}{(n-1)}} \tag{3.5}$$

where

$\overline{x}$ = Sample average

When the value of the standard deviation is known for a particular measurement, under given conditions, statistical principles can be used to estimate the percentage of measurements that will fall within selected limits under similar conditions. Therefore, the realistic deviations will help in providing realistic tolerances for specifications that will ensure that future similar construction will be as good as or better than the quality that is currently produced.

In most cases in highway construction, the difference between most values in a group and the calculated average for the group will not exceed 2 times the value of σ (Hudson, 1971).

3.4 Variation as a Quality Yardstick

Taguchi (1986) viewed variation as a lack of consistency in the product that will give rise to poor quality. Therefore, Taguchi developed methodologies aimed at reducing two elements of variation: (a) deviation from the target and (b) variation with respect to others in the group.

A typical quality measure of a product is compared to the desired state as shown in Figure 3-2. Taguchi believed that even though the product mean value is within upper and lower acceptance limits, the cost of quality goes up if it is off the target and the variation around the mean is large. The more the deviation, the higher is the expected life-cycle cost (Taguchi, 1986). Life-cycle cost is defined as the total economic worth of a usable project segment that was determined by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and surfacing costs, over the life of the project segment (Walls III and Smith, 1998). Taguchi (1986) used a simple model of the loss imparted to the seller, the buyer, and society. This model serves its purpose in highlighting the fact that a product is cheaper and better if it is consistently produced close to its target value. A distribution of more frequent achievement of the target value and smaller variation around the target value is preferred.

The bottom picture in Figure 3-2 shows the loss function model, which is

$$L(y) = k(y\text{-}TV)^2 \tag{3.6}$$

where

k	=	Constant
(y-TV)	=	The deviation form the target value

TV is the target value of a variable at which the product is expected to perform best. The horizontal axis shows values of the variable, while the vertical axis shows the loss associated with each value of the variable. The assumption of this model is that the loss at the target value is zero, and the buyer dissatisfaction is proportional only to the deviation from the target. The buyer is satisfied if the quality of the product is at the target value (Raheja, 1991).

3.5 Describing Parameters and Statistics

One difference between a population and a sample is the way the summary measures are calculated for each. Summary measures of a population are called parameters, while summary measures of a sample are called statistics. For example, if the data set is a population of values, the average is a parameter, which is called the population mean. If the data set is a sample of values, the average is a statistic, which is called the sample average (Schlotzhauer and Littell, 1997). To prevent confusion, the

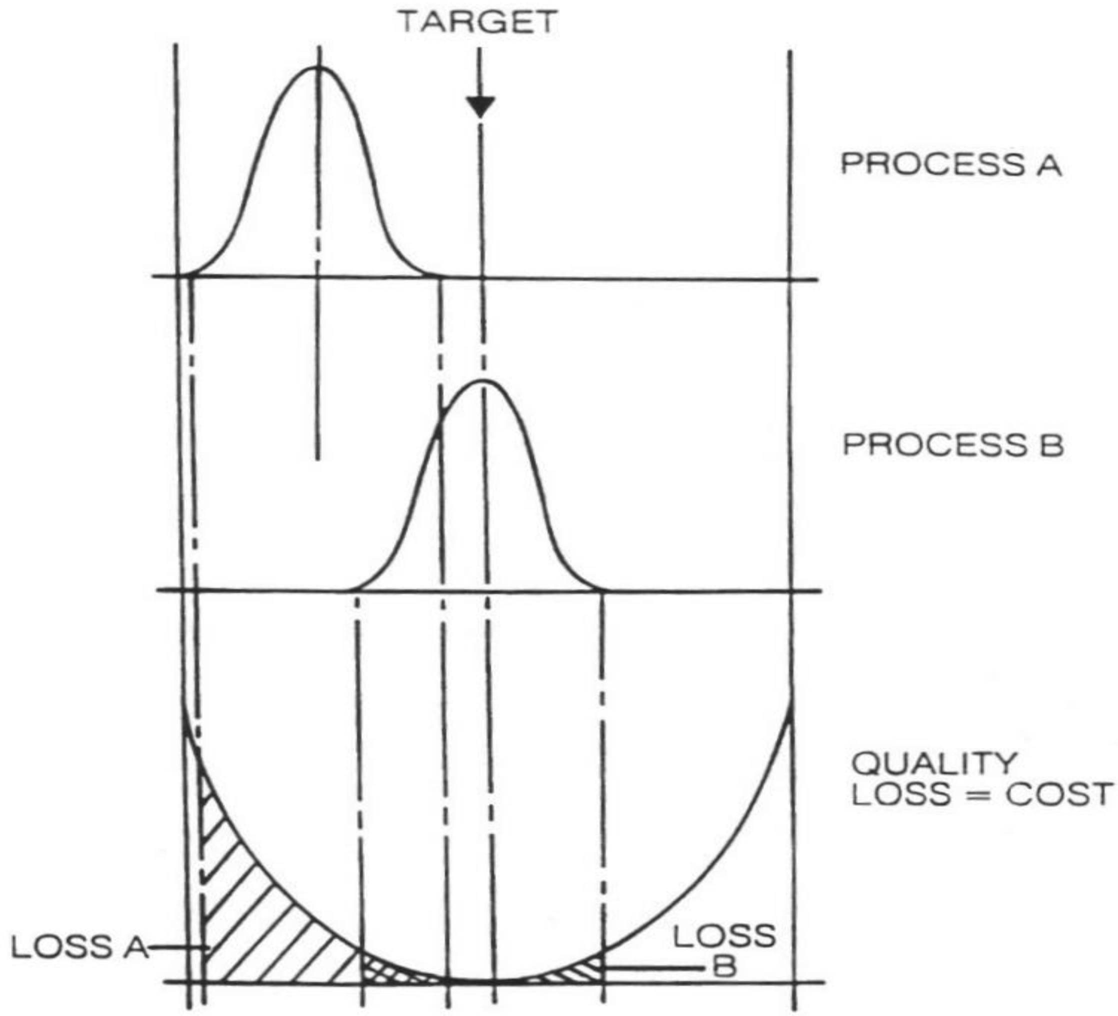


Figure 3-2. Conformance to Specification and Quality Loss

rest of this research uses mean to indicate the population mean and average to indicate the sample average. The Greek alphabet is used to denote the population parameters. The differences in notation between the sample and the population measures that are used in this research are shown in Table 3-1.

Table 3-1. Symbols used for Populations and Samples

Data Set	Average	Variance	Standard Deviation
Population	μ	σ^2	σ
Sample	$\bar{x}$	S^2	S

3.6 Specification Compliance Measures

Most states, including Florida, are using plant-produced mix properties, density, and smoothness tests to determine overall quality and acceptance of asphaltic concrete construction work. The mix properties of the asphaltic concrete describe overall material quality. The density shows the capacity of the pavement to withstand repetitive loads from traffic, while the smoothness is used to evaluate the ride quality experienced by the traveling public. These measures describe the quality level achieved during construction whether viewed independently or collectively (FDOT, 1999; Schmitt et al., 1998).

There are five different measures that are used to determine specification compliance by state highway agencies: average, quality level analysis, average absolute deviation, moving average, and range (Schmitt et al., 1998).

<u>3.6.1 Average</u>

When the average is used as a compliance measure, an assumption has been made by the developers of the acceptance plan that the variation must be known because it determines how accurately the average can be estimated from a given sample size. A confidence interval should be constructed to describe the interval of the mean that can be found at a specified probability level. The confidence interval of mean can be estimated by using the following equation:

$$Confidence \quad Interval \quad of \quad mean = \bar{x} \pm z_{\frac{a}{2}} \sqrt{\frac{s^2}{n}} \tag{3.7}$$

where

$\bar{x}$	=	Sample mean
z	=	Standardized statistic;
α	=	Confidence coefficient;
σ^2	=	Known variance; and
n	=	Number of tests.

Acceptance plan developers can make the assumption that the standard deviation is known if they have data showing that the standard deviation does not change significantly from contractor to contractor or from project to project. The FDOT uses the average method as a compliance measure for pavement density acceptance.

<u>3.6.2 Quality Level Analysis</u>

When the quality level analysis method is used for the specification compliance measure, the percent defective or the percent within limits need to be estimated. The percent defective in quality assurance specifications is the portion of the measured characteristic that falls outside a single lower or upper specification limit or outside both lower and upper limits. The smaller the percentage defective in the lot, the better the quality is. The good-quality lots will get full payment. Penalty or payment deduction will be applied to lots that have some defects. The amount of deduction will depend on the amount and the seriousness of the defects.

For asphalt content and pavement density characteristics, the potential economy of using percent defective could serve as an incentive to maintain a good quality control process. When the contractor maintains a high level of quality control, the variability of the production process will be reduced. As a result, the contractor can aim for a lower characteristic mean and still meet the specifications. The contractor with a loose quality control program will have high variability in the production process that will create difficulty in meeting the specification requirement; therefore, the contractor must aim for a higher mean. The higher the production mean is, the more expensive the cost is (Al-Azzam, 1993).

Figure 3-3 shows several sets of the average and variance value combinations that give the same percent defective result.

In order to estimate the lot percent defective (PD) or percent within limit (PWL), it is first necessary to determine either one or two quality index values (Q). One value is needed for a quality characteristic having a single specification limit. Two values are used for a quality characteristic having a double specification limit. Since the variability is estimated by the standard deviation calculated from the sample, it is a “variability-unknown” percent defective. The equations used to compute the quality index are as

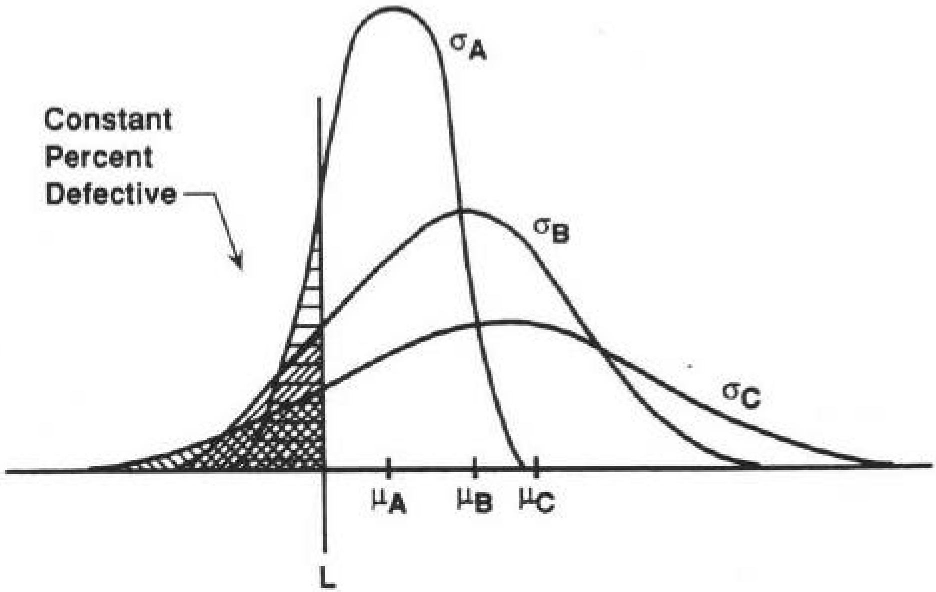


Figure 3-3. The Flexibility of the Percent Defective Quality Measure with Respect to μ and σ.

follows.

$$Q_L = \frac{\overline{x} - L}{S} \tag{3.8}$$

$$Q_U = \frac{U - \overline{x}}{S} \tag{3.9}$$

where

Q_L	=	Lower quality index
Q_u	=	Upper quality index
$\overline{x}$	=	Sample mean
S	=	Sample standard deviation
L	=	Lower specification limit

U = Upper specification limit

After obtaining the value of Q, PD/PWL can be estimated from acceptance plan tables that have values of PD/PWL associated with any specific value of Q and sample size. The individual estimates of PD are added to obtain PD for a double specification limits. Percent defective and percent within limit are shown in Figure 3-4. The total PWL can be found by the following equation:

$$\text{Total PWL} = (P_U + P_L) - 100 \tag{3.10}$$

where

PWL = Percent within limit

P_u = Upper percent within limit

P_L = Lower percent within limit

There are four cases to measure percent defective (Willenbrock and Kopac, 1976):

1. Population mean (μ) and population standard deviation (σ) are both known.
2. Population mean (μ) is known, but population standard deviation (σ) is not known.
3. Population mean (μ) is not known, but population standard deviation (σ) is known.
4. Population mean (μ) and population standard deviation (σ) are both unknown.

Case 4 is the most encountered case in construction situations and it is the one, which is assumed when a PD/PWL acceptance plan is developed.

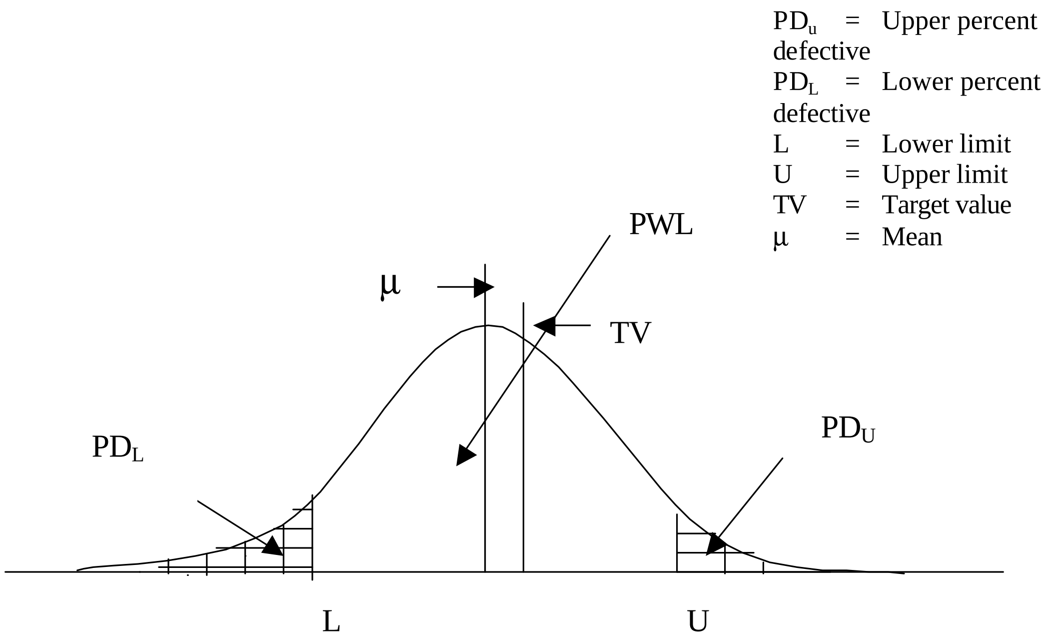


Figure 3-4. Percent Defective (PD) and Percent within Limit (PWL) under the Standardized Normal Distribution Curve.

3.6.3 Average Absolute Deviation

The asphalt content characteristic has been controlled to achieve average values approximating target values. Highway agencies often use the average of absolute deviations from target values instead of the average of arithmetic deviations to control process manipulation (Parker et al., 1993). However, the quality level analysis is the most frequently used (Schmitt et al., 1998). The average of the absolute deviations (AAD) from target values is used in Florida construction specification for asphalt content quality acceptance. Specifications are currently structured to allow greater deviations from the target for smaller sample sizes. The equation that is used to determine the average absolute deviation is as follows:

$$\Delta = \frac{(\sum_i |x_i - TV|)}{n} \tag{3.11}$$

where

Δ	=	Average absolute deviation;
x	=	Individual test result;
TV	=	Target value; and
n	=	Number of tests.

Parker et al. (1993) states that the average absolute deviation is a simple but statistically correct method that maintains consistent levels of control for both central tendency and variability of absolute deviations from the job mix formula (JMF).

Weed (1999) believes that there are some problems with AAD. The AAD should be a function of both population spread and population shift, but sometimes it is determined entirely either by the population spread or by the population shift. Moreover, two materials may yield the same value of AAD although they have different distributions. Another problem is that it is based on a target value, which normally is the midpoint between lower and upper specification limits; therefore, it is not suitable for one-sided specifications for which a single, specific target value cannot be defined. Some examples of the problems mentioned above are presented later in this chapter.

3.6.4 Moving Average

The moving average can be computed by finding the average of the test results. When a new test result is obtained, it is included in the calculation, but the oldest test result is dropped out of that set (Hudson, 1971). For a better understanding, see the following example.

Test No.	X_n	$\overline{x_5}$
1	3.55	
2	3.70	
3	3.65	
4	3.60	
5	3.60	3.62
6	3.63	3.64
7	3.57	3.61

Assume above that the sample size is 5. The value of $\overline{x_5}$ for test No.5 is the average of the values of x for the first five tests. For test No.6, the result is equal to the sum of the test results of test No.2 to 6 divided by 5. The first test result in the original set is dropped out, while the new test result is added. The other values are computed in a similar way.

3.6.5 Range

The range method is a specification compliance measure that does not use the distribution of values. Only the maximum and minimum values are used in the calculation. The range of values is compared to the specification limits. The range of the test results can be computed by the following equation:

$$\text{Range} = (\text{Max} - \text{Min}) \tag{3.12}$$

where

Max = Maximum test value; and

Min = Minimum test value.

3.6.6 Pavement Density Specification Compliance Measures

According to research done by Schmitt et al. (1998), from the information obtained from 38 states, quality level analysis is the most common compliance measure for pavement density (20 states). The next common method is the average (8 states), followed by range (4 states), absolute deviation (3 states), and moving average (3 states).

Florida is among the few states that use the average method in density pavement acceptance for type S asphaltic concrete material (FDOT, 1999).

3.6.7 Asphalt Content Specification Compliance Measures

Quality level analysis is the most frequently used compliance measure for the asphalt content property (14 states out of 38 states). Average absolute deviation is next (8 states), followed closely by moving average (7 states), and average (6 states). Range (3 states) is less commonly used (Schmitt et al., 1998).

Average absolute deviation is currently used as a compliance measure for asphalt content acceptance in Florida. The acceptance range of average absolute deviation is wider when the sample size is smaller (FDOT, 1999).

3.7 Conformal Index Approach

An alternative approach to the use of the standard deviation is a statistic referred to as the conformal index (CI). The Material Research and Development Inc., first used this approach. The conformal index can be used to estimate accurately the size and incidence of variations from a quality level target such as the target job mix formula (JMF). The CI is similar to the standard deviation; however, the standard deviation is used to measure the deviation from the arithmetic average value, while the CI measures the deviation from the target value such as the JMF value. In other words, the standard deviation is a measurement of precision, whereas the CI is a measurement of exactness (accuracy) or degree of conformance with the target value. The CI is as useful as the standard deviation. Both can be used with both percent within limits/percent defective and the loss function approach. Nevertheless, the attractiveness of CI is that it focuses on the target value, and it is this target value that is defining the quality level (Cominsky et al., 1998; Hudson et al., 1972; Kandhal et al., 1993).

The standard deviation (*S*) and conformal index (CI) can be written in equation form as follows:

$$S = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{(n-1)}} \tag{3.13}$$

$$CI = \sqrt{\frac{\sum_i (x_i - TV)^2}{n}} \tag{3.14}$$

where

TV = Target Value

n = Sample Size

The following equation shows the relationship between the standard deviation and the conformal index (Hudson, 1972):

$$CI = \sqrt{\frac{(n-1)S^2 + nd^2}{n}} \tag{3.15}$$

where

d = The average bias or offset of the average of group of measurements from the target value, i.e., $d = TV = x$

3.8 Potential Problems with Existing Quality Measures

The following examples will be considered to explore the mathematical properties of the different quality measures. In Figure 3-5, the average absolute deviation (AAD) and the conformal index (CI) are computed for a sample size of n = 2 and for two different cases. In the first case, one test result value falls on either side of the target value. In the other case, both values fall on the same side of the target value. From this example, it is seen that AAD = δ in the former case and AAD = Δ in the latter case, while CI seems to be the same for both cases. The AAD is determined entirely by the population spread in the former case and entirely by the population shift in the latter case. This effect may be less pronounced when sample sizes get larger. Nonetheless, there is some doubt concerning the consistency of AAD as a quality measurement (unless this unique property happens to characterize performance accurately). There is nothing to suggest a problem with CI as a measure of quality in Figure 3-5 because the performance is logically expected to be a function of both population location (shift) and population spread.

The three basic quality measures--AAD, CI, and PD/PWL--are explored in order to see if widely different distributions could be found that would produce the same levels of the quality measures identically as shown in Figure 3-6. Both the narrow and wide distributions have AAD = 1.59 in the top figure. Both distributions have CI = 2.00 in the middle figure. Both distributions have PD = PWL = 50 in the bottom figure. The problem with these three quality measures is that they could not distinguish between distributions that might reasonably be expected to produce markedly different levels of performance.

From the previous examples, it is seen that there are inherent mathematical inconsistencies in AAD that weaken its usefulness as a quality measure. The AAD is variably sensitive to both the shift of the mean away from the target value and the variability of the population itself. CI is somewhat more consistent than AAD; however, its weakness is that it can give the same CI value even though the combinations of mean and standard deviation are different. The PD/PWL was also found to have inconsistencies because it is insensitive to changes in variability around PD = PWL = 50, while performance may be sensitive to variability in that region (Weed, 1999).

3.9 Normal Distribution

As mentioned previously in this dissertation, test results of most highway quality characteristics are normally distributed. That is to say, if all the items in the lot were to be tested, the test results would be distributed among the possible values similar to the bell-shaped curve.

The main features of the normal distribution are a symmetrical distribution of readings on each side of the average. The relative height of the normal curve at its center depends on the value of σ. The curve is relatively tall and narrow if the σ is small. The curve becomes flatter and wider when the σ gets larger. The pattern of the frequency

δ Represents population spread within itself

Δ Represents shift of population away from target

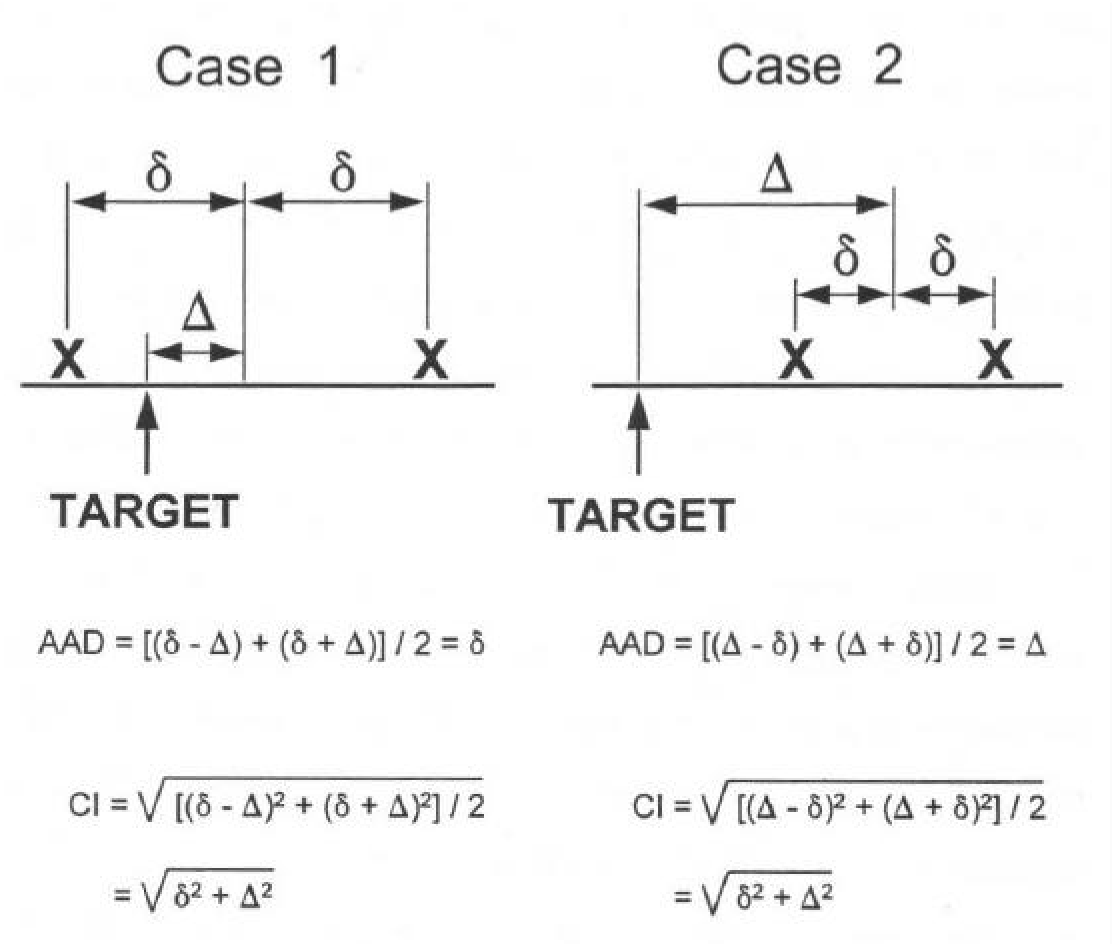


Figure 3-5. Comparison of Mathematical Properties of AAD and CI for Sample Size of n=2.

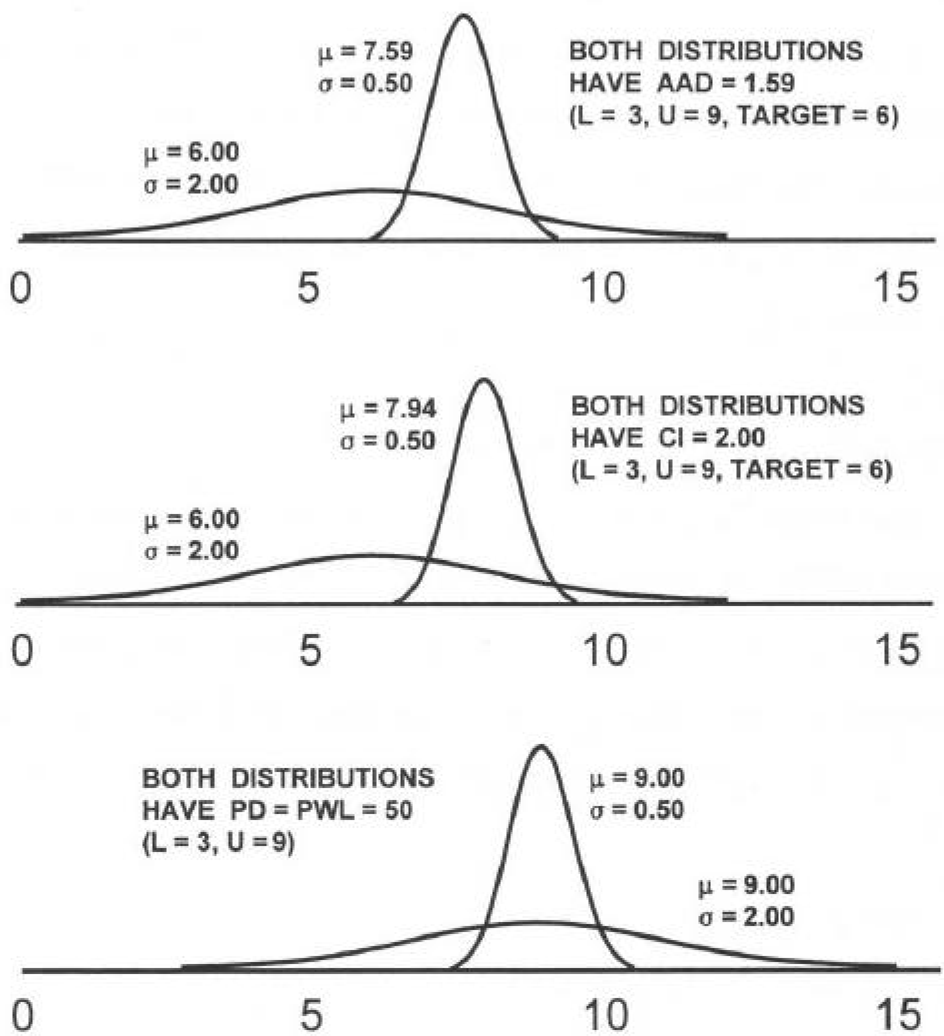


Figure 3-6. Potential Weaknesses of Common Statistical Measures of Quality

rates, as deviating from the average, should be noted in particular. The rate of decrease is slight when the values are near the average, and the rate of decrease is sharper when the values are farther from the average. Finally, the frequencies approach zero. The equation that can be used to calculate the height of this curve is:

$$y = \frac{1}{s\sqrt{2p}} e^{-\frac{(x-m)^2}{2s^2}} \tag{3.15}$$

It is assumed that the curve encloses all of the measured test results and the probability is 100 percent. With this assumption, a certain percentage of the area under the normal curve to each distance on the σ scale between the center of the curve and any selected point can be assigned. These percentages can be used to predict the future measured values that can be expected to fall between the two points.

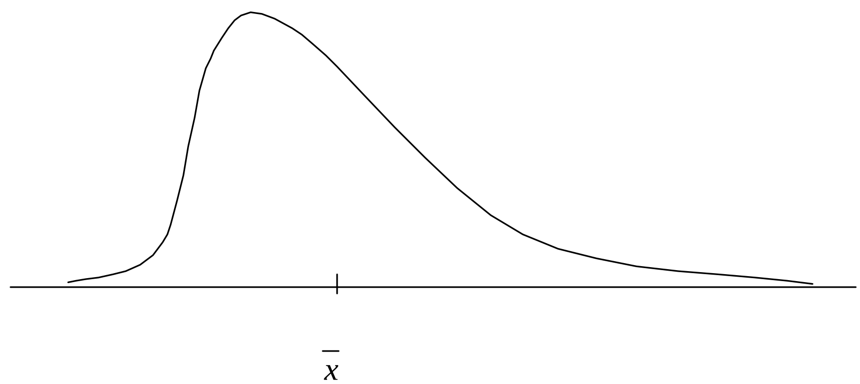
3.9.1 Skewed Distribution

In some cases, the distribution of some kinds of measurements is not symmetrical, meaning it does not have the same shape on both sides of the mean of the values. The unsymmetrical characteristic of the distribution is called skewness. If the distribution curve has a long tail on the right, then the distribution is positively skewed. On the other hand, if the long tail is on the left, the distribution is negatively skewed. Positive and negative skewed distributions are shown in Figure 3-7.

3.9.2 Distribution of Group Averages

An important theorem in statistics is the central limit theorem. The central limit theorem states that if a population has a finite variance σ^2 and a mean μ, then the distribution of the sample mean approaches the normal distribution with variance σ^2/n

a.) <u>Positively Skewed Distribution</u>



b.) <u>Negatively Skewed Distribution</u>

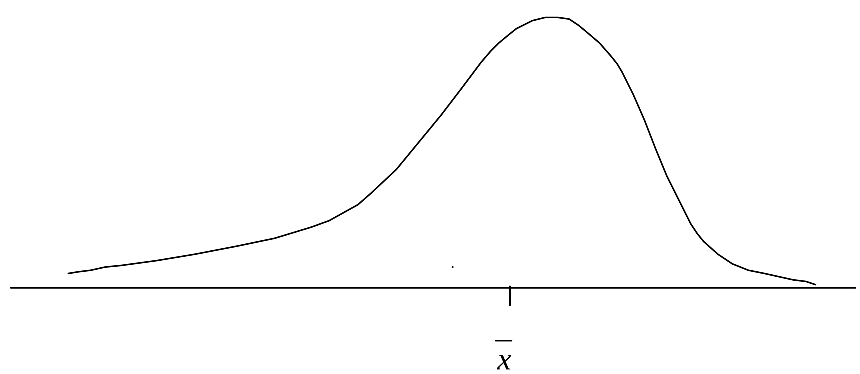


Figure 3-7. Types of Distribution

and mean μ, as the sample size increases. If the measured values are divided into groups in a random manner, the averages of these groups will form a histogram having nearly the same pattern as the normal curve. According to the central limit theorem, when the number of measured values in each group becomes larger, the shape of the histogram gets closer to that of the normal curve. The preceding statement is true even though the pattern of the individual measured values is skewed, rectangular shaped, triangle shaped, or shaped some other way. For this reason, the averages of small groups of measured values are sometimes used when basing inferences on the normal curve.

The size of the standard deviation is affected when using the averages of groups of measured values. The deviation for the distribution of the averages will be smaller than the deviation of individual measured values. The standard deviation of the averages of groups of measured values can be calculated from the deviation of the individual measured values divided by the square root of the number of values in each group as shown in the following equation:

$$S_{\bar{x}} = \frac{S}{\sqrt{n}} \tag{3.16}$$

3.10 Correcting the Bias of Sample Standard Deviation

Dr. Walter A. Shewhart, father of statistical quality control, simulated theoretical models by marking normal distribution numbers on chips, placing them in a bowl, and mixing them thoroughly. Each set of chips as different sized samples was drawn at random. In the long run, the standard deviations of samples of any size from a normal universe will follow a chance pattern that can be predicted by mathematics. These predicted numbers are used to correct the bias of sample standard deviation. The Shewhart's normal bowl played a vital role in the development of ideas and formulation of methods culminating in the Shewhart control charts (Grant and Leavenworth, 1980; Burr, 1976; American Society for Quality, 2000; National Institute of Standards and Technology, 2000).

When values of $(x - \overline{x})^2$ from samples are used to estimate universe dispersion, a source of difficulty is that the mean of the universe (μ) is unknown. Thus, the deviations that are squared must be measured from the sample average ($\overline{x}$) of each sample. $\sum_i (x_i - \overline{x})^2$ will be less than $\sum_i (x_i - m)^2$ except in the occasional case where the $\overline{x}$ happens to be identical with the unknown μ. Some compensation for this bias is, therefore, needed in any statistic based on $\sum_i (x_i - \overline{x})^2$ if the statistic is to be used to estimate the universe standard deviation ($\boldsymbol{s}$) or the universe variance ($\boldsymbol{s}^2$).

An unbiased $\boldsymbol{s}^2$ may be estimated from the sample variance (S^2) defined as follows:

$$S^2 = \frac{\sum_i (x_i - \overline{x})^2}{n - 1} \tag{3.17}$$

The use of $n - 1$ rather than n in the denominator tends to compensate for the bias created by measuring deviations from the sample average ($\overline{x}$) rather than from the unknown universe average (μ). Although S^2 gives an unbiased estimate of universe variance, S gives a biased estimate of universe standard deviation. The bias involved in the use of S may be fairly substantial where n is small (the usual condition in highway acceptance plans) (Duncan, 1974; Burr, 1976; Grant and Leavenworth, 1980; Vardeman and Jobe, 1999; Wadsworth et al., 1986).

In order to eliminate the biased estimate of universe standard deviation, *S* will be divided by a correction factor, which is equal to c_4 (The value of c_4 for subgroup sizes from 2 to 30 are given in Table A-1, Appendix A.). The corrected *S* value will give us an unbiased estimation of σ. Without this correction, the inherent bias in the use of *S* tends to give too low an estimate of σ (Duncan, 1974; Burr, 1976; Grant and Leavenworth, 1980; Vardeman and Jobe, 1999; Wadsworth et al., 1986). When the number of observations is more than 30, the correction factor is assumed equal to 1.

If samples are drawn randomly and independently from a normal population, then it can readily be proved that

$$\frac{(n-1)S^2}{\boldsymbol{s}^2} = \boldsymbol{c}^2 \qquad (3.18)$$

follows the $\boldsymbol{c}^2$ distribution with *n-1* degree of freedom. A proof may be found in any mathematical statistics book. The density function for this $\boldsymbol{c}^2$ variable is

$$f(\boldsymbol{c}^2) = \frac{(\boldsymbol{c}^2)^{[(n-1)/2]-1} e^{-\boldsymbol{c}^2/2}}{2^{(n-1)/2}\Gamma[(n-1)/2]} \qquad 0 < \boldsymbol{c}^2 < \infty$$

The gamma function in the denominator is used here to make the integral of $f(\boldsymbol{c}^2)$ from 0 to ∞ equal to 1. By definition, the value of

$$\Gamma(k) = \int_0^\infty w^{k-1} e^{-w}\, dw \qquad \text{k} > 0 \qquad (3.19)$$

depends upon the exponent k. In particular

$$\Gamma(1) = \int_0^\infty e^{-w} dw = -e^{-w} \Big]_0^\infty = 1 \tag{3.20}$$

A convenient recursion relation

$$\Gamma(k+1) = k\Gamma(k) \qquad\qquad \text{k} > 0 \tag{3.21}$$

is obtained by integration by parts:

$$\Gamma(k+1) = \int_0^\infty w^k e^{-w} dw \qquad\qquad u = w^k, dv = e^{-w} dw$$

$$du = kw^{k-1} dw, v = -e^{-w}$$

$$\Gamma(k+1) = -w^k e^{-w} \Big]_0^\infty + \int_0^\infty kw^{k-1} e^{-w} dw$$

$$= 0 + k\Gamma(k)$$

From the two relations mentioned above, taking k as any positive integer n

$$\Gamma(n) = (n-1)! \tag{3.22}$$

Therefore, the gamma function takes factorial values for positive integers and may be regarded as an interpolation formula between them.

In the c^2 distribution, $\Gamma(1/2)$ is proved to be $\sqrt{p}$. A sketch of the proof is as follows:

$$\Gamma(1/2) = \int_0^\infty w^{-1/2} e^{-w} dw > 0$$

Let $w = x^2$, $dw = 2xdx$

$$\Gamma(1/2) = \int_0^\infty 2e^{-x^2}\,dx$$

Since this cannot be evaluated directly, its square is estimated.

$$[\Gamma(1/2)]^2 = \int_0^\infty 2e^{-x^2}\,dx \int_0^\infty 2e^{-y^2}\,dy$$

$$= 4\int_0^\infty\int_0^\infty e^{-(x^2+y^2)}\,dxdy$$

Then, transforming to polar coordinates by

let $X = r \sin \theta$, $y = r \cos \theta$, $dxdy = r\,dr\,d\theta$, $x^2+y^2 = r^2$

The integral over the first quadrant becomes

$$[\Gamma(1/2)]^2 = 4\int_0^\infty\int_0^{\pi/2} re^{-r^2}\,dr\,d\theta$$

$$= \int_0^\infty e^{-r^2}\,2r\,dr \int_0^{\pi/2} d\theta$$

$$= 2[-e^{-r^2}]_0^\infty(\pi/2) = \pi$$

Since $\Gamma(1/2) > 0$

$\Gamma(1/2) = \sqrt{\pi}$ (3.23)

For the moments of S using (3.18), the density function χ^2 is as follows:

$$f(\chi^2)d\chi^2 = \frac{[\frac{(n-1)S^2}{\sigma^2}]^{(n-1)/2-1} e^{-\frac{(n-1)S^2}{2\sigma^2}}\, d\,\frac{(n-1)S^2}{\sigma^2}}{2^{(n-1)/2}\,\Gamma[(n-1)/2]}$$

Then, distributing the $2^{(n-1)/2}$ as needed, the expectation of S^i is :

$$E(S^i) = \int_0^\infty \frac{S^i \left[\frac{(n-1)S^2}{2\sigma^2}\right]^{(n-1)/2-1} e^{-\frac{(n-1)S^2}{2\sigma^2}} \, d\,\frac{(n-1)S^2}{2\sigma^2}}{\Gamma[(n-1)/2]}$$

Now let $w = \frac{(n-1)S^2}{2\sigma^2}$, $S = \sigma\sqrt{\frac{2w}{n-1}}$

$$E(S^i) = \int_0^\infty \frac{\sigma^i w^{(n-1+i)/2-1} 2^{i/2} e^{-w}}{\Gamma[(n-1)/2](n-1)^{i/2}} dw$$

and using (3.19)

$$E(S^i) = \frac{\sigma^i 2^{i/2} \Gamma[(n-1+i)/2]}{(n-1)^{i/2} \Gamma[(n-1)/2]} \qquad (3.24)$$

Taking i = 1, yields

$$E(S) = \mu_S = \sigma\sqrt{\frac{2}{n-1}} \frac{\Gamma(n/2)}{\Gamma[(n-1)/2]} = c_4 \sigma$$

Therefore,

$$c_4 = \sqrt{\frac{2}{n-1}} \frac{\Gamma(n/2)}{\Gamma[(n-1)/2]} \qquad (3.25)$$

For example, if n = 5, using (3.21)-(3.23)

$$c_4 = \sqrt{\frac{2}{5-1}} \frac{\Gamma(5/2)}{\Gamma(2)} = \frac{(3/2)(1/2)\sqrt{\pi}}{\sqrt{2}} = 0.9400$$

The objections for using s instead of s^2 in determining quality level that the contractors are providing are that a single large s^2 will have more effect on $\overline{s^2}$ than will the same sample s on $\bar{s}$. Moreover, the distribution of s^2 is far more unsymmetrical than that for s (Burr, 1976).

3.11 Combining Results of Observations

When pooling data, measured values should be separated into rational subgroups, and the average and the variance of each subgroup are calculated separately.

When standard deviations for two or more subgroups are pooled, it is assumed that they are estimates of a common true standard deviation. If the averages of subgroups are different, the standard deviation computed directly for an entire group of measured values will be larger than those computed separately for each group and then pooled. The weighted averages and the weighted variances may be combined to obtain pooled values $\overline{\overline{x_p}}$ and S_p^2 if the measured values in similar subgroups are homogeneous.

Since an average of a large subgroup of measured values is presumably more significant than the average of a small subgroup, it is usual practice to weigh each average $\bar{x}$ before the values are pooled. A weighted average of the averages can be obtained by multiplying each average by the number of measured values it represents. After that, sum these products and divide by the total number of measured values. The equation is

$$\overline{\overline{x_p}} = \frac{n_1 \overline{x_1} + n_2 \overline{x_2} + \ldots + n_k \overline{x_k}}{n_1 + n_2 + \ldots + n_k} \tag{3.26}$$

n_k = The number of measured values represented by $\overline{x_k}$

The pooled value of the standard deviations can be computed from the standard deviations of a number of independent samples. Each of the variances can be obtained by squaring the standard deviations. Next, each variance is multiplied by the corresponding number of degrees of freedom (n-1), where n is the number of measured values for which the standard deviation was computed. Finally, the summation of these products needs to be found and is to be divided by the total number of degrees of freedom to obtain a pooled value of the variance. The equation is

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2 + ... + (n_k - 1)S_k^2}{(n_1 - 1) + (n_2 - 1) + ... + (n_k - 1)} \qquad (3.27)$$

The pooled standard deviation S_p is the square root of the pooled variance (Hudson, 1971a).

3.12 Statistical Tests for Averages

A significant difference between the averages of two groups of values obtained by measurements on random samples can be determined by the t test. If the variance of the population is unknown, and we assume the population is normally distributed, then the sample variance S^2 is used to estimate σ^2. To compare the average ($\overline{x}$) of a small group measured with the grand average (m_0) of a very much larger group $(H_0 : m = m_0)$, the t test for a significant difference between the average is applied by using the equation (Hudson, 1972)

$$t_0 = \frac{\left|\bar{x} - m_0\right|\sqrt{n}}{S} \tag{3.19}$$

where

n = number of measured values in the small group

S = standard deviation for the very large group of measured values

If hypotheses are

$$H_0 : m = m_0$$
$$H_1 : m \neq m_0$$

the null hypothesis (H_0) would be rejected when $\left|t_0\right| > t_{a/2,n-1}$, where $t_{a/2,n-1}$ denotes the upper α/2 percentage point of the t distribution with ∞ degrees of freedom. If the null hypothesis is rejected, the averages of the very large group of measurements (μ_0) and the average of the small group of measurements ($\bar{x}$) are considered to be significantly different at the level α (Montgomery, 1997).

3.13 Tests for Variances

The F test is used to compare the variability of the data. The ratio of the two computed variances, S_1^2 and S_2^2 is used in this test. If the ratio is near one, it is assumed that the true variances are equal.

In practice, the computed ratio of the variances is compared with a tabular value of F. The size of this tabular value depends on the number of degrees of freedom in the numerator, the number of degrees of freedom in the denominator, and the probability of occurrence of a ratio not greater than the tabular value. In an F table, the number at the head of a column is the number of degrees of freedom in the numerator, while the numbers identifying the rows are the numbers of degrees of freedom in the denominator (Hudson, 1972).

If independent random samples of size n_1 and n_2 are taken from populations 1 and 2 respectively, then the test statistic for

$$H_0 : s_1^2 = s_2^2$$
$$H_1 : s_1^2 \neq s_2^2$$

is the ratio of the sample variances

$$F_0 = \frac{S_1^2}{S_2^2} \tag{3.25}$$

The reference distribution for F_0 is the F distribution with n_1-1 numerator degrees of freedom and n_2-1 denominator degrees of freedom. If $F_0 > F_{a/2, n_1-1, n_2-1}$, or if $F_0 < F_{1-(a/2), n_1-1, n_2-1}$, the null hypothesis would be rejected. $F_{a/2, n_1-1, n_2-1}$ and $F_{1-(a/2), n_1-1, n_2-1}$ denote the upper $\alpha/2$ and lower 1-($\alpha/2$) percentage points of the F distribution with n_1-1 and n_2-1 degrees of freedom. The upper and lower tail are related by (Montgomery, 1996)

$$F_{1-a, n_1, n_2} = \frac{1}{F_{a, n_2, n_1}} \tag{3.26}$$

where

ν = Degrees of freedom

3.14 Theory of Risk

Since a highway agency cannot test the entire lot of material or construction, the acceptance decision must be based on a small number of tests made on samples or made at selected locations. Whenever a decision is made to accept or reject a material or item of construction on the basis of a sample, there is a possibility of making an error. The computed average of test results ($\bar{x}$) from the small number of test samples will seldom or never be the same as the true mean (m) of the results of all possible tests that could have been made on an entire lot of material or construction. Since some variability always occurs in the test results, there is always a chance that a lot of good material will be rejected or a lot of poor material will be accepted.

There are two types of risks: seller's risk and buyer's risk.

1. Seller's risk or a Type I error is made when the engineer rejects acceptable material or construction. The risk associated with such an error is called the alpha (α) risk.
2. Buyer's risk or a Type II error is made when the engineer accepts rejectable material or construction. The risk associated with such an error is called beta (β) risk.

These two risks can never be entirely avoided; however, increasing the number of measurements can reduce them. Figure 3-8 shows the relationship between the type of error and its related risk (Duncan, 1974; Barker, 1994).

	Quality of the Lot	
Acceptance Decision	Good	Poor
Accept	Correct	Type II Error Buyer's Risk
Reject	Type I Error Seller's Risk	Correct

Figure 3-8. Risks Involved in Acceptance Decision

CHAPTER 4
DATA ANALYSIS

Data analysis was done in order to determine whether the FDOT's specifications were effective. The plan was to determine (1) what quality level the FDOT wanted, (2) what quality level it was specifying, and (3) what quality level it was getting. Only two quality characteristics of asphaltic concrete material were investigated--asphalt content and pavement density in terms of percent of the control strip density. The definition of the specification effectiveness in this dissertation is that what FDOT wants = what FDOT is specifying = what FDOT is getting.

The lot average, lot offset, lot average absolute deviation, within-lot and between-lot standard deviation and conformal index were all calculated and used to represent the quality the FDOT is getting.

4.1 Pavement Density

4.1.1 Historical Data

The historical data allowed the identity of the variation and the average capabilities by gathering a large number of samples from a variety of projects. In this dissertation, the statistic parameters were derived based on the data that were available in FDOT's Central Quality Recording (CQR) database, which began in 1991. The CQR database is a SAS (Statistical Analysis System) file.

The average pavement density test result of each lot was recorded in the CQR database. However, there was no individual density test result or information about sample size. The sample size that was used in density data analysis was estimated based on the assumption that the number of obtained samples per lot was equal to the required sample size in the FDOT construction specifications. The number of the sample size depends on the length of the pavement. The sample size increases when the pavement length increases.

As was noted in Chapter 2, the current density quality characteristic of the Florida road specifications for type S asphaltic concrete material specifies that the standard size of a lot is 1500m of any pass made by the paving train regardless of the width of the pass or the thickness of the course. A sublot is 300m or less. At the end of a production day when the completion of the lot is less than 1500m, it is considered a partial lot. If the partial lot length is 600m or less and a full-size lot from the same day is available, then the previous full-size lot is redefined to include this partial lot. The number of tests required is shown in Chapter 2, Table 2-1.

4.1.2 Test Method

The in-place pavement density test results of each course of asphalt mix construction in this study were determined by the nuclear gauge method. This test method is useful as a rapid nondestructive technique for determining the in-place density of compacted asphaltic concrete (Brown, 1990). With proper calibration and confirmation testing, this test method is suitable for quality control and acceptance (ASTM, 1993b). The nuclear gauge instrument uses the effects of Compton scattering and photoelectric absorption of gamma photons to measure the density of the pavement being tested. Both the source and the detectors are on the surface. A portion of the gamma photons passing into the pavement is scattered back to the detectors. Based on a count ratio between the number of counts detected in the pavement and the number of counts detected in a standard block of known density, the number of gamma photons detected by the gauge can be converted to density in kilograms per cubic meter. The brief procedures of this test method are as follow (ASTM, 1993b; FDOT, 1997):

1. Turn the instrument (Figure 4-1) on prior to use to allow it to stabilize and leave the power on during the testing day in order to provide more stable and consistent results.
2. Nuclear test devices are subject to long-term aging of the radioactive source, detectors, and electronic systems, which may alter the relationship between count rate and material density. Therefore, the apparatus may be standardized as the ratio of the measured count rate to a count rate made on a reference standard in order to offset this aging. The reference count rate should be of the same order of magnitude as the measured count rate over the useful density range of the apparatus. At the start of each day's work, the equipment should be standardized and a permanent record of these data retained.
3. Select a test location according to the specifications (Figure 4-2).
4. It is critical to maximize contact between the base of the instrument and the surface of the material under test.
5. Take a count for the normal measurement period (typically 4 minutes).

6. Determine the ratio of the reading to the standard count or the air-gap count. From this ratio and the calibration and adjustment data, determine the in-place density.

4.1.3 Selection of the data

The test results of type S asphaltic concrete material that were obtained by the nuclear gauge method were investigated in this dissertation. The data were further categorized into different sample sizes from 3 to 7.

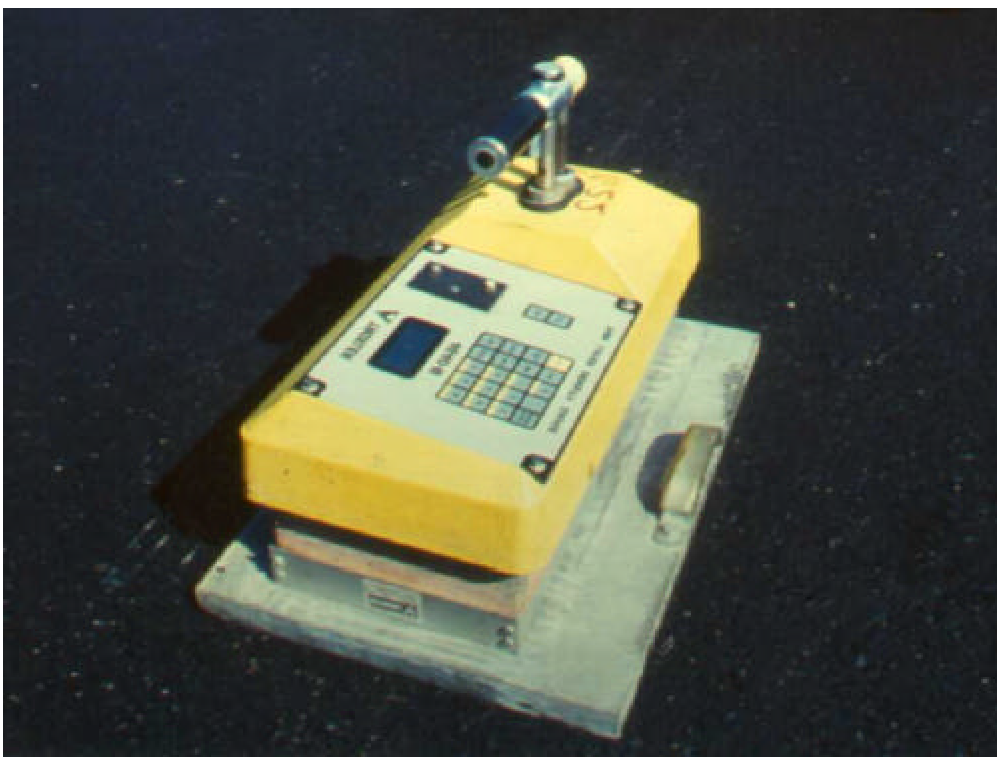


Figure 4-1. Nuclear Gauge Instrument (Obtained photo from Joint AASHTO-FHWA Industry Training Committee on Asphalt)

Figure 4-2. Select a Location and Take a Count for the Normal Measurement Period (Obtained photo from Joint AASHTO-FHWA Industry Training Committee on Asphalt)

Some of the data recorded in the CQR database were found to be in error. For example, the test results were less than 1 or more than 150 percent of the control strip. By engineering judgement, these numbers were considered as errors. Thus, some criteria need to be set to eliminate the errors and outliers of the test results in the database.

The PROC UNIVARIATE command in SAS software was used to check the errors and outliers in each group of different sample size of the pavement density data. Box plot was one of the outputs from this command that was used to eliminate errors and outliers.

A box plot is a graphical display of the measurements in a sample. The box plot attempts to highlight the sample's location and dispersion characteristics. Its purpose is to display the main distributional characteristics of a data set.

Three key components of a box plot are as follows (see Figure 4-3):

1. Box--The box contains 50 percent of the sample value which starts at the first sample quartile and ends at the third sample quartile.
2. Whisker--The two whiskers extend above and below the box up to the locations of the largest and smallest sample values that are within a distance of 1.5 times the interquartile range.
3. Outlier--The outliers are the sample values located outside the whiskers.

The box, which is represented by a rectangle in Figure 4-3, shows the relative location of the middle 50 percent of the values. An outlier is the value outside the whiskers because such a value occurs with a very small probability in random samples from normally distributed populations. The relative location of the median and the relative lengths of the whiskers are the indicators of the sample value symmetry. For ideal symmetrical data, a median is located at the center of the box, and the length of the two whiskers is equal. The difference between the upper and lower whisker lengths provides information about the difference between the lengths of the left and right tails of the sample frequency distribution. Each whisker extends up to 1.5 interquartile ranges from the end of the box. Values that are marked with 0 are the values between 1.5 and 3 interquartile ranges of the box. The values that are farther away are called outliers. The outliers indicate either that some values are not consistent with the rest of the data or that the sample has been selected from a population containing measurements with extreme values (relatively large or small values) (Cody and Smith, 1997; Schlotzhauer and Littell, 1997; Rao, 1998).

Figure 4-3 shows the box plot where the median is close to the center of the box but with unequal whisker lengths. The upper whisker is longer than the lower one, which indicates a higher concentration of data at the lower end. The two outliers are below the median, and none of them is above the median.

Figure 4-4 shows the box plot of density test result data for lots having a sample size = 3. The asterisk (*) in the box plot represents errors and outliers. Figure 4-4 shows that the highest test result is extreme, which is a value of 102500 and; therefore, should be eliminated. After all of the outliers and errors were deleted from the database that was separated into groups of different size (n= 3 to 7), the statistic parameters were calculated.

4.1.4 Determination of Statistical Parameters

The standard deviation of within-lot for pavement density characteristics could not be calculated because the individual test results were not recorded in the database. Since the calculation of between-lot standard deviation is based on the average test value of each lot, the assumption was that there was no difference in between-lot and within-lot test variation.

First, the data were separated into years 1991-1992, 1993-1994, 1995-1996, and 1997-1999. Next, the data in each period of time were further separated into different mix designs and projects. Second, the average and the standard deviation of the average values of lot density test results from the same mix design and project were calculated by using equations 4.1 and 4.2, respectively.

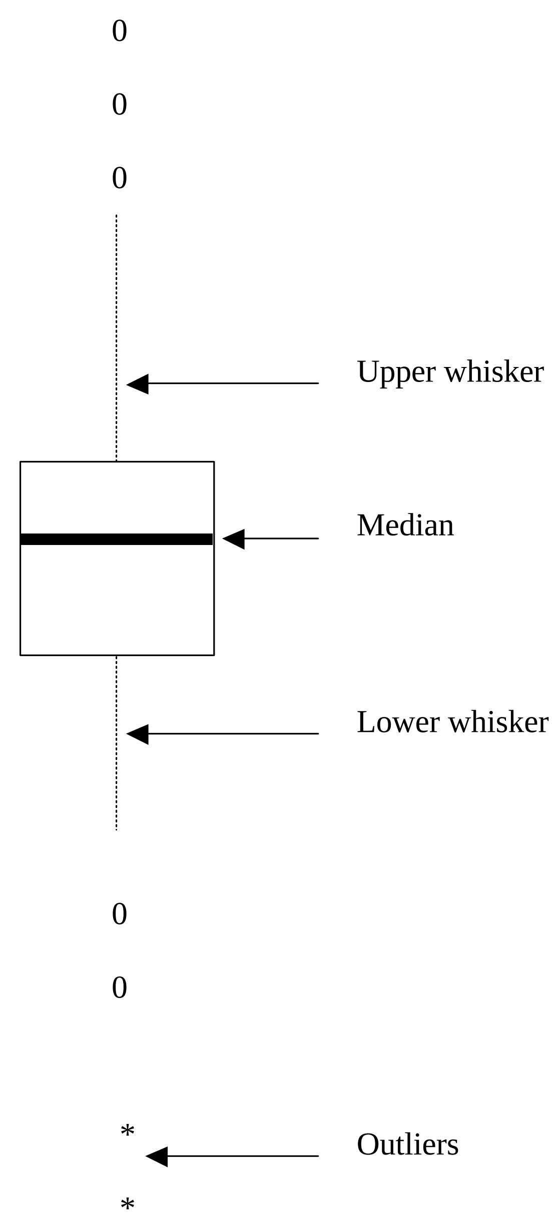


Figure 4-3. Box Plot Components

UNIVARIATE Procedure

Variable = Density (% of Control Strip)

```
                     Histogram                         #           Boxplot
102500+*                                               1              *
      .
 92500+
      .
 82500+
      .
 72500+
      .
 62500+
      .
 52500+
      .
 42500+
      .
 32500+
      .
 22500+
      .
 12500+*                                               3              *
      .*                                               2              *
  2500+************************************************ 17768      +--0--+
       ----+----+----+----+----+----+----+----+----+---
       * may represent up to 371 counts
```

Figure 4-4. Box-plot of the Density Test Results from PROC UNIVARIATE when Sample Size = 3, Asterisks under Box-plot Column show Errors and Outliers

$$\bar{x} = \frac{\sum_i x_i}{n} \tag{4.1}$$

$$S = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{(n-1)}} \tag{4.2}$$

Next, the pooled estimate of average and standard deviations by equations 4.3 and 4.4, respectively, were calculated.

$$\overline{\overline{x}}_p = \frac{n_1 \overline{x_1} + n_2 \overline{x_2} + \ldots + n_k \overline{x_k}}{n_1 + n_2 + \ldots + n_k} \tag{4.3}$$

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2 + \ldots + (n_k - 1)S_k^2}{(n_1 - 1) + (n_2 - 1) + \ldots + (n_k - 1)} \tag{4.4}$$

Finally, the pooled standard deviation at each sample size (n) was converted to the pooled standard deviation of the individual test result by multiplying by square root of the sample size (n).

$$S = S_{\bar{x}} * \sqrt{n} \tag{4.5}$$

Data analysis in this research assumes that the values in a data set are a sample from a normal distribution. In order to decide if this assumption is reasonable or not, the testing of normality was done. The procedure for testing of normality produces a test statistic for the null hypothesis that the input data values are a random sample from a normal distribution. The test statistic compares the shape of the sample distribution with the shape of a normal distribution. It is necessary to examine the probability (called P-value) associated with the test statistic to determine whether to reject the null hypothesis of normality. This probability is labeled PROB<W for the Shapiro-Wilk test or PROB>D for the Kolmogorov test. If the sample size is less than or equal to 2000, the Shapiro-Wilk statistic is computed. The P-value can range from 0 to 1. A P-value close to 0 means the idea is very doubtful and provides evidence against the idea. In this study, if the P-value is less than 0.10, then the null hypothesis is rejected, and it is concluded that the data do not come from a normal distribution (Cody and Smith, 1997; Delwiche and Slaughter, 1995; SAS Institute Inc., 1990; Schlotzhauer and Little, 1997).

The formal test for normality is obtained by specifying the NORMAL option in PROC UNIVARIATE in SAS software. This program shows one page of output. Figure 4-5 shows a portion of this page.

After the density test results were separated into groups of the same mix design and project, the normality test was done to verify the assumption that the average pavement density test results are normally distributed. If the P-value is less than 0.10, it is believed that the data do not come from a normal distribution and the null hypothesis is rejected.

4.1.5 Results and Discussions

From the test of normality, it was indicated that the average lot density test results of the same mix design and project were most likely normally distributed. As expected, the likelihood of normal distribution is greater for small groups (small number of lots) than for large groups extending over several days. From a total of 1662 same design and project groups containing a maximum of 10 lots, only 217 groups (13.06 percent) were not normally distributed. For groups containing more than 10 lots per group, 87 out of

UNIVARIATE Procedure

Variable = Density (% of Control Strip)

Moments

N	9	Sum Wgts	9
Mean	99.95556	Sum	899.6
Std Dev	0.608505	Variance	0.370278
Skewness	0.056887	Kurtosis	-0.1139
USS	89922.98	CSS	2.962222
CV	0.608775	Std Mean	0.202835
T:Mean=0	492.7928	Pr>|T|	0.0001
Num ^= 0	9	Num > 0	9
M(Sign)	4.5	Pr>=|M|	0.0039
Sgn Rank	22.5	Pr>=|S|	0.0039
W:Normal	0.988197	Pr<W	0.9915

Quantiles(Def=5)

100% Max	101	99%	101
75% Q3	100.3	95%	101
50% Med	100	90%	101
25% Q1	99.6	10%	99
0% Min	99	5%	99
		1%	99
Range	2		
Q3-Q1	0.7		
Mode	99		

Extremes

Lowest	Obs	Highest	Obs
99(	3)	100(	9)
99.3(	6)	100.2(	7)
99.6(	1)	100.3(	2)
99.8(	5)	100.4(	4)
100(	9)	101(	8)

Figure 4-5. Example of Testing for Normality of Density Data

244 groups (35.66 percent) were not normally distributed (Figure 4-6). The between-lot test results were mostly normally distributed. It was believed that the within-lot test results were normally distributed.

Florida construction specification for pavement density requires that the lot average value must be equal to or greater than 98 percent of control strip density to get full payment. There is no variation requirement.

Although FDOT's specification does not explicitly specify density variability, in one sense it encourages low variability. A contractor who can achieve low variability in density does not need to have a high mean density. On the other hand, however, because of variability not being explicitly specified, the specification can encourage higher variability. A contractor can increase mean density during compaction operations so that the sample average will be acceptable. One of the test results may be extremely low, while the other may be extremely high. If this is the case, the density specification is not working effectively (according to anybody's definition) and should be thoroughly revised. Both high and low density can cause premature failure to the pavement. High variability in density should be prevented. Every test result should be in the acceptable range and yield a suitable average value. Thus, the variability should be an important consideration in specifying the quality level for pavement density (e.g., adopt a PWL specification as recommended in AASHTO).

Typically, when developing quality assurance specifications, the highway agency wants that same quality level or just slightly higher be achieved that led to good performance in the past. Such a quality level specified is reasonable and results in satisfactory performance without increasing the cost of construction. Old records prior

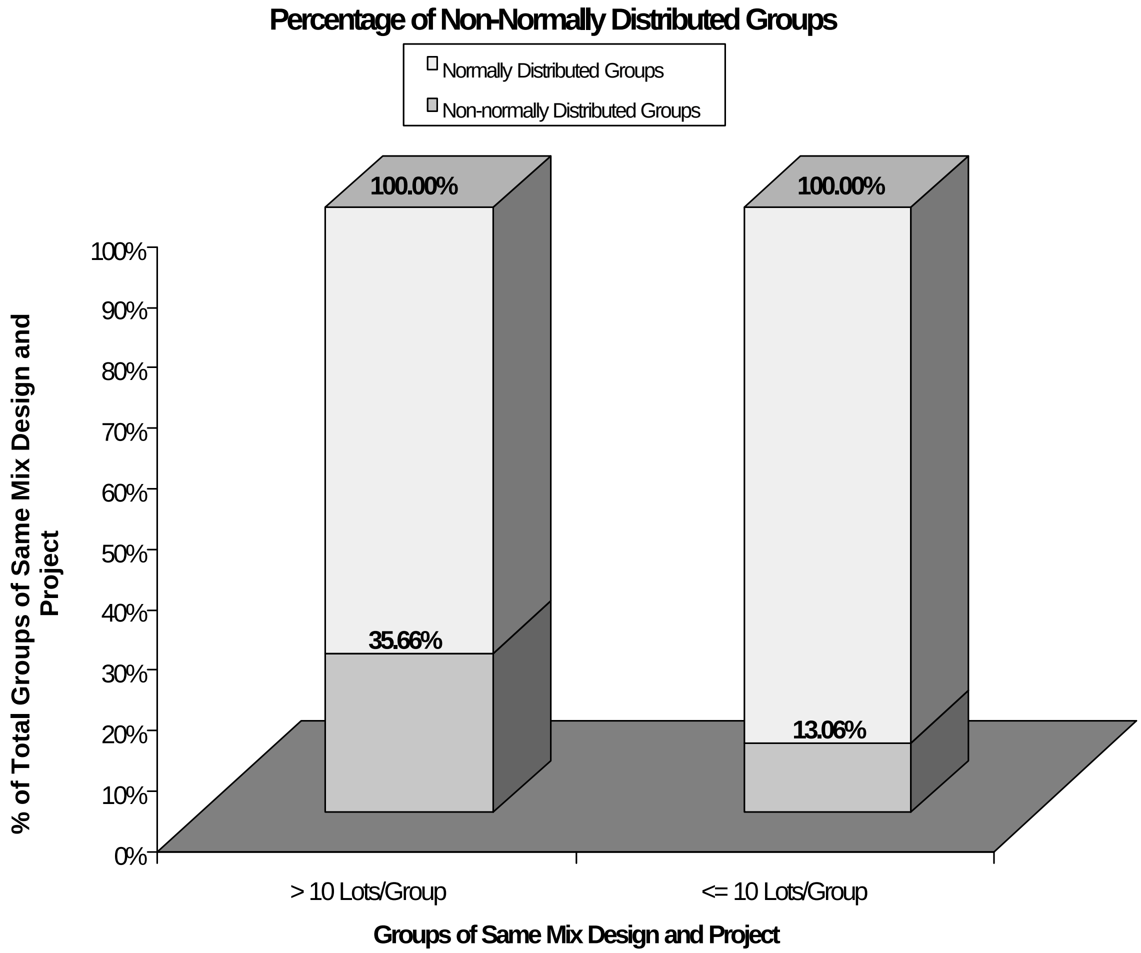


Figure 4-6. Percentage of Non-normally Distributed Groups of Same Mix Design and Project

to the development of FDOT's quality assurance specifications were few and inconclusive. The earliest accurate records of density quality level are in FDOT's CQR database, which began in 1991.

4.1.5.1 Overall Pavement Density Quality Level

Table 4-1 shows the summary of the standard deviation of density at different sample sizes in terms of percentage of the control strip density. The standard deviation of individual test results in Table 4-1 increases when the sample size increases up to n = 6, then decreases at n = 7. This is not what would be expected. An explanation of the increases may be that the sample size was determined based on the length of the lot that was recorded in the database. In the specification, the required sample size for acceptance depends on the pavement length, as mentioned in Chapter 2, Table 2-1.

Since the database does not contain the individual density test results, only the average value, the actual number of samples taken was not known. For example, when the specification specified sample size = 4, it is possible that only 3 samples were taken. Since the minimum allowable sample size for acceptance is 3, the standard deviation of the pavement density when the sample size is equal to 3 is believed to be the most reliable. Moreover, the number of lots was large enough to conclude that it could represent the estimated standard deviation of the population. Thus, the pooled standard deviation of 2.0 percent of control strip density was chosen to represent the estimation of typical standard deviation of between-lot density.

In order to provide a better estimation of quality the contractors are providing, it is recommended that the FDOT record individual test results of each lot, instead of average value in CQR database. With the recording of individual test results, the estimation of the density characteristic standard deviation of each lot can be done accurately.

Table 4-2 shows the average density of type S asphaltic concrete material at different sample sizes in terms of percentage of the control strip density. As mentioned previously, the average value of sample size equal to 3 is used to represent the typical average value of type S asphaltic concrete material. Therefore, the average value of the pavement density is 99.6 percent of control strip density.

4.1.5.2 Pavement Density Quality Level by Year

The type S asphaltic concrete data were further classified into different period of time to investigate if there is any improvement of the statistic parameters when the time changes. The data of pavement density test results from year 1991-1999 were separated into 4 groups. Each group has a 2 year-period, except the last group has a three year period (1997-1999). The standard deviation and the average of pavement density at 4 different period of time were calculated as shown in Table 4-3 to 4-10.

Some improvement in controlling the quality can be seen on year 1997-1999. The standard deviation in this time period is lower than other time periods.

4.1.5.3 Summary of Typical Pavement Density Quality

Table 4-11 shows the summary of the estimated pavement density quality, which is represented by between-lot standard deviation and the average value of pavement density (percent of control strip density) that was obtained from Table 4-1 to Table 4-10.

Table 4-1. Summary of Pooled Between-Lot Standard Deviation Density (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Std. Dev. Of the Average of Sample Size n (S)	Std. Dev. Of Individual Test Result (S' = S * SQRT of n)
3	11677	1.1279	1.9536
4	2911	1.0166	2.0332
5	2568	0.9279	2.0749
6	2065	0.9289	2.2752
7	1628	0.8137	2.1528

Table 4-2. Summary of the Average Value of Density (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Average of Sample Size (X)
3	11677	99.5694
4	2911	99.6300
5	2568	99.5768
6	2065	99.6346
7	1628	99.6101

Total Number of Lots = 20849

Table 4-3. Summary of Between-Lot Standard Deviation of Density by 1991-1992 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Std. Dev. of the Average of Sample Size n (S)	Std. Dev. Of Individual Test Result (S' = S * SQRT of n)
3	1605	1.1028	1.9100
4	414	0.9600	1.9200
5	332	0.8799	1.9674
6	243	0.7817	1.9148
7	198	0.8395	2.2211

Table 4-4. Summary of Between-Lot Standard Deviation of Density by 1993-1994 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Std. Dev. of the Average of Sample Size n (S)	Std. Dev. Of Individual Test Result (S' = S * SQRT of n)
3	4052	1.1370	1.9694
4	1064	1.0632	2.1263
5	1000	0.9312	2.0823
6	813	0.8993	2.2027
7	668	0.8393	2.2205

Table 4-5. Summary of Between-Lot Standard Deviation of Density by 1995-1996 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Std. Dev. of the Average of Sample Size n (S)	Std. Dev. Of Individual Test Result (S' = S * SQRT of n)
3	3875	1.1695	2.0256
4	1019	0.9617	1.9235
5	877	0.9555	2.1365
6	718	0.9966	2.4412
7	562	0.7808	2.0657

Table 4-6. Summary of Between-Lot Standard Deviation of Density by 1997-1999 (% of Control Strip Density)

Sample Size (n)	No. of Lots (N)	Std. Dev. of the Average of Sample Size n (S)	Std. Dev. Of Individual Test Result (S' = S * SQRT of n)
3	2145	1.0520	1.8220
4	414	1.0777	2.1555
5	359	0.8927	1.9962
6	291	0.9517	2.3312
7	200	0.7882	2.0855

Table 4-7. Summary of Average of Density by 1991-1992 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size n (X)
3	1605	99.6311
4	414	99.6458
5	332	99.5769
6	243	99.4831
7	198	99.4811

Table 4-8. Summary of Average of Density by 1993-1994 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size n (X)
3	4052	99.6255
4	1064	99.6185
5	1000	99.6089
6	813	99.7214
7	668	99.6549

Table 4-9. Summary of Average of Density by 1995-1996 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size n (X)
3	3875	99.4201
4	1019	99.6235
5	877	99.5111
6	718	99.5437
7	562	99.5318

Table 4-10. Summary of Average of Density by 1997-1999 (% of Control Strip)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size n (X)
3	2145	99.6871
4	414	99.6601
5	359	99.6480
6	291	99.7426
7	200	99.8077

Table 4-11. Estimation of Typical Pavement Density Quality

Material Type / Year	Standard Deviation	Average
Type S, Year 1991-1999	2.0%	99.6%
Type S, Year 1991-1992	1.9%	99.6%
Type S, Year 1993-1994	2.0%	99.6%
Type S, Year 1995-1996	2.0%	99.4%
Type S, Year 1997-1999	1.8%	99.7%

Since the sample size was large, it was believed that the density between-lot standard deviation in year 1997-1999 decreased significantly when comparing with in year 1991-1996. One of the reasons that could explain why the standard deviation is noticeably improved in year 1997-1999 is that there was an increased emphasis on training of inspectors on specification requirements. Before 1997 new control strips were not always constructed on projects where changes in materials characteristics had occurred. At that time, the inspectors did not carefully read the specifications and did not know there was a requirement to construct a new control strip when materials were changed. In 1997-1999, the inspectors understood the requirement, so that the variability of the pavement density as a percentage of control strip was reduced.

Compared with year 1991-1992, the standard deviation increased in years 1993-1994 and 1995-1996. After the training effort in 1996, data showed that the standard deviation decreased, and the average increased. This should support the idea that the density control (of mean and standard deviation) improved during 1997-1999 because of the training and indicates that the specification is not effective (at least according to the definition in this dissertation, since what was specified in 1991-1996 was the same as that specified in 1997-1999, but the delivered quality was different).

Although FDOT's specification does not explicitly specify density variability, the low variability is encouraged to minimize the cost to the contractor and to provide better quality to the buyer. If the FDOT were to adopt a density specification of the Percent Within Limit (PWL) type recommended in AASHTO's QA/QC 1996 Guide Specifications, it should be based on typical statistic parameters in years 1997-1999. It is anticipated that, upon use of such a PWL specification, the standard deviation of density in Florida would decrease even further.

4.1.5.4 Pay Factor

When the estimated quality level is not enough to get full payment, partial payment will be given to the contractor. According to FDOT Standard Specifications for Road and Bridge Construction 1999, the partial payment will be given for those lots that have an average density less than 98 percent of the control strip density based on the schedule in Table 4-12 (FDOT, 1999). The lot pay factors that were actually given to the contractors were recorded in CQR database.

The pay factor statistical parameters when sample size is equal to 3 were used to represent population pay factor statistical parameters. Table 4-13 shows a summary of the estimated statistical parameters of pavement density pay factor (percent) obtained from Tables 4-14 to 4-18. Table 4-14 shows a summary of average of density pay factor for material type S. Tables 4-15 to 4-18 show the summary of average density pay factor by year. Figure 4-7 shows the frequency plot of density pay factor by year when sample size = 3 in terms of percentage of total lots.

Tables 4-19 and 4-20 show the summary of percentage of lots with pay reduction obtained from CQR database and when based on 1999 specification. The pay factors based on specification were determined by comparing the lot pavement density with the payment schedule in FDOT's 1999 specification. If the average lot pavement density was less than 98 percent of the control strip, the reduction would be applied to the payment of that lot. The percentage of lots with pay reduction obtained from the database is always lower than when based on FDOT's 1999 specification.

Table 4-12. Density Payment Schedule Specified in FDOT Standard Specifications for Road and Bridge Construction 1999.

Payment Schedule for Density	
Percent of Control Strip Density	Percent of Payment
98.0 and above	100
97.0 to less than 98.0	95
96.0 to less than 97.0	90
Less than 96.0	75

Table 4-13. Summary of the Estimated Pavement Density Pay Factor (Percent)

Material Type / Year	Pay Factor Average
Type S, Year 1991-1999	99.7%
Type S, Year 1991-1992	99.7%
Type S, Year 1993-1994	99.6%
Type S, Year 1995-1996	99.7%
Type S, Year 1997-1999	99.8%

Table 4-14. Summary of Average of Pavement Density Pay Factor (Percent)

Sample Size (n)	No. of Lots (N)	Average of Sample Size (X)
3	15894	99.689839
4	3697	99.673303
5	3358	99.737165
6	2751	99.795202
7	2206	99.747552

Total Number of Lots = 27906

Table 4-15. Summary of the Pavement Density Pay Factor for Year 1991-1992 (Percent)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size (X)
3	1719	99.687027
4	491	99.743381
5	419	99.782816
6	333	99.874775
7	269	99.535316

Total Number of Lots = 3231

Table 4-16. Summary of the Pavement Density Pay Factor for Year 1993-1994 (Percent)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size (X)
3	5272	99.609067
4	1338	99.517937
5	1267	99.699290
6	1063	99.783631
7	872	99.805046

Total Number of Lots = 9812

Table 4-17. Summary of the Pavement Density Pay Factor for Year 1995-1996 (Percent)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size (X)
3	5674	99.697462
4	1297	99.697918
5	1171	99.721947
6	957	99.722675
7	742	99.727898

Total Number of Lots = 9841

Table 4-18. Summary of the Pavement Density Pay Factor for Year 1997-1999 (Percent)

Sample Size (n)	No. of Lots (N)	Average of the Sample Size (X)
3	3223	99.809463
4	568	99.920775
5	500	99.830000
6	398	99.933920
7	322	99.813665

Total Number of Lots = 5011

Table 4-19. Summary of Percentage of Lots with Pay Reduction obtained from Database and based on FDOT's 1999 Specification

Sample Size (n)	Percentage of Lots with Pay Reduction from Database	Percentage of Lots with Pay Reduction based on 1999 Specification
3	3.2%	4.6%
4	3.4%	3.6%
5	3.3%	3.5%
6	2.5%	2.8%
7	3.0%	3.3%

Table 4-20. Summary of Percentage of Lots with Pay Reduction when Sample Size = 3

Material Type/Year	Percentage of Lots with Pay Reduction from Database	Percentage of Lots with Pay Reduction based on 1999 Specification
Type S, 1991-1999	3.2%	4.6%
Type S, 1991-1992	3.4%	4.7%
Type S, 1993-1994	3.8%	5.1%
Type S, 1995-1996	3.3%	4.7%
Type S, 1997-1999	2.0%	3.3%

It is recommended that FDOT needs to enter individual density test results, not just the average value of each lot. If individual test results of each lot were recorded, the assumption of no difference between the within-lot and between-lot variation could be eliminated. It is expected that the within-lot variation is less than between-lot variation. The between-lot standard deviation could be more accurately determined by determining directly from the available data. Moreover, the within-lot standard deviation could be determined when the individual test results are known.

According to the FDOT's 1999 specifications, the acceptance test results criteria of pavement density are the same no matter what sample sizes are taken (a lot average density 98% or above of control strip). It is important also to understand that the numerical values used to identify the desired population are not the same as those numerical values used to determine whether sample test results are acceptable. To illustrate this idea, assume that FDOT wants the density quality level at the same quality level that the contractors produce (mean = 99.6% of control strip density, between-lot standard deviation = 1.8%).

Figure 4-7. Frequency Plot of Density Pay Factor by Year when Sample Size = 3

The sample average value is obtained by the following equation:

$$x = m - z\left(\frac{s}{\sqrt{n}}\right) \tag{4.7}$$

For example, if the highway agency wants an acceptance probability of 95% (z = 1.65), the sample average value for n = 3 can be estimated as follow:

$$x = 99.6 - 1.65 * \left(\frac{1.8}{\sqrt{3}}\right)$$

$$x = 97.9\%$$

By using equation 4.7, the sample average values at different n if the highway agency wants an acceptance probability of 95% are as follows:

For n = 3, a specified sample mean must be > 97.9 percent;

For n = 4, a specified sample mean must be > 98.1 percent;

For n = 5, a specified sample mean must be > 98.3 percent;

For n = 6, a specified sample mean must be > 98.4 percent;

For n = 7, a specified sample mean must be > 98.5 percent.

4.1.6 Questionnaire Responses for Density Quality Level

A questionnaire survey was conducted under this research. The purpose was to shed more light on what quality level FDOT wants, what quality level contractors interpret FDOT to want, and what quality level contractors think they are capable of achieving in terms of population mean and standard deviation. There were two different forms of questionnaires. The first set of questionnaires (Appendix B) was mailed to fifteen selected FDOT personnel and the other set (Appendix C) was mailed to fifteen selected contractor personnel. The selected FDOT and contractor personnel were engineers or technicians who were familiar with asphaltic concrete material and its specifications, and who had some statistical background. There were seven responses from FDOT and five responses from contractor personnel. Even though the specifications did not specify the quality level desired in terms of mean and standard deviation, it is expected that the FDOT and contractor personnel use their intuition and past experience to provide the answers to the questions.

Figure 4-8 and 4-9 show the results of the questionnaire survey for density quality mean and standard deviation, respectively. Most of the responses indicated that a minimum quality level, according to the specifications, for which FDOT is willing to give full payment is at the mean value of 98 percent of the control strip. However, the answers for the density standard deviation were inconclusive because several of the respondents stated that they did not know what the allowable standard deviation is. Furthermore, the responses from the FDOT personnel as well as the contractors are inconsistent because they provided various values in their answers. Half of the FDOT respondents believed that the minimum specified density quality level to get full payment should be tightened; however, most of the contractors believed that the specified quality should be left as is (Figure 4-10).

4.2 Asphalt Content

4.2.1 Historical Data

Acceptance test results of asphalt content, which were tested by an extraction method, have been recorded in CQR since 1991. However, the job mix formulas which

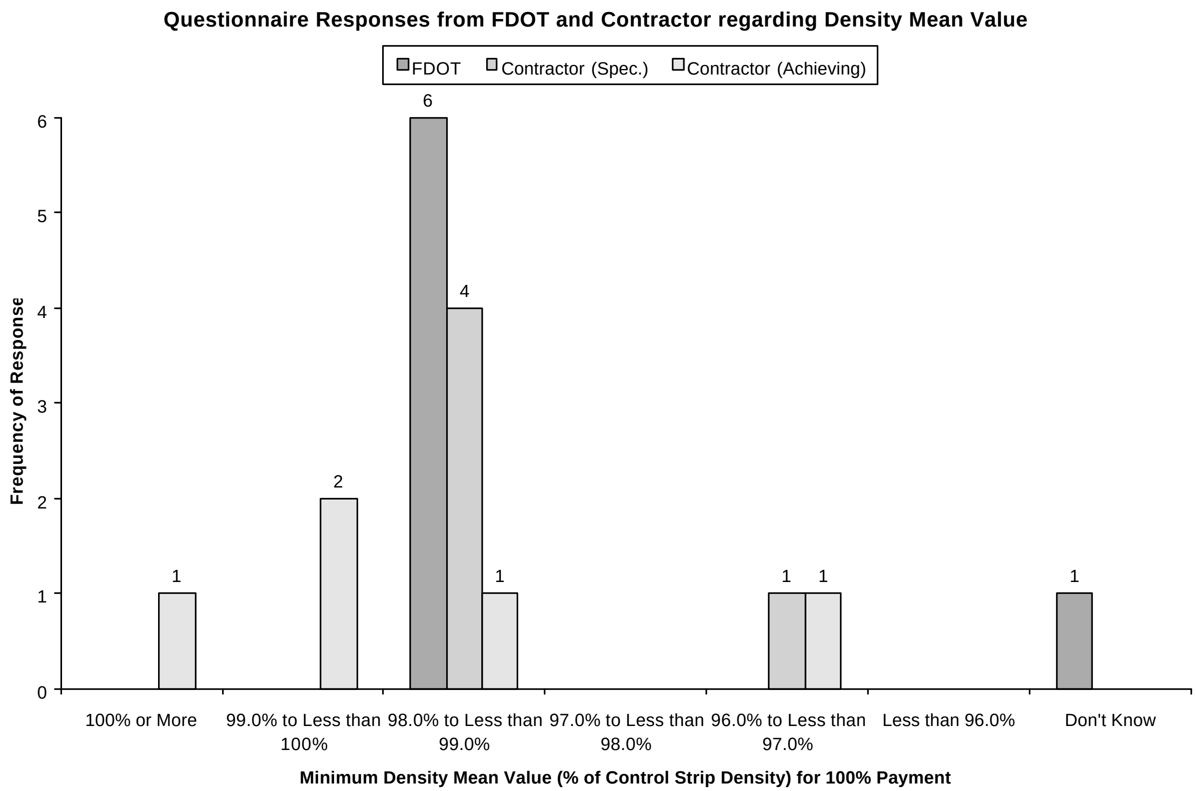


Figure 4-8. Questionnaire Responses from FDOT and Contractor Personnel Regarding Density Mean Value

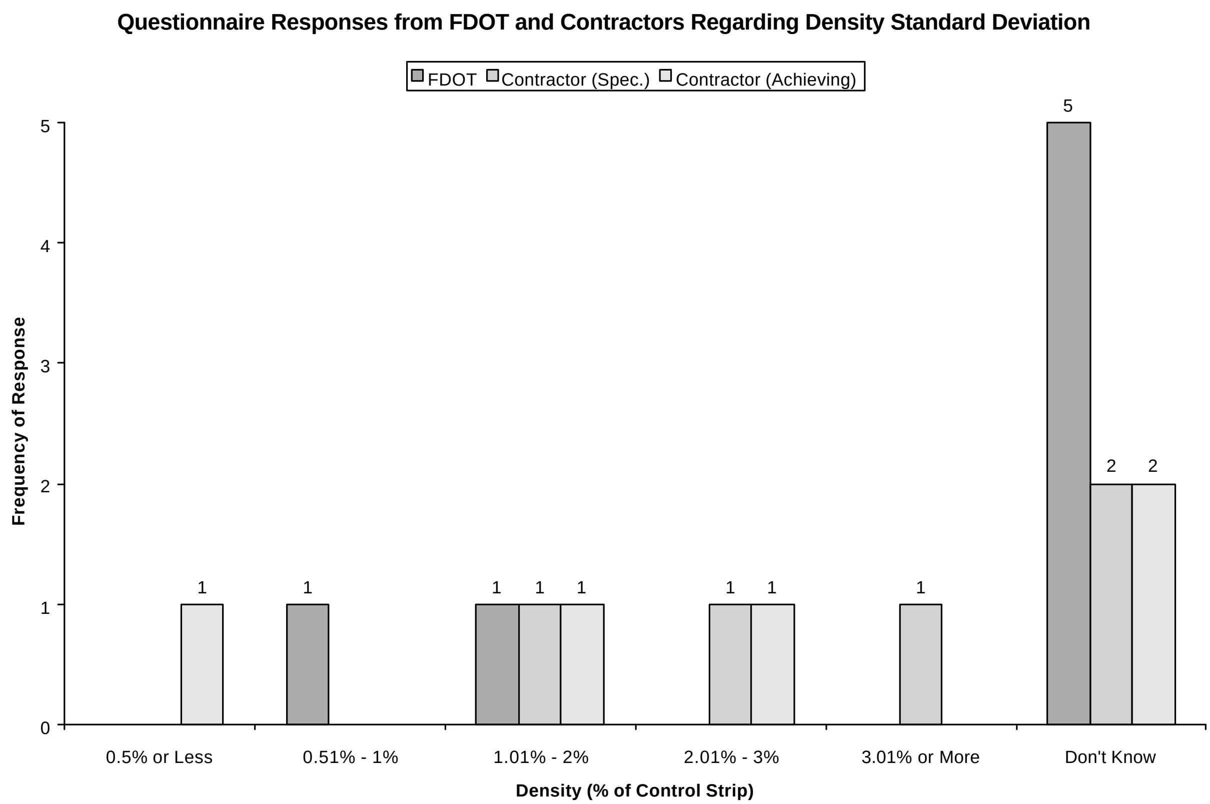


Figure 4-9. Questionnaire Responses from FDOT and Contractor Personnel Regarding Density Standard Deviation

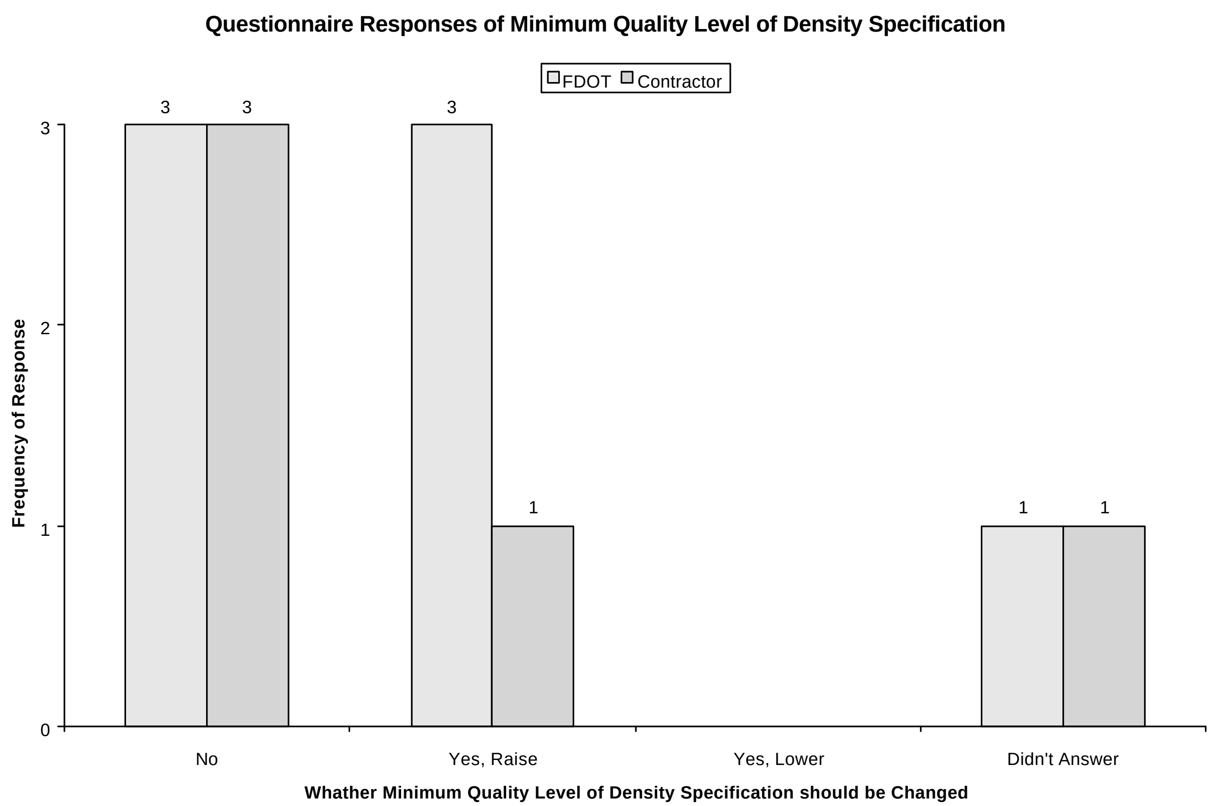


Figure 4-10. Questionnaire Responses from FDOT and Contractor Personnel Regarding Minimum Quality Level of Density Specification

vary from mix to mix have been kept separately in another system. Recording of the asphalt content target values of mix designs in the computer system was first started in 1993. In order to obtain meaningful statistical parameters of asphalt content data from combined mixes, the difference between target and measured asphalt content must be the analysis variable rather than the measured asphalt content. Therefore, the earliest asphalt content data that were used in the analysis are from 1993.

A standard size lot for asphalt content acceptance at the asphalt plant consists of 3600 metric tons with four equal sublots of 900 metric tons each. If the partial lot contains one or two sublots, this partial lot is included to the previous full-size lot from the same day (if available), and the evaluation is based on either five or six sublot determinations. When the total quantity of the mix is less than 2700 metric tons, the engineer will evaluate the partial lot for the appropriate number of sublots from n = 1 to n = 3 (FDOT, 1999).

4.2.2 Test Method

The asphalt content test results of asphaltic concrete in this study are determined by the extraction method. This test method is used for quantitative determinations of asphalt in asphaltic concrete paving mixtures for specification acceptance. The summaries of this test method are as follows (ASTM, 1993a; FDOT, 1992):

1. The asphalt is extracted from the paving mixture with trichlorethylene, 1,1,1-trichloroethane or methylene chloride using the extraction equipment. (Figure 4-11 and 4-12)

Figure 4-11. The Test Portion is Placed into a Bowl

Figure 4-12. The Extraction Equipment Extracts the Asphalt from the Paving Mixture

2. The asphalt content is calculated by the difference between the mass of the paving mixture before and after asphalt extraction, taking into account mineral matter in the extract.
3. The asphalt content is expressed as mass percent of moisture-free mixtures.

4.2.3 Selection of the Data

Due to the large amount of the data that was recorded in the CQR system, the data were separated into different project numbers by using the SAS software. Projects that had a file size bigger than 45KB were selected. The test results and the designed asphalt content of the selected projects were input into the Excel spreadsheet. The data were organized into six different groups due to the acceptance sample size per lot, from n = 1 to n = 6.

4.2.4 Determination of Statistical Parameters

In order to evaluate the effectiveness of the asphalt content specification, the statistic parameters of within-lot and between-lot of asphalt content characteristic needs to be determined.

In order to estimate the typical within-lot statistical parameters, first, the average of offset from job mix formula (JMF), standard deviation (S), average absolute deviation (AAD) of each lot, and conformal index (CI) were estimated by using equations 4-8 to 4-11, respectively.

$$AverageOffsetFromJMF = \frac{\left|\sum_i (x_i - JMF)\right|}{n} \tag{4.8}$$

$$S = \sqrt{\frac{\sum_i (x_i - \overline{x})^2}{n-1}} \tag{4.9}$$

$$AAD = \frac{\sum_i |x_i - JMF|}{n} \tag{4.10}$$

$$CI = \sqrt{\frac{\sum_i (x_i - JMF)^2}{n}} \tag{4.11}$$

Next, the characteristic statistical parameters of all lots at each sample size were estimated. To illustrate, Tables 4-21 through 4-25 are presented the examples.

Table 4-21 shows an example of the estimation of average within-lot offset of all lots when the sample size = 3. First, the within-lot offset of each lot was estimated by using equation 4.8. Next, the average of all lots was determined. This average value represents the characteristic within-lot offset when sample size = 3. The value of offset depends on number of samples per lot. The offset increases when the sample size increases.

Table 4-22 shows an example of the estimation of average within-lot standard deviation of all lots. The within-lot standard deviation, which is a biased estimate of universe within-lot standard deviation, was firstly estimated by using equation 4.9. Then, it was divided by the correction factor (mentioned in Chapter 3) to provide an unbiased estimate of universe within-lot standard deviation. At each sample size, the characteristic within-lot standard deviation was estimated from the average of all lots of an unbiased estimate of universe within-lot standard deviation.

Table 4-23 shows an example of the estimation of pooled within-lot standard deviation of all lots. First, the S^2 of each lot was calculated by using equation 4.9. Then, the average S^2 of all lots in each sample size was calculated. Finally, the square root of average S^2 was determined.

Table 4-24 shows an example of the estimation of the average of within-lot average absolute deviation (AAD) of all lots when n = 3. First, the within-lot AAD was estimated by using equation 4.10. Next, the average of within-lot AAD of all lots was determined.

Table 4-25 shows the example of estimation procedure of the characteristic within-lot CI at each sample size. First, the CI^2 of each lot was calculated by using equation 4.11. Then, the average CI^2 of all lots in each sample size was calculated. Finally, the square root of average CI^2 was determined to represent the characteristic within-lot CI at each sample size.

Table 4-21. Example of Estimation of Average within-lot Offset of all Lots when n = 3

Lot No.	Designed %AC	Test Result of Sublot1	Test Result of Sublot2	Test Result of Sublot3	Within-lot Offset
Lot 1	6.0	5.70	5.90	6.10	0.10
Lot 2	5.5	5.67	5.79	5.49	0.15
⋮	⋮	⋮	⋮	⋮	⋮
Lot N	5.7	5.51	5.60	5.72	0.09
Average of all lots					0.11

Table 4-22. Example of Estimation of an Unbiased Universe within-lot Standard Deviation of all Lots when n = 3

Lot No.	Designed %AC	Sub-lot1	Sub-lot2	Sub-lot3	Biased Within-lot *S*	Correct-ion Factor	Unbiased Within-lot *S*
1	6.0	5.70	5.90	6.10	0.2000	0.8862	0.2257
2	5.5	5.67	5.79	5.49	0.1510	0.8862	0.1704
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
N	5.7	5.51	5.60	5.72	0.1054	0.8862	0.1189
Average of all lots							0.2121

Table 4-23. Example of Estimation of a Pooled within-lot Standard Deviation of all Lots when n = 3

Lot No.	Designed %AC	Sub-lot1	Sub-lot2	Sub-lot3	Within-lot *S*	Within-lot S^2
1	6.0	5.70	5.90	6.10	0.2000	0.2257
2	5.5	5.67	5.79	5.49	0.1510	0.1704
⋮	⋮	⋮	⋮	⋮	⋮	⋮
N	5.7	5.51	5.60	5.72	0.1054	0.1189
Average S^2 of all Lots when n=3						
Characteristic within-lot S when n=3						0.22

Table 4-24. Example of the Estimation of the Average of within-lot AAD when n = 3

Lot No.	Designed %AC	Test Result of Sublot1	Test Result of Sublot2	Test Result of Sublot3	Within-lot AAD
Lot 1	6	5.70	5.90	6.10	0.1667
Lot 2	5.5	5.67	5.79	5.49	0.1567
⋮	⋮	⋮	⋮	⋮	
Lot N	5.7	5.51	5.60	5.72	0.1033
Average of all lots					0.2214

Table 4-25. Example of Estimation of the Characteristic within-lot Conformal Index of all Lots when n = 3

Lot No.	Designed %AC	Test Result of Sublot1	Test Result of Sublot2	Test Result of Sublot3	CI^2
1	6.0	5.70	5.90	6.10	0.0367
2	5.5	5.67	5.79	5.49	0.0377
⋮	⋮	⋮	⋮	⋮	⋮
N	5.7	5.51	5.60	5.72	0.0155
Average CI^2 of all Lots when n=3					0.0917
Characteristic within-lot CI when n=3					0.3028

To estimate between-lot statistical parameters, the data were divided into projects. Next, the average of offset from job mix formula (JMF), conformal index (CI), and standard deviation of the differences from JMF of each project were calculated by using equations 4.8 to 4.11, respectively. Finally, the pooled estimations of these statistical parameters were estimated.

Since data analysis in this research assumes that the values in a data set are a sample from a normal distribution, therefore the testing of normality was done to decide whether this assumption is reasonable. The test for normality was obtained by specifying the NORMAL option in PROC UNIVARIATE command in SAS software as mentioned in the pavement density section. The null hypothesis of this test is that the samples came from the normal distribution.

For the asphalt content, the differences of test results from job mix formula were separated into groups by project. The normality test of each group was done and the null hypothesis is rejected if the P-value is less than 0.10.

4.2.5 Results and Discussion

From the test of normality, it was indicated that the asphalt content test results of the within-same project groups of lots indicate most groups were normally distributed. The percentage of groups that were normally distributed is greater for small groups (small number of sublots) than for large groups extending over several days (Figure 4-13). Of 53 same-project group containing of equal to or less than 10 sublots, 7 (13.21 percent) projects were not normally distributed. Of 30 same-project group containing of more than 10 sublots but equal to or less than 20 sublots, 9 (30 percent) projects did not come from normal distribution. Of 23 same-project group containing of more than 20 sublots but less than 30 sublots, 7 (30.43 percent) projects were not normally distributed. For same-project group combining of more than 30 sublots in each group, the null hypothesis was rejected for only 4 out of 20 (20 percent) groups. Since within-same project was likely normally distributed, it was believed that within-lot test results were also normally distributed.

The AAD is used to specify quality level in FDOT Standard Specifications for Road and Bridge Construction 1999. Little knowledge exists regarding how FDOT develop the specified AAD quality level for asphalt content. A computer simulation program was developed for this research to use as a tool to relate the population mean and standard deviation to the AAD quality being specified.

A total of 1126 lots from 133 highway projects all over Florida were considered in determining within-lot and between-lot quality level of asphalt content.

4.2.5.1 Overall Within-lot Asphalt Content Quality Level

The within-lot standard deviations of the difference from JMF for sample size 2 to 5 are shown graphically in Figures 4-14 through 4-17, respectively.

In Figure 4-15 and 4-16, there is one lot in each that has extreme standard deviation value. After investigation into the raw data of these two lots, it was found that one of the test results in each lot had remarkably difference from the other test results in the same lot. These extreme values might occur because of the error during input of data or error in testing results. Therefore, these two lots were eliminated from the database before determining their statistical parameters. Next, the average of unbiased standard deviation, median unbiased standard deviation, and pooled standard deviation of each sample size was determined. After that, the characteristic population standard deviation

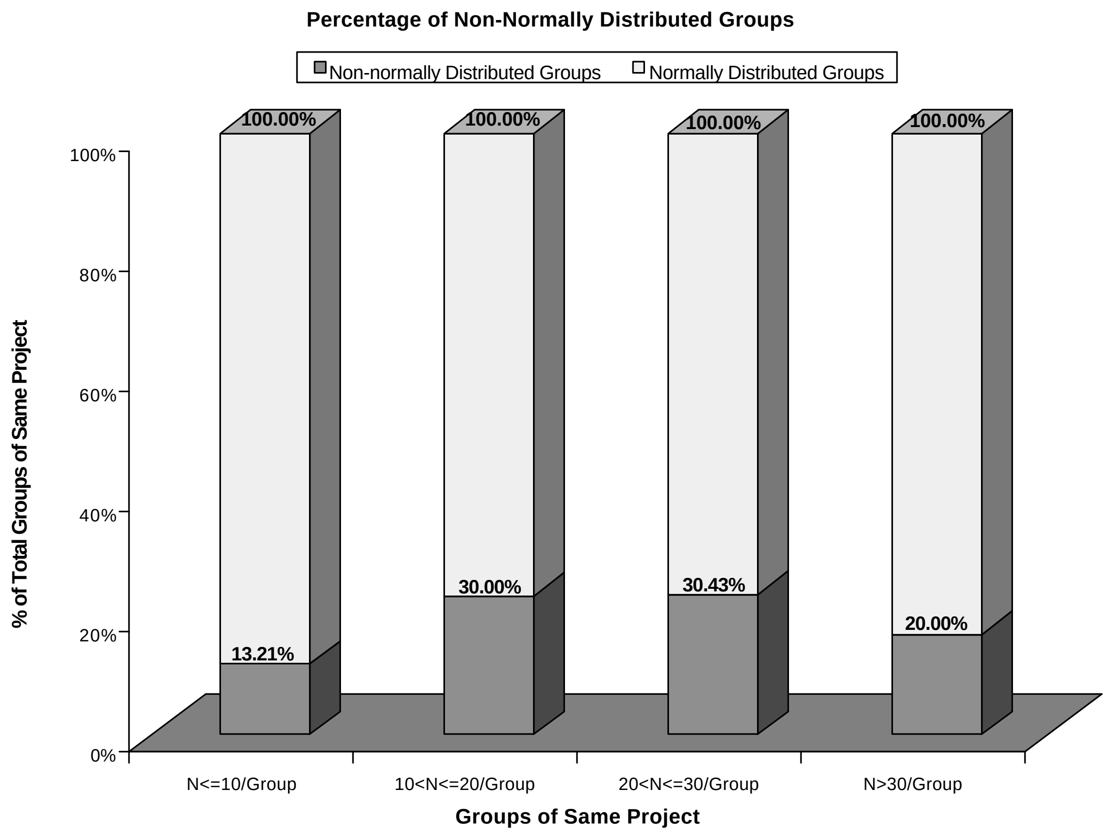


Figure 4-13. Percentage of Non-normally Distributed Groups of Same Project (N = Number of Lots)

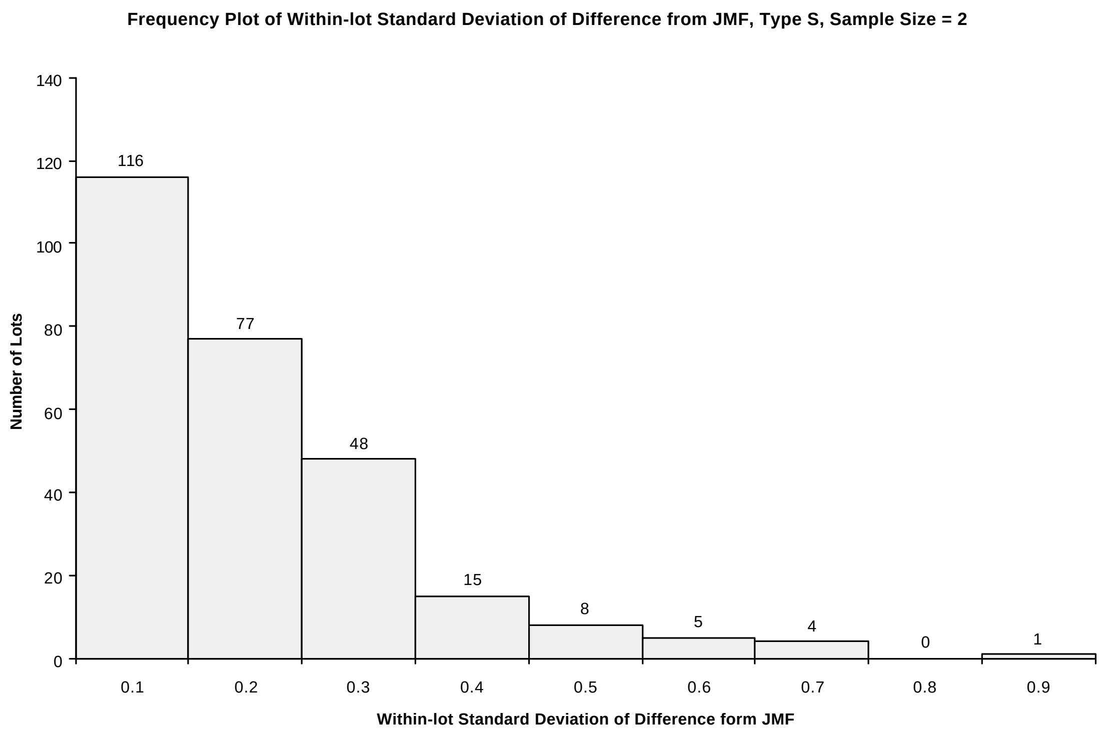


Figure 4-14. Summary Histogram for within-lot Standard Deviations of the Difference from JMF when Sample Size = 2

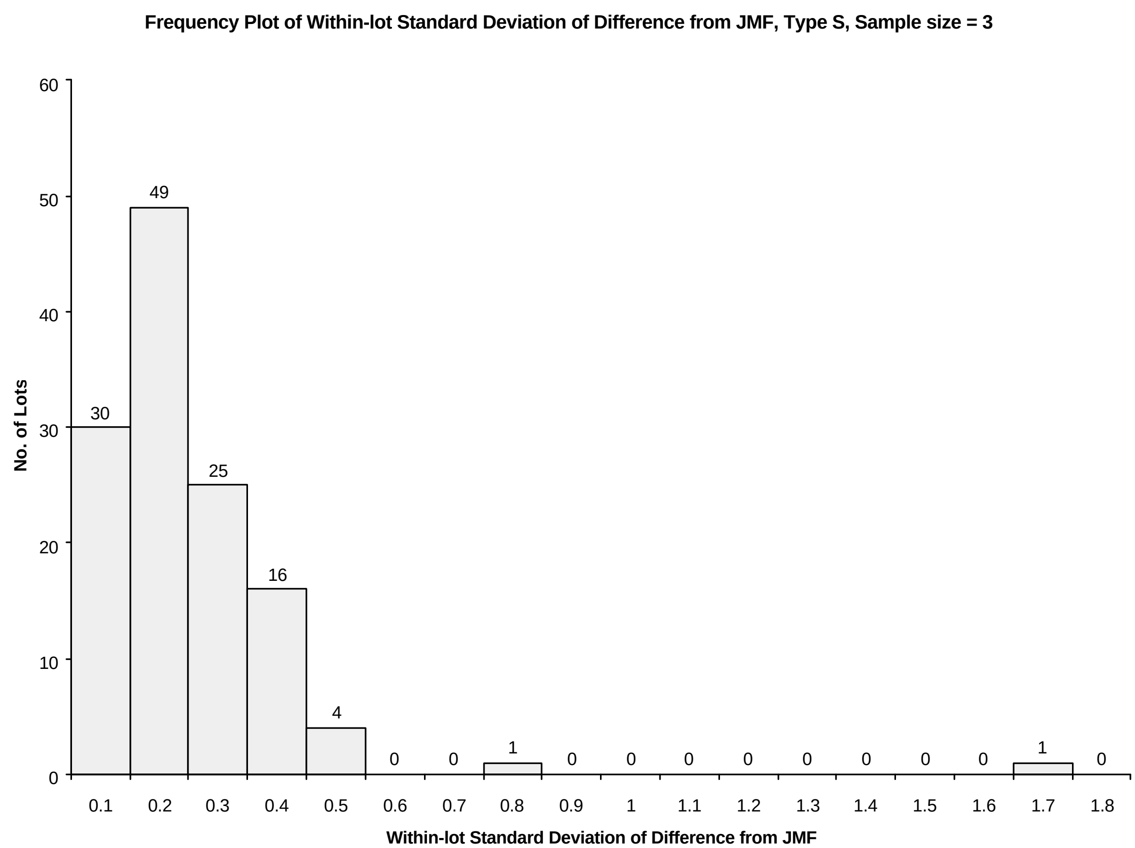


Figure 4-15. Summary Histogram for within-lot Standard Deviations of the Difference from JMF when Sample Size = 3

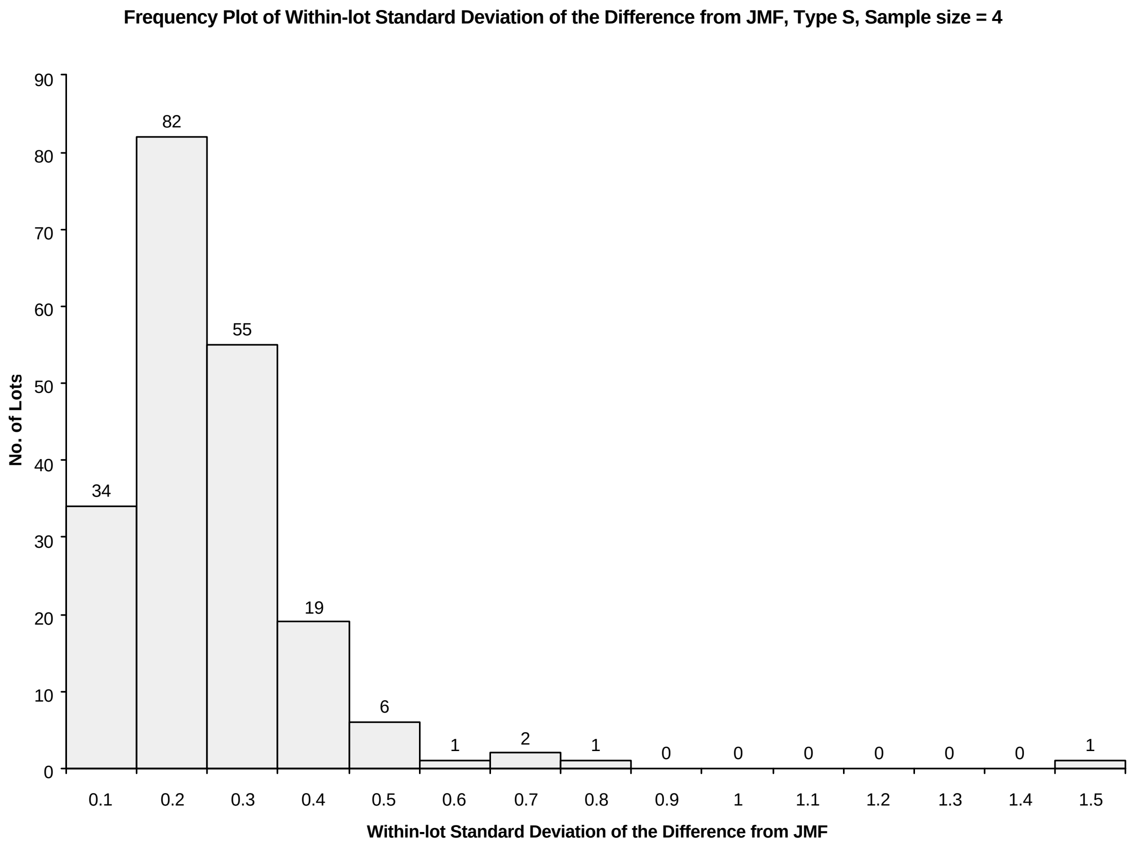


Figure 4-16. Summary Histogram for within-lot Standard Deviations of the Difference from JMF when Sample Size = 4

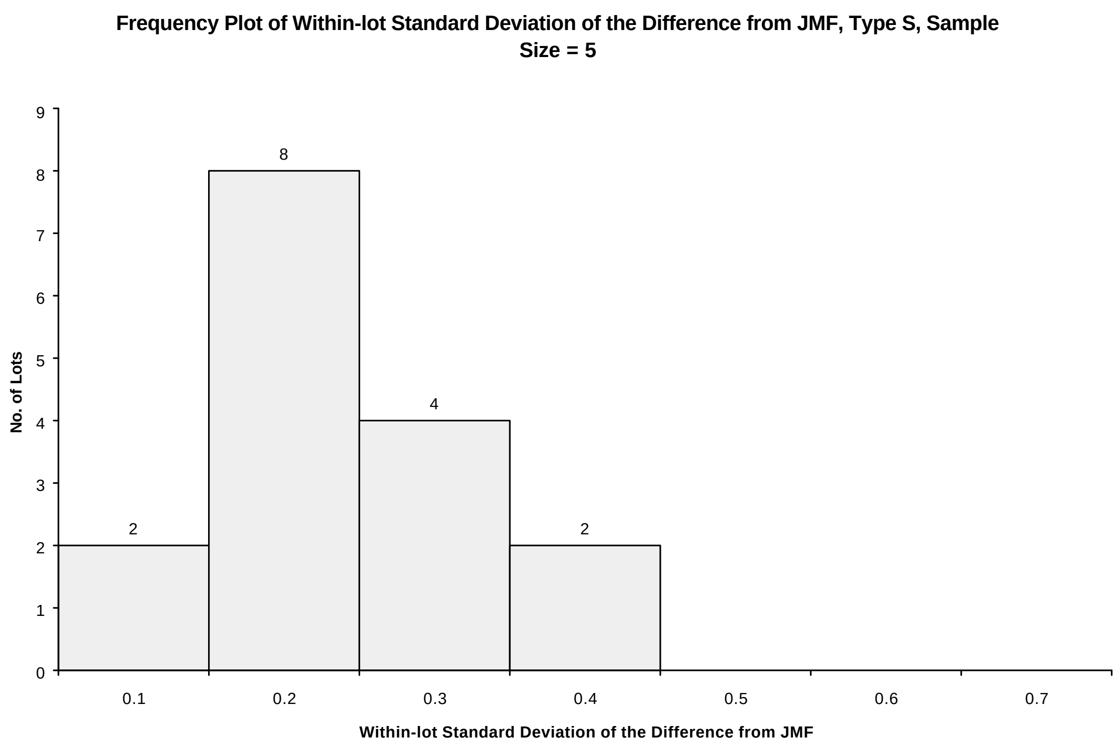


Figure 4-17. Summary Histogram for within-lot Standard Deviations of the Difference from JMF when Sample Size = 5

was estimated from the pooled standard deviation of all sample sizes, as shown in Tables 4-26 and 4-28.

Table 4-29 shows the summary of offset from JMF at different sample sizes. It can be observed that the offset tends to decrease when the sample size is increased.

Tables 4-30 and 4-31 show the average lot AAD and standard deviation of lot AAD from JMF for type S asphaltic concrete. The pooled estimate of average lot AAD was calculated to represent characteristic individual AAD.

Table 4-32 shows a summary of characteristic within-lot CI of type S asphaltic concrete. The average CI^2 at each sample size was determined. Next, the square root of average CI^2 was estimated and listed corresponding to the respective sample sizes (n) as shown in Table 4-32. Finally, the characteristic within-lot CI was estimated by determining the pooled estimate of CI of all sample sizes.

Table 4-33 shows the comparison of percentage of observations outside 95 percent confident interval of corrected (1.96*0.21) and pooled (1.96*0.22) within-lot standard deviation. It shows that the percentage of observations outside 95 percent confident interval of corrected within-lot standard deviation is closer to 5 percent than pooled. Therefore, the corrected within-lot standard deviation was used to represent typical within-lot standard deviation of asphalt content.

4.2.5.2 Within-lot Asphalt Content Characteristic by Year

The asphalt content data were divided into three different time periods (1993-1994, 1995-1996, 1997-1999). Next, an inspection of results was done to investigate if there were any changes in lot quality levels according to time periods. The quality levels of each time period are represented by within-lot standard deviation, offset from JMF, AAD and CI, as shown in Tables 4-34 through 4-45.

Table 4-26. Summary of Corrected Average within-lot Standard Deviation of Asphalt Content, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Corrected Average Within-Lot Std. Dev. (S)	Weighted Std. Dev. (w = (S^2) *N(n -1))
2	274	0.1973	10.6661
3	125	0.2121	11.2466
4	200	0.2146	27.6319
5	16	0.1983	2.5167
6	1	0.0663	0.0220

Total Number of Lots = 616

Pooled within-Lot Standard Deviation = 0.21

Table 4-27. Summary of Corrected Median within-lot Standard Deviation of Asphalt Content, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Corrected Median Within-Lot Std. Dev. (S)	Weighted Std. Dev. (w = (S^2) *N(n -1))
2	274	0.1595	6.9706
3	125	0.1879	8.8266
4	200	0.1884	21.2967
5	16	0.1775	2.0164
6	1	0.0633	0.0200

Total Number of Lots = 616

Pooled within-Lot Standard Deviation = 0.18

Table 4-28. Summary of Pooled within-lot Standard Deviation of Asphalt Content, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Within Lot Standard Deviation (S)	Weighted Std. Dev. (w = (S^2) *N(n -1))
2	274	0.2102	12.1064
3	125	0.2231	12.4434
4	200	0.2287	31.3822
5	16	0.2069	2.7397
6	1	0.0631	0.0199

Total Number of Lots = 616

Pooled within Lot Standard Deviation = 0.22

Table 4-29. Summary of Lot Offset from JMF of Asphalt Content, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Average Lot Offset from JMF (X)
1	510	0.2368
2	274	0.1718
3	125	0.1677
4	200	0.1402
5	16	0.1636
6	1	0.1417

Table 4-30. Summary of Lot Average Absolute Deviation from Job Mix Formula of Asphalt Content, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Average lot AAD from JMF (X)	Weighted Average (w = n * N * X)
1	510	0.2368	120.768
2	274	0.2090	114.532
3	125	0.2214	83.025
4	200	0.2098	167.84
5	16	0.2201	17.608
6	1	0.1417	0.8502

Total Number of Lots = 1126

Pooled Average Lot AAD from JMF = 0.22

Table 4-31. Summary of Standard Deviation of lot AAD of Asphalt Content, Material Type S

Sample Size (n)	No. of Lots (N)	Standard Deviation of Lot AAD (S)
1	510	0.2234
2	274	0.1369
3	125	0.1653
4	200	0.1053
5	16	0.1350

Table 4-32. Summary of within-lot Conformal Index of Asphalt Content, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Within-Lot Conformal Index (CI)	Weighted Conformal Index (w = n * N * CI^2)
2	274	0.2690	39.6538
3	125	0.3028	34.3829
4	200	0.2675	57.2450
5	16	0.2830	6.4071
6	1	0.1529	0.1403

Total Number of Lots = 616

Pooled Within-Lot Conformal Index = 0.28

Table 4-33. Comparison of Percentage of Observations Outside 95 percent Confident Interval of Corrected and Pooled within-lot Standard Deviation

Sample Size (n)	No. of Lots (N)	Total of Observations (N*n)	No. of Observations outside (1.96*Corrected S) (1.96*0.21)	No. of Observations outside (1.96*Pooled S) (1.96*0.22)
2	274	548	12	4
3	125	375	10	9
4	200	800	36	31
5	16	80	4	2
6	1	6	0	0
Total	616	1809	62	46

Percentage of Observation outside (1.96*0.21) = 3.43%

Percentage of Observation outside (1.96*0.22) = 2.54%

From the results in Table 4-34 through 4-45, it can be noted that the quality levels of the asphalt content characteristic has improved since 1995. The within-lot standard deviation, CI, and AAD in year 1995-1996 and 1997-1999 are lower than year 1993-1994. This implies that the hot-mix asphalt productions in year 1995 to 1999 were more consistent to mix designs than in year 1993-1994. The data indicate that the within-lot quality levels in year 1995-1996 and 1997-1999 are close to each other.

4.2.5.3 Overall Between-lot Asphalt Content Quality level

A total of 133 highway projects were considered in determining between-lot quality level of asphalt content. The statistical parameters of each project were estimated, which are the standard deviation of the differences from JMF, offset, and CI. Next, the pooled estimates of these statistical parameters were determined. Table 4-46 shows the statistical parameters that were obtained from the data analysis of the between-lot quality level. Since the sample size is very large, it can be concluded that the asphalt content between-lot standard deviation is remarkably larger than the within-lot, which is as expected. Further, the results, which are presented graphically as histograms for each parameter, are shown in Figures 4-18 through 4-20.

4.2.5.4 Pay Factor

According to FDOT Standard Specifications for Road and Bridge Construction 1999, the acceptance schedule of payment on a lot-by-lot basis of the asphalt content test results by the extraction method is as shown in Table 4-47 (FDOT, 1999).

Table 4-48 shows a summary of the average pay factor based on the asphalt content quality characteristic obtained from Tables 4-49 through 4-52. Table 4-49 shows the overall average asphalt content pay factor of type S asphaltic concrete. Tables 4-50

Table 4-34. Summary of within-lot Corrected Standard Deviation of Asphalt Content, Type S Asphaltic Concrete, Year 1993-1994

Sample Size (n)	No. of Lots (N)	Within-Lot Corrected Std. Dev. (S)	Weighted Std. Dev. (w = (S^2) *N(n -1))
2	116	0.1988	4.5845
3	54	0.2364	6.0356
4	62	0.2437	11.0465
5	6	0.2113	1.0715

Total Number of Lots = 238

Pooled within-Lot Corrected Standard Deviation = 0.23

Table 4-35. Summary of within-lot Corrected Standard Deviation of Asphalt Content, Type S Asphaltic Concrete, Year 1995-1996

Sample Size (n)	No. of Lots (N)	Within-Lot Corrected Std. Dev. (S)	Weighted Std. Dev. (w = (S^2) *N(n -1))
2	111	0.1804	3.6124
3	39	0.2015	3.1670
4	77	0.2036	9.5756
5	6	0.2020	0.9793

Total Number of Lots = 233

Pooled within-Lot Corrected Standard Deviation = 0.20

Table 4-36. Summary of within-lot Corrected Standard Deviation of Asphalt Content, Type S Asphaltic Concrete, Year 1997-1999

Sample Size (n)	No. of Lots (N)	Within-Lot Corrected Std. Dev. (S)	Weighted Std. Dev. (w = (S^2) *N(n -1))
2	47	0.2336	2.5647
3	32	0.1840	2.1668
4	61	0.1989	7.2397
5	4	0.1733	0.4805
6	1	0.0663	0.0220

Total Number of Lots = 145

Pooled within-Lot Corrected Standard Deviation = 0.20

Table 4-37. Summary of Lot Offset from JMF of Asphalt Content, Type S Asphaltic Concrete, Year 1993-1994

Sample Size (n)	No. of Lots (N)	Average Lot Offset from JMF (X)
1	200	0.23
2	116	0.18
3	54	0.20
4	62	0.14
5	6	0.13

Table 4-38. Summary of Lot Offset from JMF of Asphalt Content, Type S Asphaltic Concrete, Year 1995-1996

Sample Size (n)	No. of Lots (N)	Average Lot Offset from JMF (X)
1	187	0.24
2	111	0.18
3	39	0.15
4	77	0.15
5	6	0.14

Table 4-39. Summary of Lot Offset from JMF of Asphalt Content, Type S Asphaltic Concrete, Year 1997-1999

Sample Size (n)	No. of Lots (N)	Average Lot Offset from JMF (X)
1	123	0.25
2	47	0.14
3	32	0.13
4	61	0.13
5	4	0.25
6	1	0.14

Table 4-40. Summary of Lot Average Absolute Deviation from JMF of Asphalt Content, Type S Asphaltic Concrete, Year 1993-1994

Sample Size (n)	No. of Lots (N)	Average lot AAD from JMF (X)	Weighted Average (w = n * N * X)
1	200	0.2277	45.5400
2	116	0.2096	48.6272
3	54	0.2615	42.3630
4	62	0.2244	55.6512
5	6	0.1910	5.7300

Total Number of Lots = 438

Pooled Average Lot AAD from JMF = 0.23

Table 4-41. Summary of Lot Average Absolute Deviation from JMF of Asphalt Content, Type S Asphaltic Concrete, Year 1995-1996

Sample Size (n)	No. of Lots (N)	Average lot AAD from JMF (X)	Weighted Average (w = n * N * X)
1	187	0.2387	44.6369
2	111	0.2142	47.5524
3	39	0.1964	22.9788
4	77	0.2078	64.0024
5	6	0.1970	5.9100

Total Number of Lots = 420

Pooled Average Lot AAD from JMF = 0.21

Table 4-42. Summary of Lot Average Absolute Deviation from JMF of Asphalt Content, Type S Asphaltic Concrete, Year 1997-1999

Sample Size (n)	No. of Lots (N)	Average lot AAD from JMF (X)	Weighted Average (w = n * N * X)
1	123	0.2489	30.6147
2	47	0.1954	18.3676
3	32	0.1844	17.7024
4	61	0.1975	48.1900
5	4	0.2985	5.9700
6	1	0.1417	0.8502

Total Number of Lots = 268

Pooled Average Lot AAD from JMF = 0.21

Table 4-43. Summary of within-lot Conformal Index of Asphalt Content, Type S Asphaltic Concrete, Year 1993-1994

Sample Size (n)	No. of Lots (N)	Within Lot Conformal Index (CI)	Weighted Conformal Index (w = n * N * CI^2)
1	200	0.31	19.4314
2	116	0.27	17.1643
3	54	0.36	21.3466
4	62	0.30	21.9053
5	6	0.24	1.7367

Total Number of Lots = 438

Pooled Within-Lot Conformal Index = 0.31

Table 4-44. Summary of within-lot Conformal Index of Asphalt Content, Type S Asphaltic Concrete, Year 1995-1996

Sample Size (n)	No. of Lots (N)	Within Lot Conformal Index (CI)	Weighted Conformal Index (w = n * N * CI^2)
1	187	0.33	20.2903
2	111	0.27	16.6304
3	39	0.26	7.8667
4	77	0.25	19.9336
5	6	0.26	1.9938

Total Number of Lots = 420

Pooled Within-Lot Conformal Index = 0.28

Table 4-45. Summary of within-lot Conformal Index of Asphalt Content, Type S Asphaltic Concrete, Year 1997-1999

Sample Size (n)	No. of Lots (N)	Within-Lot Conformal Index (CI)	Weighted Conformal Index (w = n * N * CI^2)
1	123	0.34	14.2858
2	47	0.25	5.8515
3	32	0.23	5.1671
4	61	0.25	15.4090
5	4	0.37	2.6777
6	1	0.15	0.1403

Total Number of Lots = 268

Pooled Within-Lot Conformal Index = 0.27

Table 4-46. Summary of Between-Lot Statistical Parameters for Type S Asphaltic Concrete

Statistical Parameter	Between-lot (%)
Between-lot CI	0.29
Pooled estimate of between-lot standard deviation of the differences from JMF	0.27
Average of between-lot corrected standard deviation of the differences from JMF	0.26

through 4-52 show the average asphalt content pay factor by time periods: 1993-1994, 1995-1996, and 1997-1999. Table 4-53 shows the percentage of lots with reduced payment for type S asphaltic concrete. Figure 4-21 graphically shows the frequency plot of pay factor based on asphalt content characteristic.

A computer program was developed for use as a tool to indicate whether the specification is effective by investigating if the same asphalt content quality level is being specified at all possible sample sizes (n = 1 – 6). If not, new tolerances would be recommended. An explanation of the computer software and a summary of results obtained from the analysis by using the computer software will be discussed in the next chapter.

4.2.6 Questionnaire Responses for Asphalt Content Quality Level

In the same questionnaires that were mentioned in section 4.1.6, similar questions were asked for the asphalt content characteristic as for the density characteristic.

Figure 4-22 and 4-23 show the questionnaire survey results of the asphalt content quality level. Similar to the density responses, most of respondents provided the answer

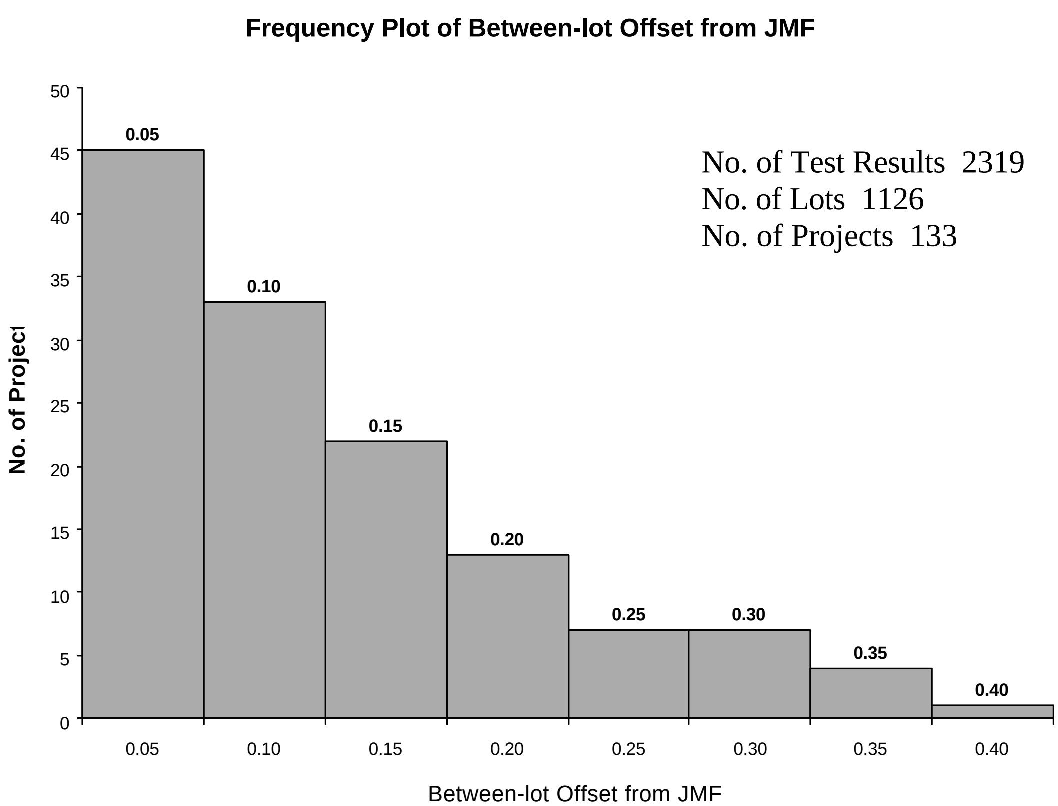


Figure 4-18. Summary Histograms of Between-Lot Offset from JMF

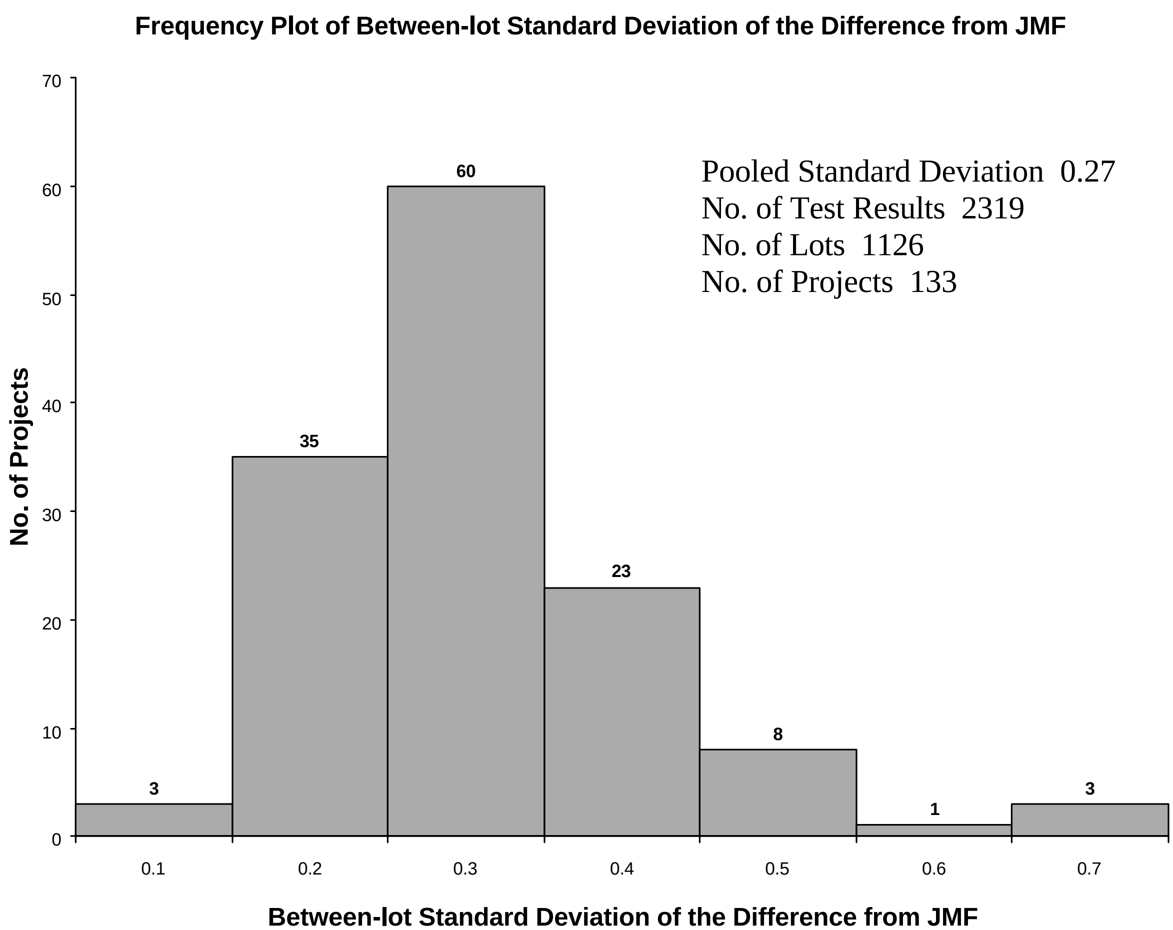


Figure 4-19. Summary Histograms of Between-Lot Standard Deviation of the Difference from JMF

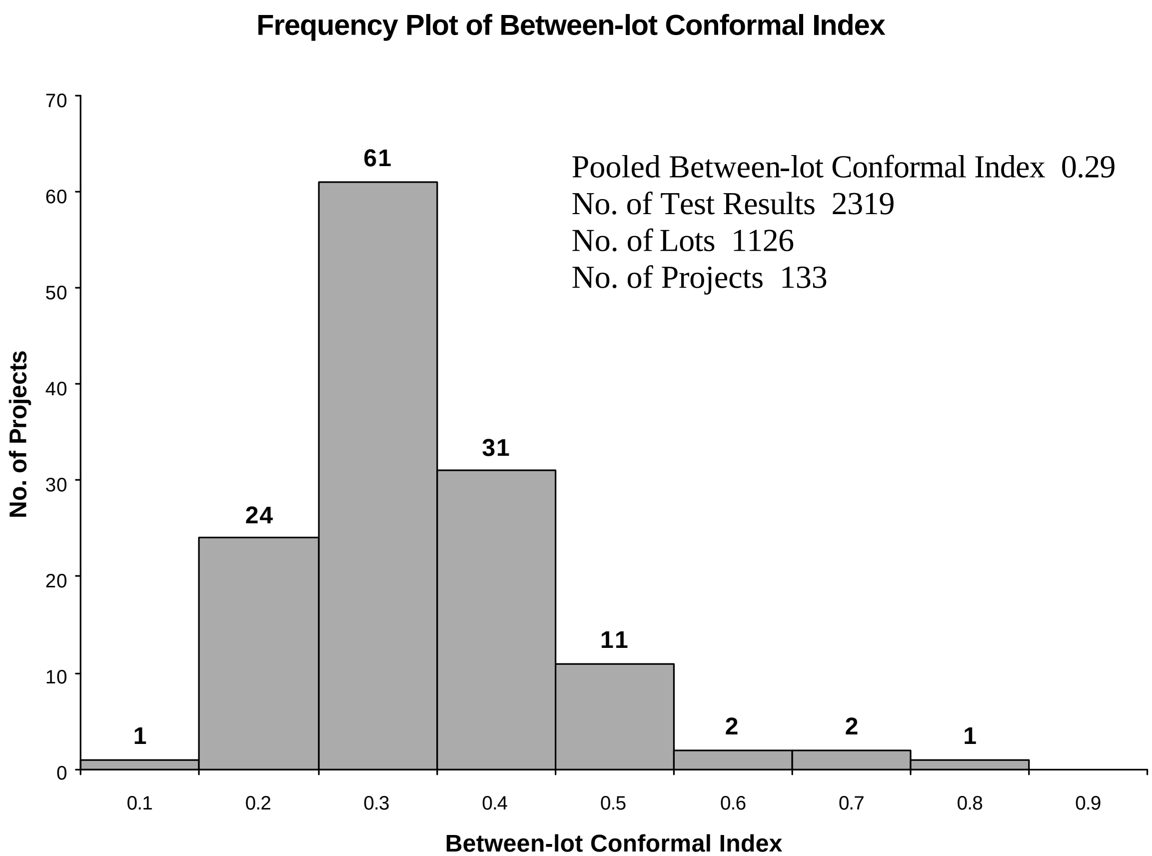


Figure 4-20. Summary Histograms of Between-Lot Conformal Index

Table 4-47. The Acceptance Schedule of Payment on Lot-by-Lot basis of the Asphalt Content Test Results by Extraction Method

Pay Factor	Average of Accumulated Deviation of the Acceptance Tests from the Mix Design					
	1-Test	2-Tests	3-Tests	4Tests	5Tests	6-Tests
1.00	0.00-0.55	0.00-0.43	0.00-0.38	0.00-0.35	0.00-0.33	0.00-0.31
0.95	0.56-0.65	0.44-0.50	0.39-0.44	0.36-0.40	0.34-0.37	0.32-0.36
0.90	0.66-0.75	0.51-0.57	0.45-0.50	0.41-0.45	0.38-0.42	0.36-0.39
0.80	> 0.75	> 0.57	> 0.50	> 0.45	> 0.42	> 0.39

Source: FDOT Standard Specifications for Road and Bridge Construction 1999 (FDOT, 1999)

Table 4-48. Summary of the Estimated Pay Factor based on Asphalt Content Characteristic

Asphaltic Concrete/Year	Pay Factor Average
Type S, Year 1993-1999	99.04%
Type S, Year 1993-1994	98.87%
Type S, Year 1995-1996	99.18%
Type s, Year 1997-1999	99.08%

Table 4-49. Summary of Average Asphalt Content Pay Factor, Type S Asphaltic Concrete

Sample Size (n)	No. of Lots (N)	Average Lot Pay Factor (X)	Weighted Average (w = N * X)
1	510	0.9899	504.8490
2	274	0.9931	272.1094
3	125	0.9868	123.3500
4	200	0.9905	198.1000
5	16	0.9844	15.7504

Total Number of Lots = 1125

Pooled Average Pay Factor = 0.9904

Table 4-50. Summary of Average Asphalt Content Pay Factor for Year 1993-1994

Sample Size (n)	No. of Lots (N)	Average Lot Pay Factor (X)	Weighted Average (w = N * X)
1	200	0.9903	198.0600
2	116	0.9935	115.2460
3	54	0.9750	52.6500
4	62	0.9855	61.1010
5	6	1.0000	6.0000

Total Number of Lots = 438

Pooled Average Pay Factor = 0.9887

Table 4-51. Summary of Average Asphalt Content Pay Factor for Year 1995-1996

Sample Size (n)	No. of Lots (N)	Average Lot Pay Factor (X)	Weighted Average (w = N * X)
1	187	0.9906	185.2422
2	111	0.9914	110.0454
3	39	0.9949	38.8011
4	77	0.9935	76.4995
5	6	0.9917	5.9502

Total Number of Lots = 420
Pooled Average Pay Factor = 0.9918

Table 4-52. Summary of Average Asphalt Content Pay Factor for Year 1997-1999

Sample Size (n)	No. of Lots (N)	Average Lot Pay Factor (X)	Weighted Average (w = N * X)
1	123	0.9882	121.5486
2	47	0.9957	46.7979
3	32	0.9969	31.9008
4	61	0.9918	60.4998
5	4	0.9500	3.8000
6	1	1.0000	1.0000

Total Number of Lots = 268
Pooled Average Pay Factor = 0.9908

Table 4-53. Summary of Percentage of Lots with Pay Reduction

Sample Size (n)	Percentage of Lots with Pay Reduction (%)
1	6.67
2	6.57
3	8.80
4	6.50
5	12.50

for the offset of mean value from job mix design but did not know the allowed standard deviation for full payment or provided inconsistent responses. Although most of respondents provided 0.3 percent as an offset of mean value, the distribution of desired quality level population could not be determined because of the absence of the standard deviation value. The standard deviation values provided by contractors were inconsistent. Although the responses from the questionnaires could not positively be concluded to identify the desired asphalt content quality level, most of the FDOT respondents believed that the current quality specified for asphalt content should be raised, especially since the ignition oven test is being adopted (increasing test precision). Most contractor respondents believed the currently specified quality levels should stay as they are. No respondents believed that the currently specified quality levels should be lowered (Figure 4-24).

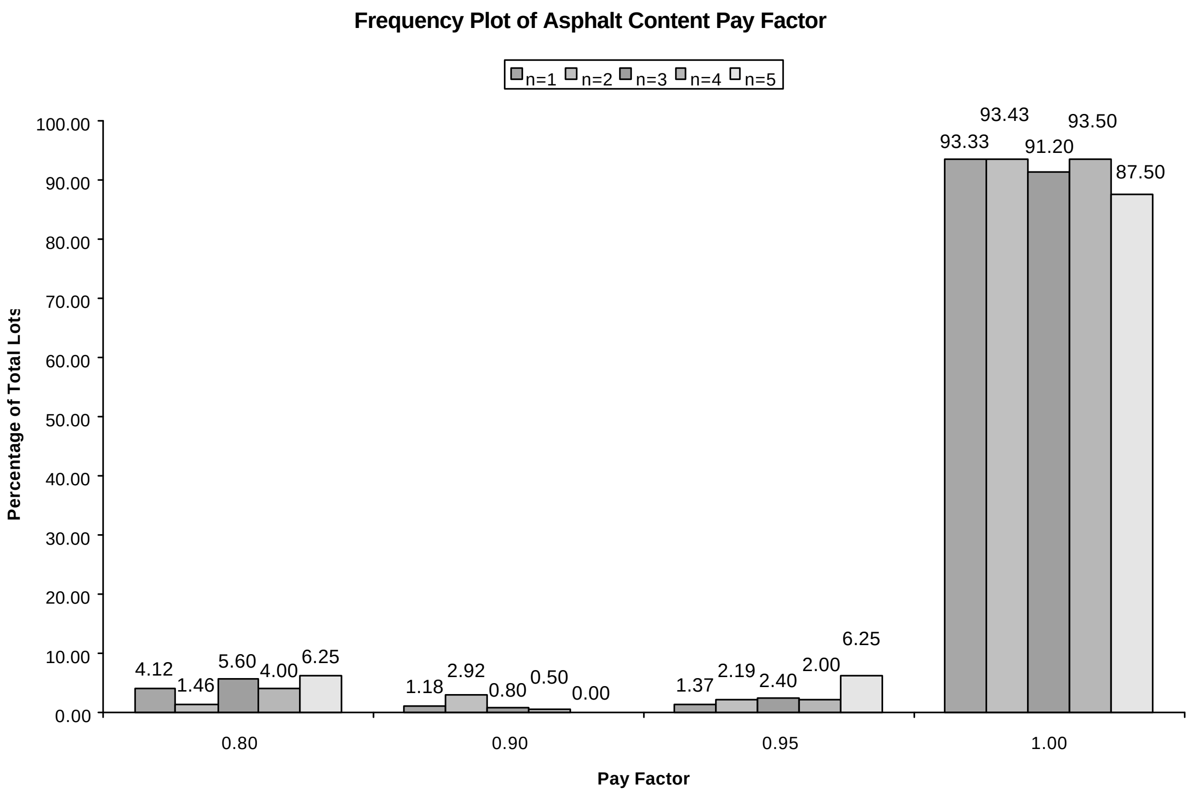


Figure 4-21. Frequency Plot of Pay Factor based on Asphalt Content Characteristic

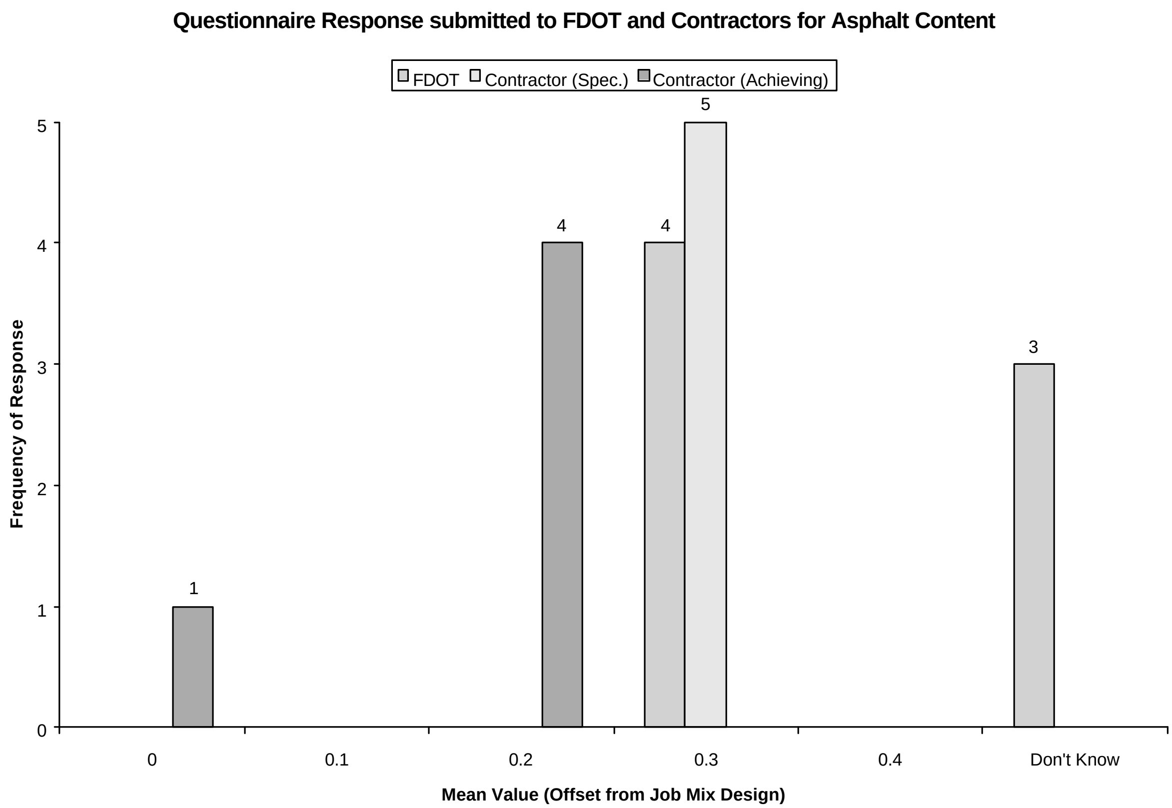


Figure 4-22. Questionnaire Responses from FDOT and Contractor Personnel Regarding Average Offset of Asphalt Content from Job Mix Design

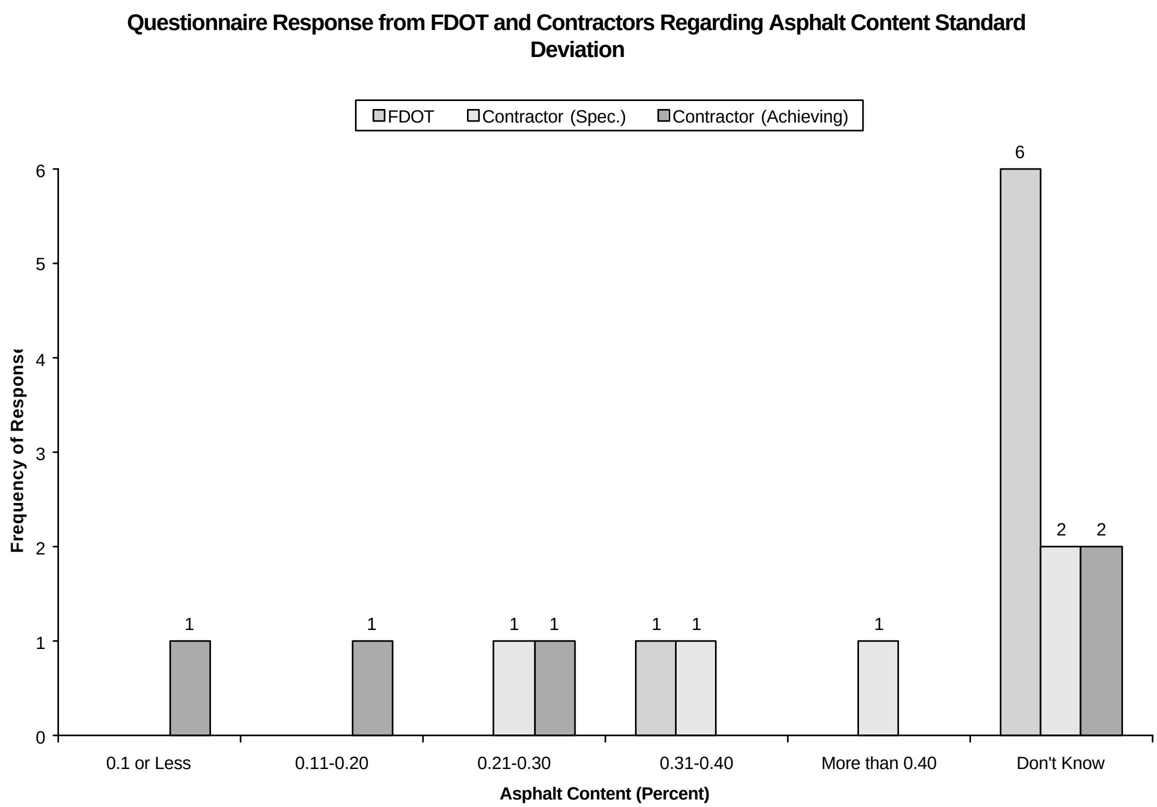


Figure 4-23. Questionnaire Responses from FDOT and Contractor Personnel Regarding Standard Deviation of Asphalt Content

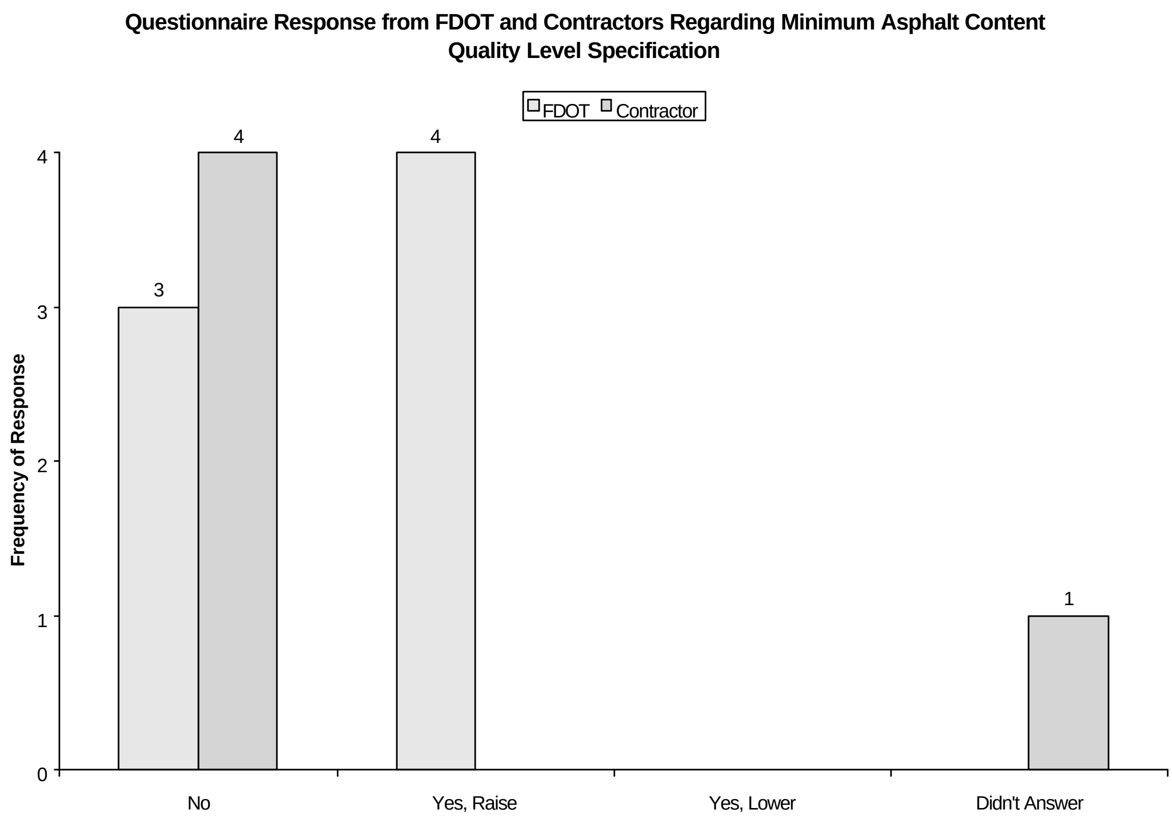


Figure 4-24. Questionnaire Responses from FDOT and Contractor Personnel Regarding Minimum Quality Level of Asphalt Content Specification

CHAPTER 5
COMPUTER PROGRAMMING

The FDOT Standard Specifications for Road and Bridge Construction 1999 specify the quality level of asphalt content in terms of AAD. However, the quality levels that FDOT contractors are providing were determined from the analysis of the CQR database in terms of offset from JMF, standard deviation, and conformal index. A computer program was developed to help in relating the within-lot statistic parameters from the data analysis to that which is specified by the FDOT.

5.1 Purpose of the Computer Simulation

Computer simulation is one of the most powerful methods available for solving problems for which direct, closed-form solutions do not exist or for which very complex mathematics would be required. It is one of the simplest methods to understand and apply. Most of the simulations conceptually require only the following three steps (Weed, 1996b):

1. Generate random data simulating the real process
2. Apply the procedure that is to be tested
3. Store the result in memory

This sequence of steps is then repeated many times to provide a large amount of data.

A computer simulation program was developed to simulate a large amount of data of the real test results of asphalt content in the field. These test results are generated based on the input of within-lot offset from JMF and standard deviations. The results are stored in memory for subsequent analysis. This requires much less time than a field trial.

5.2 Computer Program Flow Chart

The basic flow chart for the program is given in Figure 5-1, using the following variables:

n	=	Lot sample size
JMF	=	Designed asphalt content in job mix formula
OS	=	Population offset of test results from JMF
S	=	Population within-lot standard deviation
NIT	=	The number of 15,000 repetitions used in the simulation
NRnd	=	Random number from normal distribution
AAD	=	Average absolute deviation from JMF
CI	=	Conformal index
PF	=	Pay factor

This program is limited for use with a sample size of not more than 10. The program was designed to generate the pay factor based on the pay factor schedule of asphalt content specified in the FDOT Standard Specifications for Road and Bridge Construction 1999 (p.139). However, the program can easily be modified to enable new acceptance tolerances for a new pay factor schedule. Since the largest sample size specified in the FDOT 1999 specification is 6, new acceptance tolerances are needed for a sample size of more than 6.

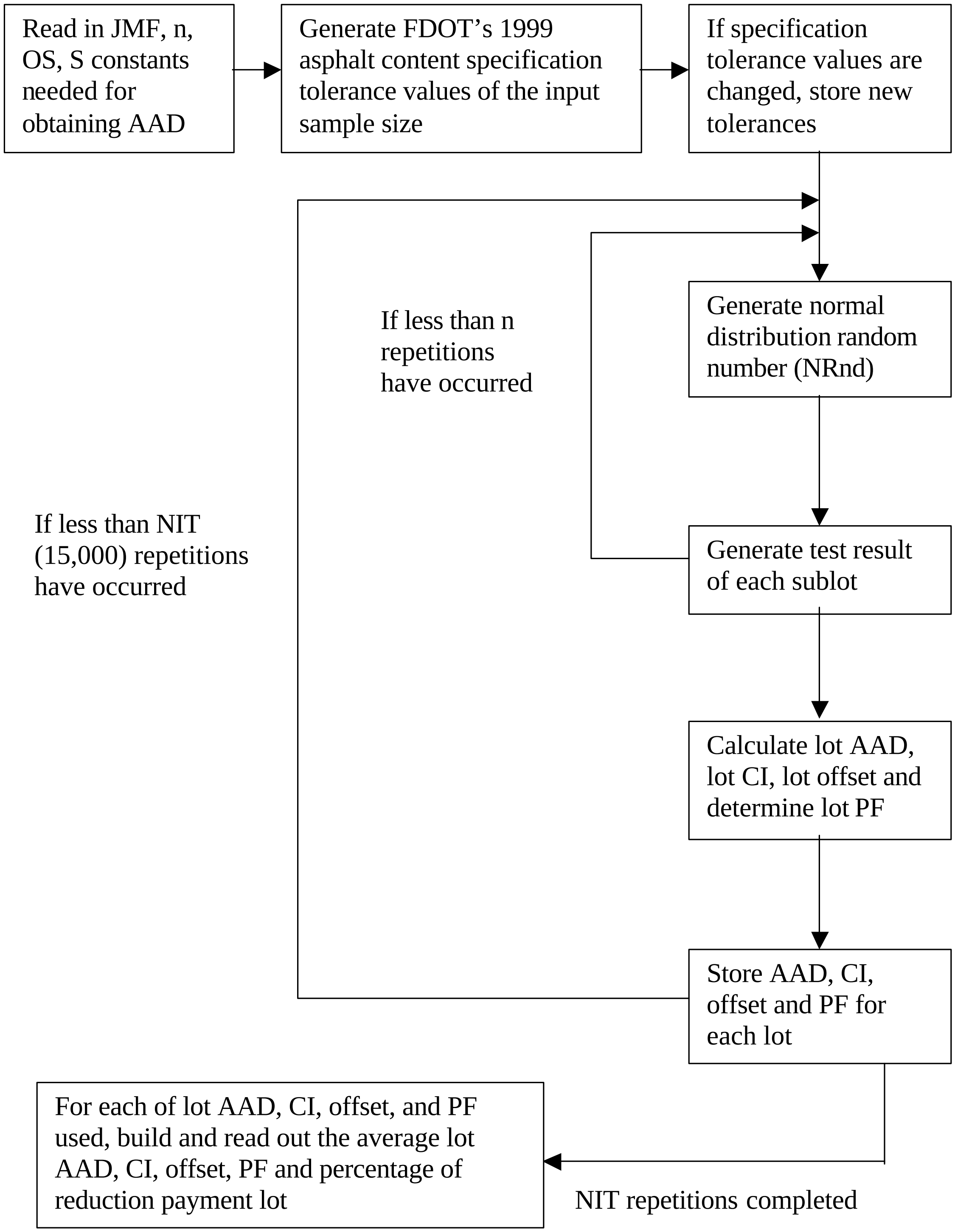


Figure 5-1. Computer Simulation Flow Chart used in Relating Offset and Standard Deviation to AAD

In the program, the number of repetitions of the sublot test result simulation is equal to the sample size. Each lot is evaluated in accordance with the acceptance tolerances specified in the input, and the results are stored in memory for subsequent analysis. The program simulates 15,000 lot-repetitions to obtain the summary results of AAD from JMF, CI, offset from JMF, and pay factor.

The output provides a histogram of pay factor distribution and a summary of the average of lot AAD from JMF, average of lot CI, average of lot offset from JMF, average of pay factor, and percentage of reduced-payment lots.

5.3 Computer Program Development

The AASHO road test provided the data in the early 1960s that illustrated in a dramatic way how variable most construction characteristics are. Many quantitative measures, including the vast majority of highway construction measurements, were found to vary widely about their target values, usually in form of the bell-shaped normal distribution (Weed, 1996b). In order to evaluate the acceptance tolerances used in highway construction, it is necessary to generate random data that are essentially identical to the normally distributed data produced at a construction site.

The AAD computer program was developed in the Microsoft Visual Basic Programming Language. The asphalt content test results are generated based on the quality level specified in the input. A random number generator is one of the most important functions in simulation programming. A uniform random number generator is provided in Visual Basic like most programming languages. It produces a random decimal value between 0.0 and 1.0. The number can be 0 but cannot ever be 1 (Cornell, 1998; Kerman and Brown, 2000). These random numbers are used to determine random sampling locations.

For the AAD computer program, it is desirable to have each run produce a unique, independent random number. This was accomplished by including the command, "Randomize," which used the exact time of the system clock to reseed the random number generator. (Reseed is the jargon for the starting a new sequence of a random number procedure.) The system clock is accurate to a small fraction of a second; therefore, it is quite unlikely that a program will start at exactly the same moment each time it is run. This causes a unique stream of random numbers to be generated for each run (Cornell, 1998; Kerman and Brown, 2000).

The random numbers from a standard normal distribution having a mean of 0.0 and a standard deviation of 1.0 were generated using SAS software. The 15,993 normal random numbers were generated and kept in the database. Although there are a variety of random numbers that can be obtained from normal distribution, a large file of 15,993 scrambled normal numbers was chosen to develop a faster procedure. At the same time, the series of 15,993 numbers are believed to be large enough to yield the appropriate results. A file of 15,993 is considered much larger when referenced with a file of 5000 scrambled normal numbers, which is currently used in the COMPSIM program by the Federal Highway Administration (FHWA) for generating simulation test results (Weed, 1996b). When a normal random number is required, a uniform random number is multiplied by 15,993, increased by 1, and then truncated to obtain a random integer from 1 to 15,993. This is then used to make a random selection from the file of normal numbers.

The asphalt content test result in each sublot is a function of designed asphalt content, offset, random number from normal distribution, and standard deviation. Each test result is estimated from equation 5.1.

$$y = JMF + offset + (NRnd * S) \tag{5.1}$$

where:

y	=	Asphalt content sublot test result
JMF	=	Designed asphalt content in JMF
Offset	=	Population offset from designed asphalt content
NRnd	=	Normal random number
S	=	Population standard deviation

The lot AAD, offset, and CI are calculated when the repetitions of test result generation are equal to number of the sample size. The lot AAD is then compared with the acceptance tolerances to determine the PF value. The lot AAD, CI, offset, and PF are then kept in memory. This program was developed to generate the test results of 15,000 lots. Finally, the PF histogram and the summary of average lot AAD, offset, CI, PF, and percentage pay reduction are shown as the results of the program. The summary of average lot offset, AAD and CI are calculated by using equations 5.2 to 5.4, respectively.

$$\text{Average Lot Offset} = \Sigma(\text{lot offset}) / 15{,}000 \tag{5.2}$$

$$\text{Average Lot AAD} = \Sigma(\text{lot AAD}) / 15{,}000 \tag{5.3}$$

$$\text{Average Lot CI} = \sqrt{(\Sigma(CI^2) / 15{,}000)} \tag{5.4}$$

5.4 Software Manual

1. Input the value of designed asphalt content, number of samples, population offset from designed asphalt content in JMF, and population standard deviation in the boxes that are provided (see Figure 5-2). Sample size must be an integer number and is limited to not more than 10. The designed asphalt content, offset, and standard deviation must be preceded by 0 when the value is less than 1, e.g., enter 0.21 instead of .21.
2. If the acceptance tolerances need to be changed, enter new tolerances in the boxes that are provided. Only lower limits need to be filled; the upper limit at each pay factor is automatically filled based on the lower limit of the next lower pay factor. Click the "Apply New Tolerances" button (see Figure 5-3) to save new tolerance values. The acceptance tolerances will be rounded up to two decimal points. If changes of the tolerances are not needed, go to step 3.
3. Click the "Calculate" button to start the simulation process.
4. The results of the pay factor distribution histogram and the summary of the average lot AAD, average lot CI, average lot offset, average pay factor, and percentage of reduced-payment lots are shown on the right of the input information (see Figure 5-4).
5. Click "Exit" to quit the program.

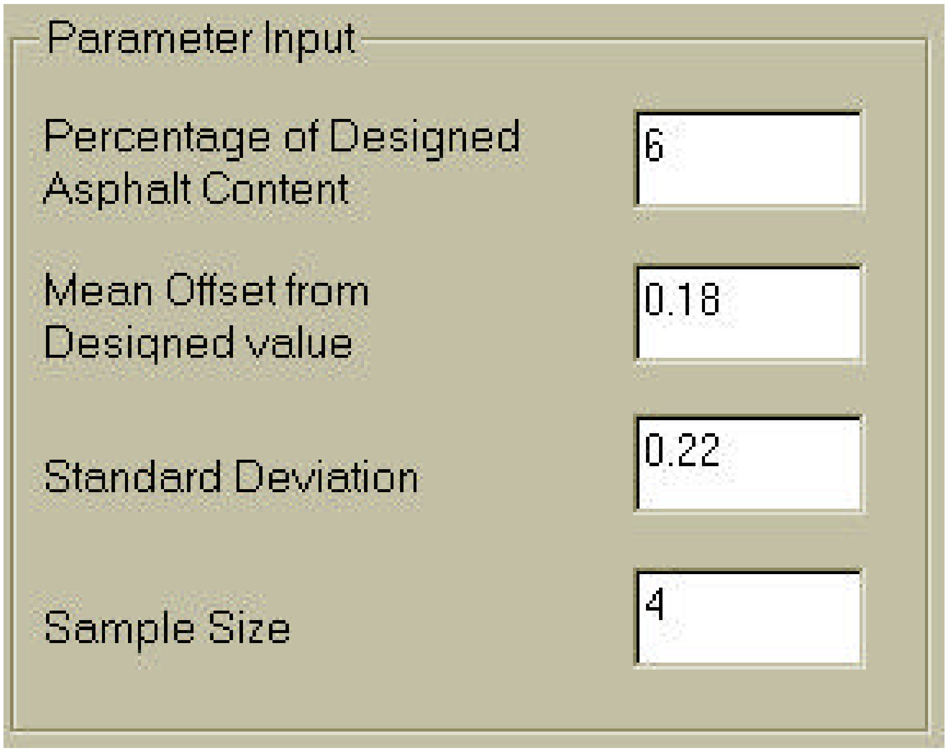


Figure 5-2. Completed Input Information

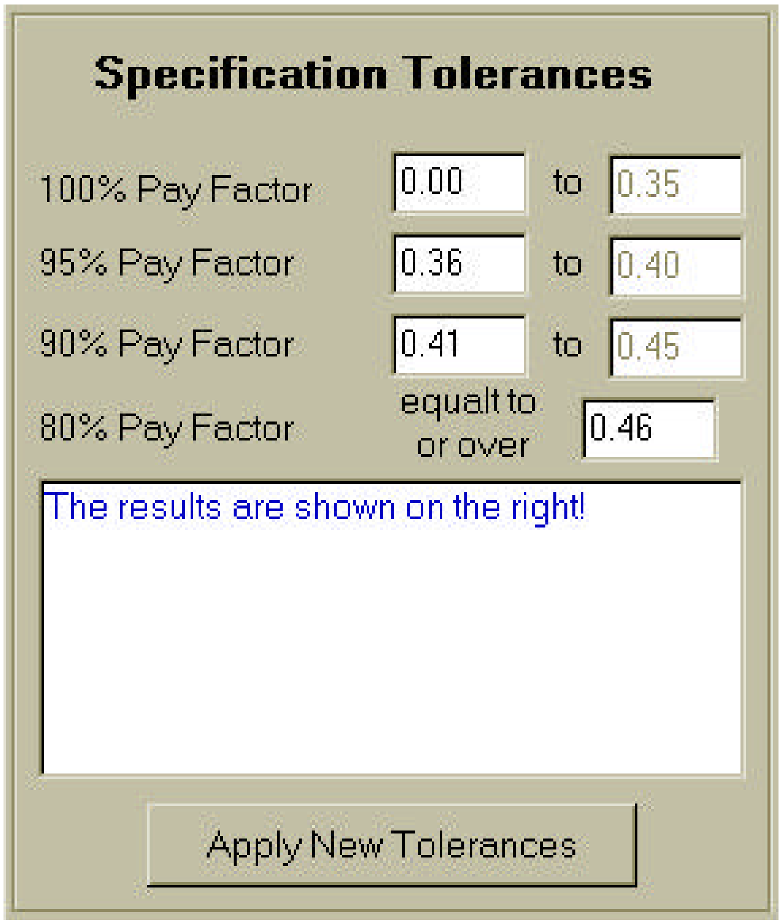


Figure 5-3. Completed Input of Specification Tolerances

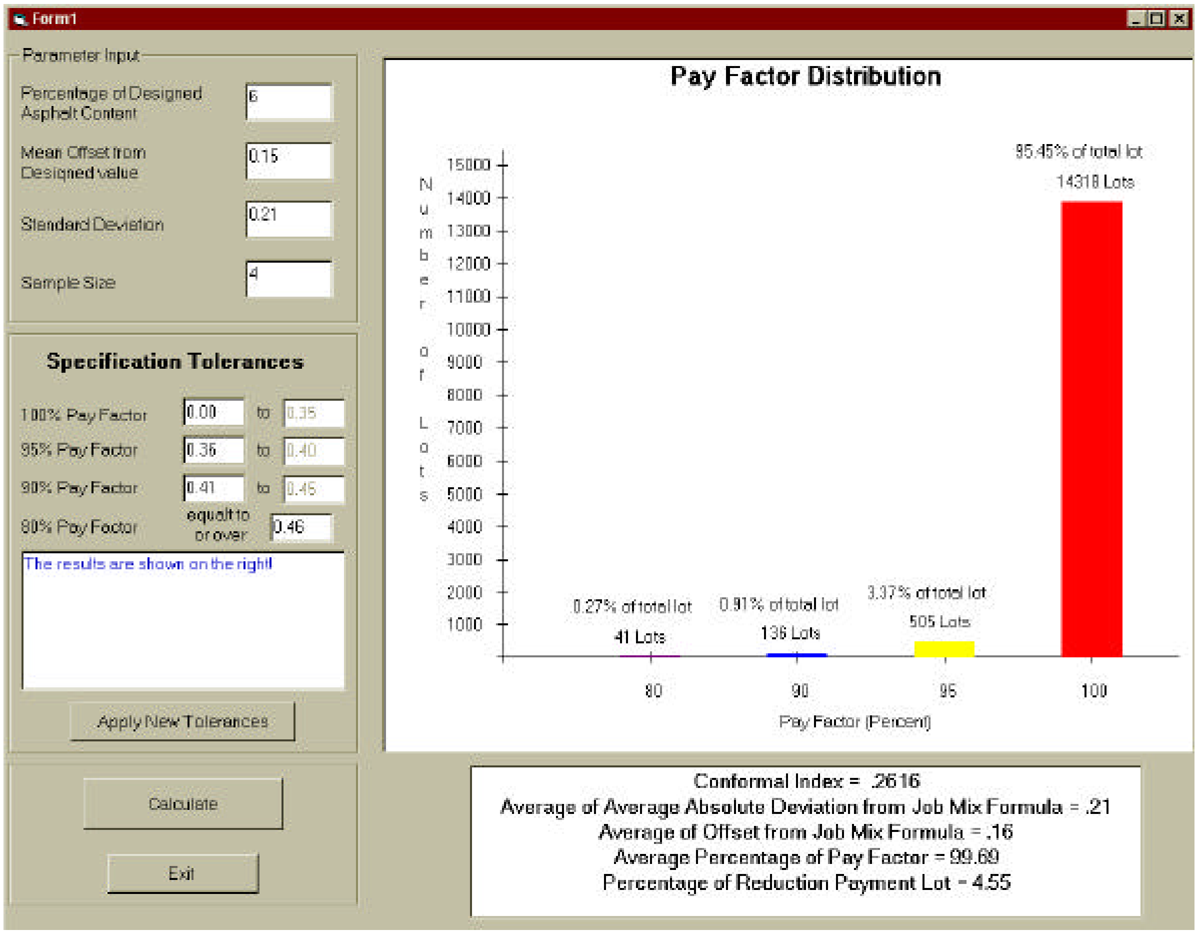


Figure 5-4. Display of the AAD Computer Program

5.5 Computer Program Output

First, the characteristic offset needs to be determined. As mentioned in Chapter 4, the average value of within-lot offset decreases when the sample size increases. In order to estimate the population offset, the computer program was used as a tool to predict the offset when the sample size is large or close to ∞. The population offset was predicted by trial and error. For each sample size, the average offset results were obtained from computer program outputs when a population standard deviation input of 0.21 at different population offset inputs were compared with the offsets obtained from data analysis of the CQR database. The offset input that gave the value closest to the offset obtained from the CQR data at different sample sizes was predicted as the population offset. From trial and error, the population offset was predicted as 0.15. The offset outputs obtained from the computer program were compared with those obtained from the data analysis, as shown in Table 5-1.

In Table 5-1, the software outputs show the difference between the sample average offsets from the CQR database and the computer simulation output. It can be observed that the offsets obtained from simulation output decrease at a similar rate as the offsets obtained from the data analysis. Moreover, the offset from simulation output after n=5 is constant, since the offsets at both $n = 5$ and $n = \infty$ is 0.15.

The corrected average standard deviation of 0.21 and the offset of 0.15, which are the average of asphalt content quality that contractors provide (obtained from CQR data analysis), were used as inputs in the program. The FDOT 1999 specifications were used to determine lot PF and generate the PF distribution. At each sample size, the program was run 10 times. Summaries of the results are shown in Table 5-2 through 5-7, with the average of the outputs obtained shown at the bottom of each table.

Table 5-8 shows the summary of the outputs from Tables 5-2 to 5-7. It can be observed that the percentage of lots with pay reduction increases when the sample size increases. Figure 5-5 graphically shows that the risks are not the same at different sample sizes. When the sample size per lot increases, there is a greater risk that contractors will get a payment reduction. On the other hand, there is a greater possibility that the FDOT will get a product with full payment paid to the contractors as the sample size decreases. Since the average pay for a given lot changes with sample size, it can be interpreted that the FDOT asphalt content specification is not effective. The greater the difference in percentage of lot with pay reduction when the sample size is different, the greater the

Table 5-1. Comparison between Lot Offsets from Computer Outputs when Characteristic Offset Input = 0.15, S Input = 0.21 and Lot Offsets from Data Analysis of CQR Database

Sample Size (n)	Offset from CQR Data	Offset from Computer Output
1	0.2368	0.21
2	0.1718	0.18
3	0.1677	0.16
4	0.1402	0.16
5	0.1636	0.16
6	0.1417	0.15

Table 5-2. Summary of the Results from Computer Simulation Based on 1999 FDOT Specification for Sample Size = 1, Offset = 0.15, and Standard Deviation = 0.21

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.17	0.49	2.15	97.19	0.26	0.21	99.81	2.81
2	0.18	0.47	2.34	97.01	0.26	0.21	99.80	2.99
3	0.23	0.45	1.64	97.67	0.26	0.21	99.83	2.33
4	0.25	0.49	2.09	97.17	0.26	0.21	99.80	2.83
5	0.14	0.54	2.15	97.17	0.26	0.21	99.81	2.83
6	0.21	0.42	2.22	97.15	0.26	0.21	99.80	2.85
7	0.13	0.69	1.84	97.34	0.26	0.21	99.81	2.66
8	0.30	0.42	1.95	97.33	0.26	0.21	99.80	2.67
9	0.17	0.36	2.01	97.46	0.26	0.21	99.83	2.54
10	0.17	0.53	1.89	97.42	0.26	0.21	99.82	2.58
Average	0.20	0.49	2.03	97.29	0.26	0.21	99.81	2.71
				Standard Deviation				0.1918

Table 5-3. Summary of the Results from Computer Simulation Based on 1999 FDOT Specification for Sample Size = 2, Offset = 0.15, and Standard Deviation = 0.21

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.11	0.59	2.31	96.99	0.26	0.21	99.80	3.01
2	0.18	0.60	2.18	97.04	0.26	0.21	99.79	2.96
3	0.19	0.59	2.09	97.13	0.26	0.21	99.80	2.87
4	0.25	0.60	2.03	97.13	0.26	0.21	99.79	2.87
5	0.20	0.53	2.27	97.00	0.26	0.21	99.79	3.00
6	0.25	0.58	2.54	96.63	0.26	0.21	99.76	3.37
7	0.33	0.64	1.93	97.10	0.26	0.21	99.77	2.90
8	0.26	0.59	2.01	97.14	0.26	0.21	99.79	2.86
9	0.28	0.55	2.41	96.76	0.26	0.21	99.77	3.24
10	0.25	0.68	2.21	96.86	0.26	0.21	99.77	3.14
Average	0.23	0.60	2.20	96.98	0.26	0.21	99.78	3.02
				Standard Deviation				0.1746

Table 5-4. Summary of the Results from Computer Simulation Based on 1999 FDOT Specification for Sample Size = 3, Offset = 0.15, and Standard Deviation = 0.21

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.15	0.77	2.83	96.25	0.26	0.21	99.75	3.75
2	0.22	0.69	2.69	96.41	0.26	0.21	99.75	3.59
3	0.19	0.69	2.26	96.86	0.26	0.21	99.78	3.14
4	0.18	0.58	2.65	96.59	0.26	0.21	99.77	3.41
5	0.22	0.74	2.59	96.45	0.26	0.21	99.75	3.55
6	0.13	0.59	2.55	96.72	0.26	0.21	99.79	3.28
7	0.21	0.65	2.30	96.84	0.26	0.21	99.78	3.16
8	0.22	0.79	2.49	96.51	0.26	0.21	99.75	3.49
9	0.11	0.67	2.67	96.54	0.26	0.21	99.78	3.46
10	0.21	0.81	2.63	96.35	0.26	0.21	99.75	3.65
Average	0.18	0.70	2.57	96.55	0.26	0.21	99.77	3.45
				Standard Deviation				0.2033

Table 5-5. Summary of the Results from Computer Simulation Based on 1999 FDOT Specification for Sample Size = 4, Offset = 0.15, and Standard Deviation = 0.21

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.27	0.84	2.87	96.02	0.26	0.21	99.72	3.98
2	0.27	0.77	3.21	95.76	0.26	0.21	99.71	4.24
3	0.16	0.86	2.75	96.23	0.26	0.21	99.74	3.77
4	0.34	0.87	2.77	96.02	0.26	0.21	99.71	3.98
5	0.22	0.77	3.09	95.93	0.26	0.21	99.72	4.07
6	0.25	0.63	2.79	96.33	0.26	0.21	99.75	3.67
7	0.10	0.92	2.92	96.06	0.26	0.21	99.74	3.94
8	0.22	0.81	2.66	96.31	0.26	0.21	99.74	3.69
9	0.21	0.94	3.01	95.84	0.26	0.21	99.71	4.16
10	0.27	0.65	2.74	96.33	0.26	0.21	99.74	3.67
Average	0.23	0.81	2.88	96.08	0.26	0.21	99.73	3.92
				Standard Deviation				0.2083

Table 5-6. Summary of the Results from Computer Simulation Based on 1999 FDOT Specification for Sample Size = 5, Offset = 0.15, and Standard Deviation = 0.21

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.17	1.11	2.93	95.78	0.26	0.21	99.71	4.22
2	0.32	1.23	2.81	95.65	0.26	0.21	99.67	4.35
3	0.24	0.96	2.78	96.02	0.26	0.21	99.72	3.98
4	0.23	1.15	2.74	95.88	0.26	0.21	99.70	4.12
5	0.33	1.23	2.92	95.53	0.26	0.21	99.67	4.47
6	0.37	1.25	2.93	95.45	0.26	0.21	99.65	4.55
7	0.22	1.27	2.76	95.75	0.26	0.21	99.69	4.25
8	0.27	1.07	3.03	95.63	0.26	0.21	99.69	4.37
9	0.23	0.97	2.69	96.11	0.26	0.21	99.72	3.89
10	0.21	1.19	3.09	95.51	0.26	0.21	99.68	4.49
Average	0.26	1.14	2.87	95.73	0.26	0.21	99.69	4.27
				Standard Deviation				0.2204

Table 5-7. Summary of the Results from Computer Simulation Based on 1999 FDOT Specification for Sample Size = 6, Offset = 0.15, and Standard Deviation = 0.21

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.33	0.66	4.24	94.77	0.26	0.21	99.66	5.23
2	0.39	0.66	4.33	94.63	0.26	0.21	99.64	5.37
3	0.48	0.83	4.41	94.27	0.26	0.21	99.60	5.73
4	0.38	0.67	4.26	94.69	0.26	0.21	99.64	5.31
5	0.33	0.67	4.04	94.96	0.26	0.21	99.66	5.04
6	0.31	0.76	4.23	94.70	0.26	0.21	99.65	5.30
7	0.34	0.89	4.15	94.62	0.26	0.21	99.64	5.38
8	0.44	0.86	4.28	94.42	0.26	0.21	99.61	5.58
9	0.33	0.69	4.33	94.65	0.26	0.21	99.65	5.35
10	0.38	0.80	4.30	94.52	0.26	0.21	99.63	5.48
Average	0.37	0.75	4.26	94.62	0.26	0.21	99.64	5.38
				Standard Deviation				0.1894

possibility the specifications lack of effectiveness. The ideal pay factor tolerances should give contractors and highway agencies consistent risk no matter how many samples are taken from each lot.

In order to develop new asphalt content tolerances which yield the same risk or approximately the same risk, a trial and error was done. The target value of the PF distribution and percentage of lot with pay reduction was estimated from the quality level that the contractors provide by finding the average of the PF distribution and percentage of lot with pay reduction of all sample sizes, as shown in Table 5-8. The asphalt content population offset and standard deviation, which are 0.15% and 0.21%, were entered as inputs in the computer simulation program. The new tolerances were determined by trial and error of tolerances that yield the target PF output. At each set of pay factor tolerances of one particular sample size, the computer program was run 10 times. The average of PF distribution of these 10 runs was then calculated. When pay factor is estimated based on the recommended tolerances, the average of PF distribution should yield approximately 0.25% at 80% PF, 0.75% at 90% PF, 2.80% at 95% PF, 96.21% at 100% PF. Moreover, the average PF should be close to 99.74% and the percentage of lots with pay reduction should be close to 3.79% (see Table 5-8).

Tables 5-9 through 5-11 show the computer simulation PF distribution results based on recommended tolerances of sample sizes 1, 2, and 6, respectively. New tolerances were not recommended for sample sizes 3, 4, and 5 because the existing tolerances already yielded the PF distribution close to the target distribution (see Tables 5-4 through 5-6).

Table 5-12 shows the comparison of the current FDOT asphalt content specification and the recommended specification tolerances of type S asphaltic concrete. For sample size = 1 and 2, the recommended tolerances are more restricted than the existing specification. Conversely, the recommended tolerances are less restricted for sample size = 6.

Table 5-8. Results of the Average of PF Distribution and Percentage of Lot with Pay Reduction of All Sample Sizes that are used as Target Values to Develop New Tolerances (Offset = 0.15, Standard Deviation = 0.21)

Sample Size	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
n=1	0.20	0.49	2.03	97.29	0.26	0.21	99.81	2.71
n=2	0.23	0.60	2.20	96.98	0.26	0.21	99.78	3.02
n=3	0.18	0.70	2.57	96.55	0.26	0.21	99.77	3.45
n=4	0.23	0.81	2.88	96.08	0.26	0.21	99.73	3.92
n=5	0.26	1.14	2.87	95.73	0.26	0.21	99.69	4.27
n=6	0.37	0.75	4.26	94.62	0.26	0.21	99.64	5.38
Average	0.25	0.75	2.80	96.21	0.26	0.21	99.74	3.79

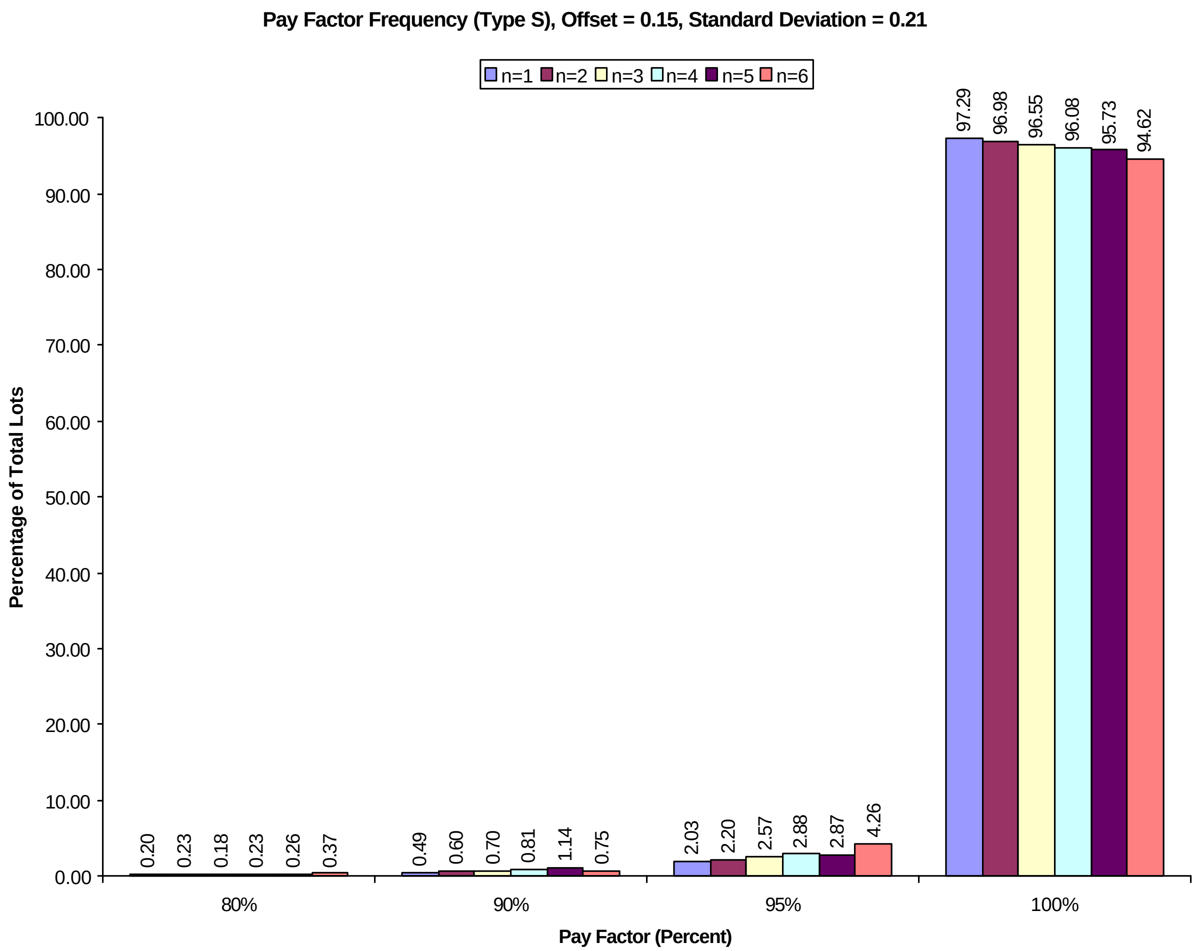


Figure 5-5. Pay Factor Frequency Plot of Type S Asphaltic Concrete gotten from Computer Simulation when Offset = 0.15 and Standard Deviation = 0.21

Table 5-9. Summary of Trial and Error Results from Computer Simulation when Sample Size = 1

Try:	0.00-0.52 for 100%Pf	0.53-0.63 for 95%PF
	0.64-0.75 for 90%PF	≥ 0.76 for 80% PF

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.20	0.76	2.74	96.30	0.26	0.21	99.75	3.70
2	0.26	0.79	2.82	96.13	0.26	0.21	99.73	3.87
3	0.27	0.57	3.09	96.07	0.26	0.21	99.74	3.93
4	0.12	0.91	2.51	96.45	0.26	0.21	99.76	3.55
5	0.17	0.95	2.76	96.12	0.26	0.21	99.73	3.88
6	0.28	0.85	2.77	96.09	0.26	0.21	99.72	3.91
7	0.16	0.73	2.65	96.47	0.26	0.21	99.76	3.53
8	0.16	0.63	2.52	96.69	0.26	0.21	99.78	3.31
9	0.17	0.72	3.07	96.04	0.26	0.21	99.74	3.96
10	0.23	0.89	3.11	95.77	0.26	0.21	99.71	4.23
Average	0.20	0.78	2.80	96.21	0.26	0.21	99.74	3.79

Table 5-10. Summary of Trial and Error Results from Computer Simulation when Sample Size = 2

Try: 0.00-0.42 for 100%Pf 0.43-0.50 for 95%PF

0.51-0.57 for 90%PF ≥ 0.58 for 80% PF

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.41	0.73	2.65	96.20	0.26	0.21	99.71	3.80
2	0.20	0.69	2.41	96.70	0.26	0.21	99.77	3.30
3	0.20	0.54	2.43	96.83	0.26	0.21	99.78	3.17
4	0.21	0.81	2.55	96.42	0.26	0.21	99.75	3.58
5	0.19	0.73	2.71	96.37	0.26	0.21	99.75	3.63
6	0.12	0.85	2.54	96.46	0.26	0.21	99.76	3.51
7	0.23	0.81	2.93	96.04	0.26	0.21	99.73	3.96
8	0.22	0.59	2.93	96.27	0.26	0.21	99.75	3.73
9	0.20	0.71	2.46	96.63	0.26	0.21	99.77	3.37
10	0.22	0.68	2.75	96.35	0.26	0.21	99.75	3.65
Average	0.22	0.71	2.64	96.43	0.26	0.21	99.75	3.57

Table 5-11. Summary of Trial and Error Results from Computer Simulation when Sample Size = 6

Try: 0.00-0.32 for 100%PF 0.33-0.36 for 95%PF

0.37-0.40 for 90%PF ≥ 0.41 for 80% PF

No. of Run	Pay Factor				CI	AAD	PF	% of Lots with Pay Reduction
	80%	90%	95%	100%				
1	0.32	0.89	2.86	95.93	0.26	0.21	99.70	4.07
2	0.31	0.95	2.94	95.79	0.26	0.21	99.69	4.21
3	0.20	0.91	2.97	95.92	0.26	0.21	99.72	4.08
4	0.22	0.87	2.77	96.15	0.26	0.21	99.73	3.85
5	0.30	0.81	2.85	96.03	0.26	0.21	99.72	3.97
6	0.27	0.91	3.05	95.77	0.26	0.21	99.70	4.23
7	0.21	0.74	2.74	96.31	0.26	0.21	99.75	3.69
8	0.25	0.94	2.96	95.85	0.26	0.21	99.71	4.15
9	0.22	0.89	2.69	96.21	0.26	0.21	99.73	3.79
10	0.27	0.90	2.81	96.01	0.26	0.21	99.71	3.99
Average	0.26	0.88	2.86	96.00	0.26	0.21	99.72	4.00

Table 5-12. Comparison of Existing FDOT Specification and Recommended Asphalt Content Tolerances (when S = 0.21, Offset = 0.15) for Type S Asphaltic Concrete

Sample Size	Pay Factor	1999 FDOT Specification	Recommended Tolerances
1	100%	0.00-0.55	0.00-0.52
	95%	0.56-0.65	0.53-0.63
	90%	0.66-0.75	0.64-0.75
	80%	≥ 0.76	≥ 0.76
2	100%	0.00-0.43	0.00-0.42
	95%	0.44-0.50	0.43-0.50
	90%	0.51-0.57	0.51-0.57
	80%	≥ 0.58	≥ 0.58
3	100%	0.00-0.38	0.00-0.38
	95%	0.39-0.44	0.39-0.44
	90%	0.45-0.50	0.45-0.50
	80%	≥ 0.51	≥ 0.51
4	100%	0.00-0.35	0.00-0.35
	95%	0.36-0.40	0.36-0.40
	90%	0.41-0.45	0.41-0.45
	80%	≥ 0.46	≥ 0.46
5	100%	0.00-0.33	0.00-0.33
	95%	0.34-0.37	0.34-0.37
	90%	0.38-0.42	0.38-0.42
	80%	≥ 0.43	≥ 0.43
6	100%	0.00-0.31	0.00-0.32
	95%	0.32-0.36	0.33-0.36
	90%	0.37-0.39	0.37-0.40
	80%	≥ 0.40	≥ 0.41

CHAPTER 6
CONCLUSION AND RECOMMENDATIONS

6.1 Research Summary

Specifications are the communication means that tell the contractor what level of construction quality is desired. However, it is not clear what quality level is being asked for in most highway construction specifications. Either a lower quality level or an unnecessarily higher quality level than that desired can be a detriment to society and the travelling public. The lower quality level results in a highway that will exhibit premature distresses (potholes, roughness, cracking, etc.) and will need added maintenance or early rehabilitation, often increasing highway user delay costs and accident potential. The unnecessary higher quality level invariably results in higher initial construction costs.

Even though the quality assurance specifications are generally believed to be an improvement over recipe specifications, no one has actually quantified their effectiveness yet. Some may be effective, but others not; all can probably be improved. In this research, a method was developed to assess the effectiveness of highway construction specifications. Up until now, no truly objective method existed that could be applied to any state highway agency's specifications. According to the method in this research, a specification is effective when the quality level that the highway agency wants is the same as the quality level the highway agency specifies and the same as the quality level that the contractors are providing.

The method was tested and demonstrated on the pavement density and asphalt content data obtained from FDOT's type S asphaltic concrete from years 1991 to 1999 obtained from the FDOT. A computer program called AAD1_5 was developed to assist with asphalt content data analysis. The AAD1_5 program helps to relate statistical parameters (offset and standard deviation) that were estimated from the CQR data analysis to AAD, the statistical parameter that was specified in FDOT asphalt content specification. It was concluded that the 1999 FDOT construction specifications lack effectiveness. There were several inconsistencies between what FDOT wants, what FDOT specifies, and what FDOT is getting.

In an attempt to identify the quality level the FDOT wants, a literature review was conducted and a questionnaire was used to survey FDOT and contractor personnel. Although the result was not confidently conclusive in addressing the population parameter that FDOT wants, it was concluded that most FDOT respondents believed that currently specified quality levels should be raised. At the same time, most contractor respondents believe that currently specified quality levels should stay as they are. Even though the quality level desired was not positively identified, enough information was gathered to summarize that there were various inconsistencies that made the specifications ineffective.

Like most other states, FDOT is specifying several possible population quality levels allowing contractors to choose among different combinations of target means and standard deviations. However, FDOT is also specifying a different quality level at each sample size (n); it is here that FDOT cannot be correctly specifying what it wants. The risk of a contractor receiving pay reduction is different at each n for both density and asphalt content characteristics because a different quality level is being specified.

The density specification is based solely on the average value determined from field measurements. Since the specification lacks a variability requirement, a pavement may be compacted to the specified value in the specifications; however, it may have such variability associated with it that its future performance may be suspect. The data analysis shows that the density quality was improved significantly from 1997 to 1999 although the same specification was in effect as before.

The contractors are providing a similar asphalt content quality level at each sample size, while the specification specifies a different quality level. Therefore, there are some inconsistencies between what FDOT is asking for and what it is getting.

Recommendations were made in this research to improve FDOT's specifications and increase their effectiveness. Recommendations for improving the CQR database were also provided. Currently, FDOT is implementing new specifications, with features in line with the recommendations of this research. In addition, the statistical parameters determined in this research can be used by FDOT to evaluate how the new specifications will perform.

Besides evaluating specification effectiveness, the methodology documented in this research can be used by FDOT or any other state highway agencies to monitor their specifications. For FDOT, the values of the statistical parameters presented in this research can provide a baseline quality level from which one can assess whether the quality level provided by contractor in the future is improving (as should be the case with new specifications or with new construction procedures and developments).

Some research needs were also identified. Among those needs, it is critical that FDOT and other state highway agencies formally address and answer the important basic question: "What quality do we want?" Ideally, the desired quality should be the optimum quality that results in the lowest life cycle cost of the construction. Only when the optimum level is specified and delivered can an agency claim it has not only effective specifications but truly cost-effective specifications.

6.2 Research Findings and Recommendations

The results, recommendations, and the approach to quantify the specification effectiveness in this dissertation, if adopted, will enhance the FDOT's ability to develop effective and efficient quality assurance specifications.

The results of this research were as follows:

1. FDOT density and asphalt content specifications are ineffective.
    - A different mean density quality level is being specified at each sample size; therefore, a different risk is applied to different sample sizes. Density specifications should be revised so that the same population quality level is specified for all possible sample sizes.
    - To obtain better quality, the density acceptance schedule should be a function of both the mean and the standard deviation. Without a variability requirement, contractors are allowed to perform process manipulation in order to get 100% payment.
    - The density quality level provided by Florida contractors improved significantly from 1997 to 1999, but the same specifications were in effect as before.

- A different asphalt content quality level is being specified at each sample size; however, contractors are providing the same asphalt content quality level at each sample size. There is more risk of rejected lots when taking a larger sample size than a smaller sample size. The solution to this problem can be done by slightly changing some of FDOT's AAD tolerances. FDOT can use AAD software to make other changes that may desired to decrease acceptance risks.
- FDOT should consider giving pay adjustment bonuses to contractors for providing high quality work. Without bonuses, contractors cannot expect to receive 100% pay in the long run, no matter how good a quality level they provide.

2. Statistical parameters from CQR database.

- The estimation of pavement density statistical parameters.

    1) Mean = 99.6% of the control strip density
    2) Pooled between-lot standard deviation* = 2.0% of the control strip density
    3) Pooled between-lot standard deviation (1997-1999)* = 1.8% of the control strip density
    4) Average pay factor = 99.7%
    5) Percentage of lots with pay reduction = 3.2%

(* Note: The "between-lot" values provided are to be interpreted as "within-project, same mix design.")

- The estimation of asphalt content statistical parameters.

    1) Corrected median within-lot standard deviation = 0.18%

2) Corrected average within-lot standard deviation = 0.21%

3) Average between-lot standard deviation** = 0.26%

4) Pooled between-lot standard deviation** = 0.27%

5) Pooled Within-lot conformal index = 0.28%

6) Pooled Between-lot conformal index** = 0.29%

7) Offset = 0.15%

8) Average lot AAD = 0.22%

9) Average pay factor = 99.04%

10) Percentage of lots with pay reduction = 7.1%

(** Note: The "between-lot" values provided are to be interpreted as "within-project.")

3. For better estimation of statistical parameters for density, the individual density test results need to be recorded in the CQR database. With the individual test results data, the within-lot standard deviation can be estimated and the number of samples per lot will be known.

4. FDOT should clearly and explicitly state the quality level it is specifying, i.e., the acceptance quality level (AQL).

5. FDOT should monitor its specifications for changes in quality levels. When quality has increased from one year to another (as it did for density in the 1997-1999 time period), an increase in the specified quality level may be in order to reflect the increased contractor capability.

6. FDOT should use the statistical parameters (determined in this research or updated as necessary) when developing new specifications.

7. The approach used to quantify specification effectiveness in this dissertation should be used by FDOT and any other highway agency to monitor their specifications to determine whether statistical parameters are changing. It is easier to determine statistical parameters when there are few projects (or lots) with considerable data per lot. The procedure developed in this dissertation should provide the guidance to enable FDOT and other state highway agencies to summarize statistic quality parameters when there are many lots but little data per lot, such as in CQR.

6.3 Recommendation for Future Research

The acceptance decision in quality assurance specifications depends on the measure of test result statistical parameters. However, research to correlate quality parameters that contractors are providing (recorded in CQR database) with performance data (condition surveys) should be done in order to help highway agencies answer the question "what do we want?" Ideally, the desired quality should be the optimum quality, i.e., a quality level not so great as to result in overly high initial construction costs and not so low as to lead to poor performance of the constructed item. In other words, the optimum quality level should be that which results in the lowest life cycle cost of the construction. Only when the optimum level is specified and delivered can an agency claim it has not only effective specifications but truly cost-effective specifications. Quality statistical parameters when linked with performance data can further be used to determine which method of determining overall payment (weight, multiplication, sums, minimum pay, average pay, or other method) best reflects performance.

Development of integrated software for a quality assurance database is suggested. The job mix formula and CQR database were stored within individual programs and cannot be accessed and analyzed as a whole. There is a need to link them together so that the effectiveness of quality assurance specifications and processes can be assessed and improved. Moreover, the performance data should also be integrated.

The FDOT and other highway agencies should not only use the approach taken in this research to monitor and improve their specifications for type S asphaltic concrete material but also for other materials (e.g., portland cement concrete, Superpave) and other quality characteristics (e.g., gradation and thickness). When the quality level has increased from one year to another, an increase in the specified quality level may be in order to reflect the increased contractor capability.

APPENDIX A
FACTORS FOR ESTIMATING UNIVERSE STANDARD DEVIATIONS

Number of Observation in Subgroup	C_4
2	0.7979
3	0.8862
4	0.9213
5	0.9400
6	0.9515
7	0.9594
8	0.9650
9	0.9693
10	0.9727
11	0.9754
12	0.9776
13	0.9794
14	0.9810
15	0.9823
16	0.9835
17	0.9845
18	0.9854
19	0.9862
20	0.9869
21	0.9876
22	0.9882
23	0.9887
24	0.9892
25	0.9896
26	0.9901
27	0.9904
28	0.9908
29	0.9911
30	0.9914

Source: Burr, Irving W. 1976. *Statistical Quality Methods.* Marcel Dekker, Inc., New York.
Note: c_4 is the ratio of the mean of standard deviation to universe standard deviation.

APPENDIX B
FDOT QUESTIONNAIRE

Dear Sir / Madam,

A high level of quality in highway materials and construction leads to high performance pavements and structures that can serve well past their design life. One of the most important ways to assure a high level of materials and construction quality is to properly specify the desired quality level. Often, however, specifications describe desired quality in statistical terms; and it may be difficult, both for the contractor and the agency, to interpret just what quality level is being sought.

To help us better understand how FDOT's specifications are being interpreted, I am seeking your cooperation in completing the enclosed short questionnaire. The purpose of the questionnaire is to study the perceptions of key contractor and agency personnel with respect to the quality levels being specified in FDOT's standard specifications book. The questionnaire is a part of a larger study which is expected to result in improved specifications and subsequent improvements in construction quality and pavement performance. Your response is important to us and will be kept highly confidential.

I would like to thank you in advance for thoughtfully completing the questionnaire. Please return your response using stamped envelope provided to:

Dr. Fazil T. Najafi, Associate Professor
Attn: Sutharin Pathomvanich, Graduate Student
345 Weil Hall
PO Box 116580
Gainesville, FL 32611-2450
E-mail: sutharin@grove.ufl.edu

Upon the completion of this study, please let me know if you desire to have the conclusion of this study.

Respectfully yours,

Fazil T. Najafi, PhD
Phone: (352) 392-1033
Fax: (352) 392-3394

Instructions: The questions below apply to FDOT's hot-mix asphalt quality levels specified for asphalt content and density. Specifically, they are meant to be answered with respect to Type S mixes governed by FDOT's current (latest) standard specifications. You may want to refer to FDOT's specifications when answering the questions. Please check only one box under each column of boxes and answer every question. If you don't understand a question, please contact Sutharin Pathomvanich, University of Florida graduate student, at (352) 392-9531; e-mail: sutharin@grove.ufl.edu.

Note: For those not familiar with the standard deviation, the following is a brief explanation to assist you in completing the questionnaire: Most test results obtained from materials and construction processes vary according to a normal distribution (bell-shaped) curve. The standard deviation is a measure of this variability. Conceptually, when the test results are normally distributed,

- *About 68% of the results are within one standard deviation of the mean (m +/- s).*
- *About 95% of the results are within two standard deviations of the mean (m +/- 2s).*
- *Almost all (about 99.7%) of the results are within three standard deviations of the mean (m +/- 3s).*

According to NCHRP Synthesis of Highway Practice 232, some typical standard deviation values for the asphalt content percentage from extraction tests are: 0.15 (in Colorado, 1993), 0.18 (in Virginia, 1994), 0.21 (in Arkansas, 1994), and 0.24 (in Washington, 1993).

Name________________________________ Position________________________
Phone_______________

1. What would you say is that minimum quality level, according to the specifications, for which FDOT is willing to pay 100 percent (i.e., no price reduction)?

For asphalt content (AC) , mean value	For asphalt content, standard deviation (sd)
~ AC exactly at JMF design value	~ sd of 0.10 or less
~ 0.1 offset from JMF design value	~ sd of 0.11 to 0.20
~ 0.2 offset from JMF design value	~ sd of 0.21 to 0.30
~ 0.3 offset from JMF design value	~ sd of 0.31 to 0.40
~ 0.4 offset from JMF design value	~ sd of 0.41 or more
~ Do not know	~ Do not know

2. Do you believe the minimum asphalt content quality level for which FDOT is willing to pay 100 percent should be changed?

~ No, it is OK as is

~ Yes, it should be raised (the specifications should be tightened and/or a higher level of quality should be specified)

~ Yes, it should be lowered (the specifications should be loosened and/or a lower level of quality should be specified)

Comments?____
____
____

3. What would you say is that minimum quality level, according to the specifications, for which FDOT is willing to pay 100 percent (i.e., no price reduction)?

For density, % of control strip, mean value

~ 100% or more
~ 99.0 to less than 100%
~ 98.0 to less than 99.0%
~ 97.0 to less than 98.0%
~ 96.0 to less than 97.0%
~ Less than 96%
~ Do not know

For density, standard deviation (sd)

~ sd of 0.5% or less
~ sd of 0.51 to 1%
~ sd of 1.01 to 2%
~ sd of 2.01 to 3%
~ sd of 3.01% or more
~ Do not know

4. Do you believe the minimum density quality level for which FDOT is willing to pay 100 percent should be changed?

~ No, it is OK as is
~ Yes, it should be raised (the specifications should be tightened and/or a higher level of quality should be specified)
~ Yes, it should be lowered (the specifications should be loosened and/or a lower level of quality should be specified)

Comments?____
____
____

Thank You

APPENDIX C
CONTRACTOR QUESTIONNAIRE

Dear Sir / Madam,

A high level of quality in highway materials and construction leads to high performance pavements and structures that can serve well past their design life. One of the most important ways to assure a high level of materials and construction quality is to properly specify the desired quality level. Often, however, specifications describe desired quality in statistical terms; and it may be difficult, both for the contractor and the agency, to interpret just what quality level is being sought.

To help us better understand how FDOT's specifications are being interpreted, I am seeking your cooperation in completing the enclosed short questionnaire. The purpose of the questionnaire is to study the perceptions of key contractor and agency personnel with respect to the quality levels being specified in FDOT's standard specifications book. The questionnaire is a part of a larger study which is expected to result in improved specifications and subsequent improvements in construction quality and pavement performance. Your response is important to us and will be kept highly confidential.

I would like to thank you in advance for thoughtfully completing the questionnaire.
Please return your response using stamped envelope provided to:

Dr. Fazil T. Najafi, Associate Professor
Attn: Sutharin Pathomvanich, Graduate Student
345 Weil Hall
PO Box 116580
Gainesville, FL 32611-2450
E-mail: sutharin@grove.ufl.edu

Upon the completion of this study, please let me know if you desire to have the conclusion of this study.

Respectfully yours,

Fazil T. Najafi, PhD
Phone: (352) 392-1033
Fax: (352) 392-3394

Instructions: The questions below apply to FDOT's hot-mix asphalt quality levels specified for asphalt content and density. Specifically, they are meant to be answered with respect to Type S mixes governed by FDOT's current (latest) standard specifications. You may want to refer to FDOT's specifications when answering the questions. Please check only one box under each column of boxes and answer every question. If you don't understand a question, please contact Sutharin Pathomvanich, University of Florida graduate student, at (352) 392-9531; e-mail: sutharin@grove.ufl.edu.

Note: For those not familiar with the standard deviation, the following is a brief explanation to assist you in completing the questionnaire: Most test results obtained from materials and construction processes vary according to a normal distribution (bell-shaped) curve. The standard deviation is a measure of this variability. Conceptually, when the test results are normally distributed,

- About 68% of the results are within one standard deviation of the mean (m +/- s).
- *About 95% of the results are within two standard deviations of the mean (m +/- 2s).*
- *Almost all (about 99.7%) of the results are within three standard deviations of the mean (m +/- 3s).*

According to NCHRP Synthesis of Highway Practice 232, some typical standard deviation values for the asphalt content percentage from extraction tests are: 0.15 (in Colorado, 1993), 0.18 (in Virginia, 1994), 0.21 (in Arkansas, 1994), and 0.24 (in Washington, 1993).

Name of organization____
Address of organization____
Person completing questionnaire:
Name____
Position______________________________________
Telephone number______________________________

1. What would you say is that minimum quality level, according to the specifications, for which FDOT is willing to pay 100 percent (i.e., no price reduction)?

<u>For asphalt content (AC), mean value</u>	<u>For asphalt content, standard deviation (sd)</u>
~ AC exactly at JMF design value	~ sd of 0.10 or less
~ 0.1 offset from JMF design value	~ sd of 0.11 to 0.20
~ 0.2 offset from JMF design value	~ sd of 0.21 to 0.30
~ 0.3 offset from JMF design value	~ sd of 0.31 to 0.40
~ 0.4 offset from JMF design value	~ sd of 0.41 or more
~ Do not know	~ Do not know

2. What would you say is the typical quality level your company assumes it will achieve? Consider, in your response, only projects done in the past year.

<u>For asphalt content (AC), mean value</u>	<u>For asphalt content, standard deviation (sd)</u>
~ AC exactly at JMF design value	~ sd of 0.10 or less
~ 0.1 offset from JMF design value	~ sd of 0.11 to 0.20
~ 0.2 offset from JMF design value	~ sd of 0.21 to 0.30
~ 0.3 offset from JMF design value	~ sd of 0.31 to 0.40
~ 0.4 offset from JMF design value	~ sd of 0.41 or more
~ Do not know	~ Do not know

3. Do you believe the minimum asphalt content quality level for which FDOT is willing to pay 100 percent should be changed?
~ No, it is OK as is
~ Yes, it should be raised (the specifications should be tightened and/or a higher level of quality should be specified)
~ Yes, it should be lowered (the specifications should be loosened and/or a lower level of quality should be specified)
Comments?____
____

4. What would you say is that minimum quality level, according to the specifications, for which FDOT is willing to pay 100 percent (i.e., no price reduction)?

For density, % of control strip, mean value	For density, standard deviation (sd)
~ 100% or more	~ sd of 0.5% or less
~ 99.0 to less than 100%	~ sd of 0.51 to 1%
~ 98.0 to less than 99.0%	~ sd of 1.01 to 2%
~ 97.0 to less than 98.0%	~ sd of 2.01 to 3%
~ 96.0 to less than 97.0%	~ sd of 3.01% or more
~ Less than 96%	~ Do not know
~ Do not know	

5. What would you say is the typical quality level your company assumes it will achieve? Consider, in your response, only projects done in the past year.

For density, %of control strip, mean value	For density, standard deviation (sd)
~ 100% or more	~ sd of 0.5% or less
~ 99.0 to less than 100%	~ sd of 0.51 to 1%
~ 98.0 to less than 99.0%	~ sd of 1.01 to 2%
~ 97.0 to less than 98.0%	~ sd of 2.01 to 3%
~ 96.0 to less than 97.0%	~ sd of 3.01% or more
~ Less than 96%	~ Do not know
~ Do not know	

6. Do you believe the minimum density quality level for which FDOT is willing to pay 100 percent should be changed?
~ No, it is OK as is
~ Yes, it should be raised (the specifications should be tightened and/or a higher level of quality should be specified)
~ Yes, it should be lowered (the specifications should be loosened and/or a lower level of quality should be specified)
Comments?____
____

Thank you

APPENDIX D
COMPUTER SIMULATION PROGRAM (AAD1_5) SCRIPTING CODE

```
Option Base 1

'Declaring Variables
Dim JMF As Single, Offset As Single, StdDev As Single   'Input
Dim n As Integer       'Number of sample size
Dim FreqPF100 As Integer, FreqPF95 As Integer, FreqPF90 As Integer, FreqPF80 As Integer   'Frequency
of each pay factor
Dim AvgAAD As Single, AvgPF As Single, AvgOffset As Single
Dim CI As Single, ReducPayLot As Single, AvgCI As Single
Dim Upper100 As Single, Upper95 As Single, Upper90 As Single
Dim Lower100 As Single, Lower95 As Single, Lower90 As Single, Lower80 As Single
Dim UpperLimit100 As Single, UpperLimit95 As Single, UpperLimit90 As Single
Dim DefaultTolerances As Boolean
Dim NewTolerances As Boolean
Dim CheckInput As Boolean
Dim ClearOutput As Boolean
Dim subgroup(15000) As Lot     'Array to keep 15000 test results simulation


Private Sub CmdChangeSpecs_Click()

'Check the validity of specs tolerances and saved in the array
Call CheckToleranceInput
CheckInput = True
comcalculate.Enabled = True

'Show a message when tolerances are valid
If NewTolerances = True Then
   Picmessage.Cls
   Picmessage.Print "New tolerances have been saved."
   Picmessage.Print "Next, click CALCULATE button."
End If

'Show a message when tolerances are valid
If (DefaultTolerances = False) And (NewTolerances = False) Then
   Picmessage.Cls
   Picmessage.Print "New tolerances have been saved."
   Picmessage.Print "Next, click CALCULATE button."
End If

End Sub


Private Sub Form_Load()

Row = 4
```

```
Column = 10
ReDim PayFactor(Row, Column) As Single

'Call function to save random no. and pay factor no. in the arrays
Call GETNORMRAN
Call GETPAYFACTOR

End Sub


Private Sub txtJMF_Change()

'Check if the input is appropriate.  If not, show message.
Call ClearScreen
Beginning1:
If (IsNumeric(txtJMF.Text)) Then
   If (txtJMF.Text <= 0) Then
      txtJMF.Text = InputBox("Enter new number.  Job Mix Formula has to be a positive number.")
      GoTo Beginning1
   End If
Else
   txtJMF.Text = InputBox("Enter new number.  Job Mix Formula has to be a positive number.")
   GoTo Beginning1
End If

JMF = txtJMF.Text

End Sub


Private Sub txtoffset_Change()

'Check if the input is appropriate.  If not, show message.
Call ClearScreen
Beginning2:
If (IsNumeric(txtoffset.Text)) Then
   If (txtoffset.Text < 0) Then
   txtoffset.Text = InputBox("Enter new number.  Offset must be an absolute value.  Zero must be
preceeding the decimal point.")
   GoTo Beginning2
   End If
Else
   txtoffset.Text = InputBox("Enter new number.  Offset must be an absolute value.  Zero must be
preceeding the decimal point.")
   GoTo Beginning2
End If

Offset = txtoffset.Text

End Sub


Private Sub txtS_Change()

'Check if the input is appropriate.  If not, show message.
Call ClearScreen
```

```
Beginning3:
If (IsNumeric(txtS.Text)) Then
   If (txtS.Text < 0) Then
   txtS.Text = InputBox("Enter new number.  Standard Deviation cannot be a negative value.  Zero must be
preceeding the decimal point.")
   GoTo Beginning3
   End If
Else
   txtS.Text = InputBox("Enter new number.  Standard Deviation cannot be a negative value.  Zero must be
preceeding the decimal point.")
   GoTo Beginning3
End If

StdDev = txtS.Text

End Sub


Private Sub txtn_Change()
Dim Message As String

'Check if the input is appropriate.  If not, show message.
Call ClearScreen
Beginning4:
If (IsNumeric(txtn.Text)) Then
   If (txtn.Text <= 0) Or (txtn.Text > 10) Then
      txtn.Text = InputBox("Enter new number.  Sample size has to be a positive integer from 1 to 10.")
      GoTo Beginning4
   ElseIf ((CInt(txtn.Text) / txtn.Text) <> 1) Then
      txtn.Text = InputBox("Enter new number.  Sample size has to be a positive integer from 1 to 10.")
      GoTo Beginning4
   End If
Else
   txtn.Text = InputBox("Enter new number.  Sample size has to be a positive integer from 1 to 10.")
   GoTo Beginning4
End If

n = txtn.Text

'Show the default tolerances in the boxes when no. of sample size is specified
TxtLower100.Text = Format((PayFactor(1, n)), "#0.00")
TxtLower95.Text = Format((PayFactor(2, n)), "#0.00")

UpperLimit100 = Round((PayFactor(2, n) - 0.01), 2)
If UpperLimit100 >= 0 Then
   TxtUpper100.Text = Format(UpperLimit100, "#0.00")
Else
   TxtUpper100.Text = Format(0, "#0.00")
End If

Txtlower90.Text = Format((PayFactor(3, n)), "#0.00")

UpperLimit95 = Round((PayFactor(3, n) - 0.01), 2)
If UpperLimit95 >= 0 Then
   TxtUpper95.Text = Format(UpperLimit95, "#0.00")
Else
```

```
   TxtUpper95.Text = Format(0, "#0.00")
End If

TxtLower80.Text = Format((PayFactor(4, n)), "#0.00")

UpperLimit90 = Round((PayFactor(4, n) - 0.01), 2)
If UpperLimit90 >= 0 Then
   TxtUpper90.Text = Format(UpperLimit90, "#0.00")
Else
   TxtUpper90.Text = Format(0, "#0.00")
End If

'Provide instruction to users
Picmessage.Cls
Picmessage.Print "If the specification tolerances when sample"
Picmessage.Print "size = "; n & " needs to be changed, CLICK"
Picmessage.Print "the CHANGE SPECIFICATIONS"
Picmessage.Print "TOLERANCES button AFTER"
Picmessage.Print "entering new tolerances.  The tolerances"
Picmessage.Print "are limited to two decimal."

End Sub


Private Sub TxtLower100_Change()
Dim RdLower100 As Single, RdTxtLower100 As Single

'Not allow tolerances entering without entering the sample size
Call ClearScreen
Begin1:
If IsNumeric(txtn.Text) Then
Else
   txtn.Text = InputBox("Number of sample size is not entered.  You must enter now.  Sample size must be
a positive integer from 1 to 10.")
   GoTo Begin1
End If

End Sub


Private Sub TxtLower95_Change()
Dim RdLower95 As Single, RdTxtLower95 As Single

'Not allow tolerances entering without entering the sample size
Call ClearScreen
Begin2:
If IsNumeric(txtn.Text) Then
Else
   txtn.Text = InputBox("Number of sample size is not entered.  You must enter now.  Sample size must be
a positive integer from 1 to 10.")
   GoTo Begin2
End If

End Sub
```

```
Private Sub Txtlower90_Change()
Dim RdLower90 As Single, RdTxtLower90 As Single

'Not allow tolerances entering without entering the sample size
Call ClearScreen
Begin3:
If IsNumeric(txtn.Text) Then
Else
   txtn.Text = InputBox("Number of sample size is not entered.  You must enter now.  Sample size must be
a positive integer from 1 to 10.")
   GoTo Begin3
End If

End Sub


Private Sub TxtLower80_Change()
Dim RdLower80 As Single, RdTxtLower80 As Single

'Not allow tolerances entering without entering the sample size
Call ClearScreen
Begin4:
If IsNumeric(txtn.Text) Then
Else
   txtn.Text = InputBox("Number of sample size is not entered.  You must enter now.  Sample size must be
a positive integer from 1 to 10.")
   GoTo Begin4
End If

End Sub


Private Sub CheckToleranceInput()

'Check the validity of tolerances input.  If invalid, use default no.
CheckInput = False
If (IsNumeric(TxtLower100.Text)) And (IsNumeric(TxtLower95.Text)) And
(IsNumeric(Txtlower90.Text)) And (IsNumeric(TxtLower80.Text)) Then
   If (TxtLower100.Text >= 0) And (TxtLower95.Text >= 0) And (Txtlower90.Text >= 0) And
(TxtLower80.Text >= 0) Then
      If (TxtLower100.Text = 0) Then
            Lower100 = Round(TxtLower100.Text, 2)
            Lower95 = Round(TxtLower95.Text, 2)
            Lower90 = Round(Txtlower90.Text, 2)
            Lower80 = Round(TxtLower80.Text, 2)
            Upper100 = Round(Lower95 - 0.01, 2)
            Upper95 = Round(Lower90 - 0.01, 2)
            Upper90 = Round(Lower80 - 0.01, 2)
         If (Lower95 - Lower100 >= 0.01) And (Lower90 - Lower95 >= 0.01) And (Lower80 - Lower90 >=
0.01) Then
            'Check wheather the new tolerance input is the same as in the array.  If yes, exit.  If not, save in
the array
            If (PayFactor(1, n) = Lower100) And (PayFactor(2, n) = Lower95) And (PayFactor(3, n) =
Lower90) And (PayFactor(4, n) = Lower80) Then
               TxtLower100.Text = Format(Lower100, "#0.00")
               TxtLower95.Text = Format(Lower95, "#0.00")
```

```
                If Upper100 >= 0 Then
                   TxtUpper100.Text = Format(Upper100, "#0.00")
                Else
                   TxtUpper100.Text = Format(0, "#0.00")
                End If
                Txtlower90.Text = Format(Lower90, "#0.00")
                If Upper95 >= 0 Then
                   TxtUpper95.Text = Format(Upper95, "#0.00")
                Else
                   TxtUpper95.Text = Format(0, "#0.00")
                End If
                TxtLower80.Text = Format(Lower80, "#0.00")
                If Upper90 >= 0 Then
                   TxtUpper90.Text = Format(Upper90, "#0.00")
                Else
                   TxtUpper90.Text = Format(0, "#0.00")
                End If
                DefaultTolerances = False
                NewTolerances = False
                Exit Sub
             Else
                TxtLower100.Text = Format(Lower100, "#0.00")
                PayFactor(1, n) = Lower100
                TxtLower95.Text = Format(Lower95, "#0.00")
                PayFactor(2, n) = Lower95
                'Show upper limit value of full payment in the text box.
                TxtUpper100.Text = Format(Upper100, "#0.00")
                Txtlower90.Text = Format(Lower90, "#0.00")
                PayFactor(3, n) = Lower90
                'Show upper limit value of 95% pay in the text box.
                TxtUpper95.Text = Format(Upper95, "#0.00")
                TxtLower80.Text = Format(Lower80, "#0.00")
                PayFactor(4, n) = Lower80
                'Show upper limit value of 90% pay in the text box.
                TxtUpper90.Text = Format(Upper90, "#0.00")
                NewTolerances = True
                DefaultTolerances = False
                Exit Sub
             End If
          Else
             MsgBox "Invalid tolerances input, enter new values.  The tolerance limits increase as the
payment deduction increases."
             GoTo DefaultTolerances
          End If
       Else
          MsgBox "Invalid tolerances input, enter new values.  The lower limit for full payment must equal to
0."
          GoTo DefaultTolerances
       End If
    Else
       MsgBox "Invalid tolerances input, enter new values.  All of the tolerances need to be positive
numbers."
       GoTo DefaultTolerances
    End If
Else
    MsgBox "Invalid tolerances input, enter new values.  All of the tolerances need to be positive numbers."
```

```
    GoTo DefaultTolerances
End If

DefaultTolerances:
    Lower100 = Round(PayFactor(1, n), 2)
    TxtLower100.Text = Format(Lower100, "#0.00")

    Lower95 = Round(PayFactor(2, n), 2)
    TxtLower95.Text = Format(Lower95, "#0.00")
    Upper100 = Round((Lower95 - 0.01), 2)
    If Upper100 >= 0 Then
        TxtUpper100.Text = Format(Upper100, "#0.00")
    Else
        TxtUpper100.Text = Format(0, "#0.00")
    End If
    Lower90 = Round(PayFactor(3, n), 2)
    Txtlower90.Text = Format(Lower90, "#0.00")
    Upper95 = Round((Lower90 - 0.01), 2)
    If Upper95 >= 0 Then
        TxtUpper95.Text = Format(Upper95, "#0.00")
    Else
        TxtUpper95.Text = Format(0, "#0.00")
    End If
    Lower80 = Round(PayFactor(4, n), 2)
    TxtLower80.Text = Format(Lower80, "#0.00")
    Upper90 = Round((Lower80 - 0.01), 2)
    If Upper90 >= 0 Then
        TxtUpper90.Text = Format(Upper90, "#0.00")
    Else
        TxtUpper90.Text = Format(0, "#0.00")
    End If
    DefaultTolerances = True
    NewTolerances = False
    Exit Sub
End Sub


Private Sub comcalculate_GotFocus()

'Show a message to the user, what is going on.
Picmessage.Cls
Picmessage.Print "Wait! Computer is calculating."

End Sub


Private Sub comcalculate_Click()

Dim count As Integer        'Loop counter
Dim counter As Integer      'Loop counter
Dim SumAbsDev As Single, SumCI As Single, SumDiffJMF As Single
Dim LotSqCI As Single, LotCI As Single
Dim SumSqCI As Single
Dim SumLotSqCI As Single, SumLotCI As Single
Dim NormRnd As Single
```

```
comcalculate.Enabled = False
'Check the validity of sample size input
Begin1:
If IsNumeric(txtn.Text) Then
   If (txtn.Text > 0) And (txtn.Text <= 10) Then
      n = txtn.Text
      For counter = 1 To 15000
         ReDim subgroup(counter).x(1 To n) As Single
      Next counter
   Else
      txtn.Text = InputBox("Enter new number.  Sample size has to be a positive integer from 1 to 10.")
      GoTo Begin1
   End If
Else
   txtn.Text = InputBox("Enter new number.  Sample size has to be a positive integer from 1 to 10.")
   GoTo Begin1
End If

'Check the validity of JMF input
Begin2:
If (IsNumeric(txtJMF.Text)) Then
   If (txtJMF.Text > 0) Then
      JMF = txtJMF.Text
   Else
      txtJMF.Text = InputBox("Enter new number.  Job Mix Formula has to be a positive number.")
      GoTo Begin2
   End If
Else
   txtJMF.Text = InputBox("Enter new number.  Job Mix Formula has to be a positive number.")
   GoTo Begin2
End If

'Check the validity of offset input
Begin3:
If (IsNumeric(txtoffset.Text)) Then
   If (txtoffset.Text >= 0) Then
      Offset = txtoffset.Text
   Else
      txtoffset.Text = InputBox("Enter new number.  Offset must be an absolute value.  Zero must be
preceeding the decimal point.")
      GoTo Begin3
   End If
Else
   txtoffset.Text = InputBox("Enter new number.  Offset must be an absolute value.  Zero must be
preceeding the decimal point.")
   GoTo Begin3
End If

'Check the validity of standard deviation input
Begin4:
If (IsNumeric(txtS.Text)) Then
   If (txtS.Text >= 0) Then
      StdDev = txtS.Text
   Else
      txtS.Text = InputBox("Enter new number.  Standard Deviation cannot be a negative value.  Zero must
be preceeding the decimal point.")
```

```
        GoTo Begin4
    End If
Else
    txtS.Text = InputBox("Enter new number.  Standard Deviation cannot be a negative value.  Zero must be
preceeding the decimal point.")
    GoTo Begin4
End If

'Call function to check the validity of tolerance input
Call CheckToleranceInput

'Clear the message box before quitting the calculation.
If (TxtLower100.Text = 0) And (TxtLower95.Text = 0) And (Txtlower90.Text = 0) Then
   Picmessage.Cls
   comcalculate.Enabled = True
        If CheckInput = True Then
            CheckInput = False
        End If
   Exit Sub
End If

'Clear the message box before quitting the calculation
If (TxtLower80.Text <= Txtlower90.Text) And (Txtlower90.Text <= TxtLower95.Text) And
(TxtLower95.Text <= TxtLower100.Text) Then
    comcalculate.Enabled = True
    Picmessage.Cls
        If CheckInput = True Then
            CheckInput = False
        End If
End If

'User must click the apply new tolerance input to save new toleraces before processing the calculation.
If CheckInput = True Then
Else
    If NewTolerances = True Then
        Picmessage.Cls
        MsgBox "Click apply new tolerances button before click calculate button."
        Exit Sub
    End If
End If

'Show a message and quit the calculation when the tolerance input is invalid.
If DefaultTolerances = True Then
    Picmessage.Cls
    Picmessage.Print "Invalid tolerances input, enter new positive"
    Picmessage.Print "numbers.  The tolerance limits increase as"
    Picmessage.Print "the payment deduction increases."
    comcalculate.Enabled = True
    Exit Sub
End If

'Start Calculation
SumLotSqCI = 0     'Set SumLotSqCI = 0 before start calculation
SumLotCI = 0       'set SumLotCI = 0 before start calculation
SumLotAAD = 0      'Set SumLotAAD = 0 before start calculation
SumLotOffset = 0   'Set SumLotOffset = 0 before start calculation
```

```
For counter = 1 To 15000    'Simulate 15000 lots of test results
   subgroup(counter).LotNo = counter
   SumAbsDev = 0
   SumCI = 0
   SumDiffJMF = 0
   'Obtaining ramdom no. and generating test results
   For count = 1 To n  'Simulate the testing values within a lot
      Randomize       'Change seed
      NormRnd = NormRan(Int(15993 * Rnd + 1))  'Get normal random no.
      subgroup(counter).x(count) = Round((JMF + Offset + (NormRnd * StdDev)), 2) 'Equation to generate
test values
      SumAbsDev = SumAbsDev + Abs(subgroup(counter).x(count) - JMF)  'Find SumAbsDev in each lot
      SumDiffJMF = SumDiffJMF + (subgroup(counter).x(count) - JMF)
      SumCI = SumCI + (subgroup(counter).x(count) - JMF) ^ 2
   Next count

   'Find lot parameter and add up some parameters for future calculation.
   subgroup(counter).LotAAD = (SumAbsDev / CSng(n))        'Find AAD in each lot.
   subgroup(counter).LotOffset = Abs(SumDiffJMF / CSng(n))
   LotSqCI = SumCI / CSng(n)        'Find CI^2 in each lot.
   subgroup(counter).LotCI = Sqr(LotSqCI)      'Find CI in each lot
   SumLotSqCI = SumLotSqCI + LotSqCI           'Add up
   SumLotCI = SumLotCI + subgroup(counter).LotCI
   SumLotAAD = SumLotAAD + subgroup(counter).LotAAD       'Add up
   SumLotOffset = SumLotOffset + subgroup(counter).LotOffset

'Find pay factor of each lot
   If (Round(subgroup(counter).LotAAD, 2) >= PayFactor(1, n)) And (Round(subgroup(counter).LotAAD,
2) < PayFactor(2, n)) Then
      subgroup(counter).LotPF = 100
   ElseIf (Round(subgroup(counter).LotAAD, 2) >= PayFactor(2, n)) And
(Round(subgroup(counter).LotAAD, 2) < PayFactor(3, n)) Then
      subgroup(counter).LotPF = 95
   ElseIf (Round(subgroup(counter).LotAAD, 2) >= PayFactor(3, n)) And
(Round(subgroup(counter).LotAAD, 2) < PayFactor(4, n)) Then
      subgroup(counter).LotPF = 90
   ElseIf (Round(subgroup(counter).LotAAD, 2) >= PayFactor(4, n)) Then
      subgroup(counter).LotPF = 80
   End If

Next counter

'Find lot frequency at each percentage of payment
FreqPF100 = 0
FreqPF95 = 0
FreqPF90 = 0
FreqPF80 = 0
For counter = 1 To 15000
   If subgroup(counter).LotPF = 100 Then
      FreqPF100 = FreqPF100 + 1
   ElseIf subgroup(counter).LotPF = 95 Then
      FreqPF95 = FreqPF95 + 1
   ElseIf subgroup(counter).LotPF = 90 Then
      FreqPF90 = FreqPF90 + 1
   ElseIf subgroup(counter).LotPF = 80 Then
      FreqPF80 = FreqPF80 + 1
```

```
   End If
Next counter

'Call funtion to display graph
Call DisplayGraphic

'Find CI & Avg. Pay Factor & Avg. AAD
CI = Sqr(SumLotSqCI / 15000)
AvgCI = (SumLotCI / 15000)
AvgAAD = (SumLotAAD / 15000)
AvgOffset = (SumLotOffset / 15000)
AvgPF = ((100 * CSng(FreqPF100)) + (95 * CSng(FreqPF95)) + (90 * CSng(FreqPF90)) + (80 *
CSng(FreqPF80))) / 15000
ReducPayLot = (FreqPF95 + FreqPF90 + FreqPF80) * (100 / 15000)
'Show summary of calculation results.
Call DisplayCI
comcalculate.Enabled = True
CheckInput = False
NewTolerances = False
DefaultTolerances = False
ClearOutput = True

End Sub


Private Sub DisplayGraphic()

Dim x As Single, Y As Single, z As Single
Dim Message As String
Dim PFvalue(4) As Integer
Dim Lots As Integer
Dim Freq(4) As Integer

'Center and print the heading with larger font
picOutput.Cls
picOutput.Font.Size = 12
picOutput.Font.Bold = True
Message = "Pay Factor Distribution"
length = picOutput.TextWidth(Message)
picOutput.CurrentX = (picOutput.ScaleWidth / 2) - length / 2
picOutput.Print Message

'Change the font size back to regular size
picOutput.Font.Size = 8
picOutput.Font.Bold = False

'Draw the x and y axes
picOutput.Line (20, 100)-(135, 100)
picOutput.Line (20, 100)-(20, 15)

'Draw a hash mark at every 25 units on the x axis
For x = 20 To 140 Step 25
   picOutput.Line (x, 99)-(x, 101)
Next x

'Draw a hash mark at every 5.5 units on the y axis
```

```
For Y = 100 To 15 Step -5.5
   picOutput.Line (19, Y)-(21, Y)
Next Y

'Show value on x axis
PFvalue(1) = 80
PFvalue(2) = 90
PFvalue(3) = 95
PFvalue(4) = 100
z = 104
picOutput.CurrentX = 10
For I = 1 To 4
   picOutput.CurrentX = 20 + (25 * I) - (picOutput.TextWidth(PFvalue(I))) / 2
   picOutput.CurrentY = z
   picOutput.Print PFvalue(I)
Next

'Label the x axis
xaxis = "Pay Factor (Percent)"
picOutput.CurrentX = 80 - (picOutput.TextWidth(xaxis)) / 2
picOutput.CurrentY = 109
picOutput.Print xaxis

'Show value on y axis
x = 10
For I = 1 To 15
   Lots = 1000 * I
   picOutput.CurrentX = x
   picOutput.CurrentY = 100 - (5.5 * I) - (picOutput.TextHeight(Lots)) / 2
   picOutput.Print Lots
Next

'Label the y axis
LetterHeight = 4
For I = 1 To 15
   picOutput.CurrentX = 6
   picOutput.CurrentY = 15 + (I * LetterHeight)
   picOutput.Print Mid$("Number of Lots", I, 1)
Next I

'Plot the graph
picOutput.Line (40, 100 - (80 * (FreqPF80 / 15000)))-(50, 100), QBColor(5), BF
picOutput.Line (65, 100 - (80 * (FreqPF90 / 15000)))-(75, 100), QBColor(9), BF
picOutput.Line (90, 100 - (80 * (FreqPF95 / 15000)))-(100, 100), QBColor(14), BF
picOutput.Line (115, 100 - (80 * (FreqPF100 / 15000)))-(125, 100), QBColor(12), BF

'Show value on each graph
x = 14
Freq(1) = FreqPF80
Freq(2) = FreqPF90
Freq(3) = FreqPF95
Freq(4) = FreqPF100

For I = 1 To 4
   picOutput.CurrentX = (x + I * 25)
   picOutput.CurrentY = 100 - (80 * (Freq(I) / 15000)) - 5
```

```
   picOutput.Print Freq(I) & " Lots"
   picOutput.CurrentX = (x - 7 + I * 25)
   picOutput.CurrentY = 100 - (80 * (Freq(I) / 15000)) - 10
   picOutput.Print Format((Freq(I) / 150), "#0.00") & "% of total lot"
Next

'Show a message to the user.
Picmessage.Cls
Picmessage.Print "The results are shown on the right!"

End Sub


Private Sub DisplayCI()

Dim Message(6) As String
Dim length(6) As Single

'Showing calculation results of CI, Avg. AAD, and Percentage of reduction payment lots

'Center and print the results.
PicValue.Cls
j = 1
Message(j) = "Conformal Index = " & Str(Round(CI, 4))
Message(j + 1) = "Average Conformal Index = " & Str(Round(AvgCI, 4))
Message(j + 2) = "Average of Average Absolute Deviation from Job Mix Formula =" &
Str(Round(AvgAAD, 2))
Message(j + 3) = "Average of Offset from Job Mix Formula =" & Str(Round(AvgOffset, 2))
Message(j + 4) = "Average Percentage of Pay Factor =" & Str(Round(AvgPF, 2))
Message(j + 5) = "Percentage of Reduction Payment Lot =" & Str(Round(ReducPayLot, 2))

For I = 1 To 6
   length(I) = PicValue.TextWidth(Message(I))
   PicValue.CurrentX = (PicValue.ScaleWidth / 2) - length(I) / 2
   PicValue.Print Message(I)
Next

End Sub


Private Sub ClearScreen()

'Clear screen if the input is changed
If (ClearOutput = True) Then
   picOutput.Cls
   PicValue.Cls
   ClearOutput = False
End If
End Sub


Private Sub ComExit_Click()
'Exit the program.
End
End Sub
```

```
'FUNCTION MODULE
Option Base 1

Public Sub GETNORMRAN()
Dim line As String
Dim data(10) As Double
Dim k As Long

NormRanFile = CurDir & "\Ran1777.dat"
Open NormRanFile For Input As #1

'Get random number from the file and saved in the arrays
k = 0
For j = 1 To 1777
   Line Input #1, line
   If EOF(1) Then Exit Sub
   Call GETDATA(line, data, 9)
   For I = 1 To 9
      k = k + 1
      NormRan(k) = data(I)
   Next
Next
End Sub

Public Sub GETPAYFACTOR()
Dim line As String
Dim PFdata(2) As Single

PayFactorFile = CurDir & "\PayFactor.dat"
Open PayFactorFile For Input As #2

'Get pay factor value from the file and saved in the arrays
For j = 1 To Column
   For I = 1 To Row
      Line Input #2, line
      If EOF(2) Then Exit Sub
      Call GETPFDATA(line, PFdata, 2)
      PayFactor(I, j) = PFdata(1)
   Next
Next
End Sub

Public Sub GETDATA(strings As String, data() As Double, Ndata As Integer)
Dim R As String, Result As Double
Dim ISep(4) As Integer 'index separator , " " tab and end line
Dim ISepMin As Integer, Ls As Integer
Dim I As Integer, IP As Integer

'Read data in the randon number file line by line
'On Error GoTo ErrorLine
   Ls = Len(strings) + 1      'Ls=last position in the strings
   IP = 0
      For I = 1 To Ndata
         Do
         IP = IP + 1
         Loop While (Mid(strings, IP, 1) = " ")
```

```
        ps = IP  'Start at the first element of the line
        ISep(2) = InStr(ps, strings, " ")
        ISep(4) = Ls
        If (ISep(2) < ISep(4) And ISep(2) <> 0) Then
          ISepMin = ISep(2)
        Else
          ISepMin = ISep(4)
        End If
        Pn = ISepMin
        Dp = Pn - ps
        R = Mid(strings, ps, Dp)
        'Find if the string,R, has an arithmetic save them to array
        Result = R
        IP = Pn
        data(I) = Result
      Next
Exit Sub
ErrorLine:
  MsgBox ("There is an error in data, Error Number =" & Err.Number)

End Sub


'GLOBAL VARIABLES MODULE
Option Base 1

Type Lot
  LotNo As Integer       'Lot number
  x() As Single          'Dynamic array of test results
  LotAAD As Single       'AAD of each lot
  LotOffset As Single
  LotCI As Single        'CI of each lot
  LotPF As Single        'PF of each lot
End Type

Public NormRan(15993) As Single
Public PayFactor() As Single
Public Row As Integer, Column As Integer


'PAY FACTOR MODULE
Option Base 1

Public Sub GETPFDATA(strings As String, PFdata() As Single, Ndata As Integer)
Dim R As String, Result As Single
Dim ISep(2) As Integer 'index separator " " and end line
Dim ISepMin As Integer, Ls As Integer
Dim I As Integer, IP As Integer

'Read pay factor from file line by line
'On Error GoTo ErrorLine
  Ls = Len(strings) + 1     'Ls=last position in the strings
  IP = 0
    For I = 1 To Ndata
      Do
      IP = IP + 1
```

```
            Loop While (Mid(strings, IP, 1) = " ")
            ps = IP  'Start at the first element of the line
            ISep(1) = InStr(ps, strings, " ")
            ISep(2) = Ls
            If (ISep(1) < ISep(2) And ISep(1) <> 0) Then
               ISepMin = ISep(1)
            Else
               ISepMin = ISep(2)
            End If
            Pn = ISepMin
            Dp = Pn - ps
            R = Mid(strings, ps, Dp)
            'Find if the string,R, has an arithmetic save them to array
            Result = R
            IP = Pn
            PFdata(I) = Result
        Next
Exit Sub
ErrorLine:
   MsgBox ("There is an error in data, Error Number =" & Err.Number)

End Sub
```

APPENDIX E
EXAMPLE OF SAS PROGRAM SOURCE CODE

```
/*  This source code is for merging the CQR database density files and sort them by project number, sample
date, sample ID and CQR form sequence number.  */

libname sue 'f:\r29';

  data one ;
  set sue.r29c34d;

  data two;
  set sue.r29c78d;

  data r29ts;
  set one two;
    proc sort;
      by WPITEM SAMPLEDT SAMPLEID CQFRMSEQ;

run;


/*  This source code is for merging the CQR database asphalt content files and sort them by project
number, sample date, sample ID and CQR form sequence number.  */

libname sue 'f:\r28';

  data one ;
  set sue.r28c34d;

  data two;
  set sue.r28c78d;

  data r28ts;
  set one two;
    proc sort;
      by WPITEM SAMPLEDT SAMPLEID CQFRMSEQ;

run;


/*  This source code is for separating test results of material type S from others.  */

libname sue 'c:\sas\saswork\#td58329';
  data r29TyS;
  set sue.r29ts;
    where SAMPLEID like 'S____';
run;
```

/* This source code is for determining the number of sample sizes and separating into different sample sizes. Number of the sample sizes depends on the length of the pavement */

```
libname sue 'f:\r29\TypeS';

  data sample3 sample4 sample5 sample6 sample7;
  set sue.r29TyS;

  if CQTESTYP = 'I1' and CQRSLTN < 3000 then output sample3;
    else if CQTESTYP = 'I1' and CQRSLTN > 3000 and CQRSLTN < 4000 then output sample4;
    else if CQTESTYP = 'I1' and CQRSLTN > 4000 and CQRSLTN < 5000 then output sample5;
    else if CQTESTYP = 'I1' and CQRSLTN > 5000 and CQRSLTN < 6000 then output sample6;
    else if CQTESTYP = 'I1' and CQRSLTN > 6000 and CQRSLTN < 7000 then output sample7;

run;
```

/* This source code is for separating the mix design number from the rest of information. */

```
libname sue 'c:\public\r29\TypeS';
  data H5;
  set sue.R29TyS;
    if cqtestyp = 'H5' then output DesignNo;
run;
```

/* This source code is for separating the density test results in terms of percentage of the control strip density from the rest of information. */

```
libname sue 'c:\public\r29\TypeS';
  data H9;
  set sue.R29TyS;
    if cqtestyp = 'H9' then output density;
run;
```

/* This source code is for separating the pay factor from the rest of information. */

```
libname sue 'c:\public\r29\TypeS';
  data I0;
  set sue.R29TyS;
    if cqtestyp = 'I0' then output density;
run;
```

/* This source code is for merging the mix design number data to the file that has specific number of sample size (in this example n=3) and deleting unnecessary information */

```
libname sue 'c:\R29\TypeS';

  data one ;
  set sue.Sample3;
    proc sort;
      by WPITEM SAMPLEID SAMPLEDT;
```

```
 data two;
 set sue.H5;
  proc sort;
   by WPITEM SAMPLEID SAMPLEDT;

 data m3n1;
  merge one (drop = EXTRACDT REPORTNO CQFRMSEC CQRSLTMS CQTSTMIN CQTSTMAX
CQTSTSTA CQTSTCST SPECYEAR CQUPDFLG WPITMSEG WPPHAZE FINPRJSQ STATNFRM
STATNTO LOCATION CQSOURCE CQPLANT SAMVEND CQMTLQTY MEASCODE CQINUSE
CQMEMO CQMATLTS RDWYSIDE CQOFFSFT CQOFFSDR CQMAINFL CQTSTQUA RDWYID
BEGSECPT ENDSECPT MEASRTYP CQTSTRSA);
        two (drop = EXTRACDT REPORTNO CQFRMSEC CQRSLTMS CQTSTMIN CQTSTMAX
CQTSTSTA CQTSTCST SPECYEAR CQUPDFLG WPITMSEG WPPHAZE FINPRJSQ STATNFRM
STATNTO LOCATION CQSOURCE CQPLANT SAMVEND CQMTLQTY MEASCODE CQINUSE
CQMEMO CQMATLTS RDWYSIDE CQOFFSFT CQOFFSDR CQMAINFL CQTSTQUA RDWYID
BEGSECPT ENDSECPT MEASRTYP CQRSLTN
rename = (CQFRMSEQ=CQFRMSE1 CQTESTYP=CQTESTY1 CQTESTNM=CQTESTN1
CQTSTRSA=CQTSTRS1));
        by WPITEM SAMPLEID SAMPLEDT;

run;


/*  This source code is for merging the density test result data to the file that previously merged and
deleting unnecessary information  */

libname sue 'f:\R29\TypeS';

 data one ;
 set sue.m3n1;
  proc sort;
   by WPITEM SAMPLEID SAMPLEDT;

 data two;
 set sue.H9;
  proc sort;
   by WPITEM SAMPLEID SAMPLEDT;

 data m3n2;
  merge one
        two (drop = EXTRACDT REPORTNO CQFRMSEC CQRSLTMS CQTSTMIN CQTSTMAX
CQTSTSTA CQTSTCST SPECYEAR CQUPDFLG WPITMSEG WPPHAZE FINPRJSQ STATNFRM
STATNTO LOCATION CQSOURCE CQPLANT SAMVEND CQMTLQTY MEASCODE CQINUSE
CQMEMO CQMATLTS RDWYSIDE CQOFFSFT CQOFFSDR CQMAINFL CQTSTQUA RDWYID
BEGSECPT ENDSECPT MEASRTYP CQTSTRSA
rename = (CQFRMSEQ=CQFRMSE2 CQTESTYP=CQTESTY2 CQTESTNM=CQTESTN2
CQRSLTN=CQRSLT2));
        by WPITEM SAMPLEID SAMPLEDT;

run;


/*  This source code is for merging the pay factor data to the file that previously merged and deleting
unnecessary information  */

libname sue 'f:\R29\TypeS';
```

```
 data one ;
 set sue.m3n2;
   proc sort;
     by WPITEM SAMPLEID SAMPLEDT;

 data two;
 set sue.I0;
   proc sort;
     by WPITEM SAMPLEID SAMPLEDT;

 data m3n3;
 merge one (
           two (drop = EXTRACDT REPORTNO CQFRMSEC CQRSLTMS CQTSTMIN CQTSTMAX
CQTSTSTA CQTSTCST SPECYEAR CQUPDFLG WPITMSEG WPPHAZE FINPRJSQ STATNFRM
STATNTO LOCATION CQSOURCE CQPLANT SAMVEND CQMTLQTY MEASCODE CQINUSE
CQMEMO CQMATLTS RDWYSIDE CQOFFSFT CQOFFSDR CQMAINFL CQTSTQUA RDWYID
BEGSECPT ENDSECPT MEASRTYP CQTSTRSA
rename = (CQFRMSEQ=CQFRMSE3 CQTESTYP=CQTESTY3 CQTESTNM=CQTESTN3
CQRSLTN=CQRSLT3));
      by WPITEM SAMPLEID SAMPLEDT;

run;
```

```
/*  This source code is for deleting the samples that have missing value.  */

libname sue 'c:\sas\saswork\#td94989';
 data m3del;
 set sue.M3n3;
   if CQRSLTN = . OR CQRSLT2 = . OR CQRSLT3 = . OR CQRSLTN = 0 OR CQRSLT2 = 0 OR
   CQRSLT3 = 0 then delete;
   else output m3del;
run;
```

```
/*  This source code is for generating box plot that shows the outliers.  */

libname sue 'c:\sas\saswork\#td84563';
 data m3n3out;
 set sue.m3del;
   proc univariate normal plot;
     var CQRSLT2;
     Title 'Summary Box Plot of Pavement Density (% of control strip)';
     Title2 'Type S, Sample Size = 3';
run;
```

```
/*  This source code is for separating into groups of time period.  */

libname sue 'c:\sas\saswork\#td79991';
 data m3yr93;
 set sue.m3out1;
   where SAMPLEDT like '93____' or SAMPLEDT like '94____';
run;
```

```
/*  This source code is for calculating the within-project mean and standard deviation values.  */

libname sue 'c:\public\R29newest\New';

  data mn4y91;
  set sue.m4yr91;
    proc sort;
      by WPITEM;
    proc means;
      var CQRSLT2;
      by WPITEM;
      Title 'Density Mean and Standard Deviation by Project';
      Title2 'Sample Size = 4, Type S, Year 1991-1992';

run;


/*  This source code is for testing the normality of the data.  */

libname sue 'c:\public\R29newest\new';

  data nor3yr95;
  set sue.M3yr95;
    proc sort;
      by WPITEM;
    proc univariate normal;
      var CQRSLT2;
        by WPITEM;
        Title ' Normality Test for Pavement Density (% of control strip)';
        Title2 'Type S, Sample Size = 3, Year 1995-1996';

run;


/*  This source code is for generating random numbers from normal distribution.  These random numbers
were used in AAD1_5 simulation program.  */

proc iml;
  a = j(1777,9,0);
  y = normal(a);
  z = round(y,.01);
  print z;
run;
```

LIST OF REFERENCES

Adam, Verdi, and S. C. Shah. 1966. *Tolerances for Asphaltic Concrete and Base Courses.* Louisiana Highway Research. Louisiana Department of Highways, Baton Rouge, LA.

Al-Azzam, Absulrahman Abdullah. 1993. *Statistically Based Acceptance Procedures with Price Adjustment Provisions and Realistic Job Mix Formula Tolerances for Flexible Pavement Material.* Doctoral Dissertation, University of Florida, Gainesville, Florida.

American Association of State Highway and Transportation Officials (AASHTO). 1996. *Quality Assurance Guide Specification--A report of the AASHTO Highway Subcommittee on Construction.* AASHTO, Inc., Washington, DC.

American Society for Quality. 2000. http://www.asq.org/about/history/shewhart.html, viewed on July 3, 2000.

American Society for Testing and Materials (ASTM). 1993a. "D2172-93 Standard Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures." *Annual Book of ASTM standards,* Vol. 4, pp. 204- 215.

American Society for Testing and Materials (ASTM). 1993b. "D2950-91 Standard Test Method for Density of Bituminous Concrete in Place by Nuclear Methods." *Annual Book of ASTM standards,* Vol. 4, pp. 257-286.

Anglade, Yves Joseph. 1998. *Development of Methodology for Highway Agencies to follow in Establishing Optimum Acceptance Plans for Pavements.* Doctoral Dissertation, University of Florida, Gainesville, Florida.

Barker, Thomas B. 1994. *Quality by Experimental Design.* 2nd Edition. Marcel Dekker, Inc., New York.

Bowker, Albert H., and Henry P. Goode. 1952. *Sampling Inspection by Variables.* McGraw-Hill, Inc., New York.

Brown E. R. 1990. "Density of Asphalt Concrete-How Much is Needed?" *Transportation Research Board 1282*, pp. 27-32.

Burr, Irving W. 1976. *Statistical Quality Methods.* Marcel Dekker, Inc., New York.

Chang, Luh-Maan, and Machine Hsie. 1995. "Developing Acceptance-Sampling Methods for Quality Construction." *Journal of Construction Engineering and Management*, Vol. 121, No. 2, pp. 246-253.

Cody, Ronald P. and Jeffrey K. Smith 1997. *Applied statistics and the SAS Programming Language.* 4th Edition. Prentice-Hall, Inc., Upper Saddle River, NJ.

Cominsky, Ronald J., Brian M. Killingsworth, R. Michael Anderson, David A. Anderson, and William W. Crockford. 1998. *NCHRP Report 409--Quality Control and Acceptance of Superpave-Designed Hot Mix Asphalt.* National Academy Press, Washington, DC.

Cornell, Gary. 1998. *Visual Basic 6 from the Ground Up.* McGraw-Hill, Inc., Berkeley, CA.

Delwiche, Lora D. and Susan J. Slaughter 1995. *The Little SAS Book: A Primer*. SAS Institute, Inc., Cary, NC.

Dobrowolski, Joe, and Terrie Bressette. 1998. "Development of Quality Control/Quality Assurance Specifications Using Statistical Quality Assurance for Asphalt Concrete Pavements in California." *Transportation Research Board,* 77th Annual Meeting, Washington , DC.

Drain, David. 1996. *Statistical Methods for Industrial Process Control.* Chapman & Hall, New York.

Duncan, Acheson J. 1974. *Quality Control and Industrial Statistics*. 4th Edition. Richard D. Irwin, Inc., Homewood, IL.

Engineering News Record. 1979. "Spec Problems that Cost Billions could be eliminated." 11 October 1979, p.11.

Federal Highway Administration (FHWA). 1977. *Highway Condition and Quality of Highway Construction Survey Report.* U.S. DOT, Washington, DC.

Federal Highway Administration (FHWA). 1995. "Rules and Regulations." *Federal Register*, Vol. 60, No. 125, pp. 33713-33719.

Florida Department of Transportation (FDOT). 1982. *Standard Specifications for Road and Bridge Construction 1982.* Tallahassee, FL.

Florida Department of Transportation (FDOT). 1991. *Standard Specifications for Road and Bridge Construction 1991.* Tallahassee, FL.

Florida Department of Transportation (FDOT). 1997. *Asphalt Paving Technical Manual*. 1997 Edition. The State Materials Office and the State Construction Office, Gainesville, FL.

Florida Department of Transportation (FDOT). 1999. *Standard Specifications for Road and Bridge Construction 1999.* Tallahassee, FL.

Grant, Eugene L., and Richard S. Leavenworth 1980. *Statistical Quality Control.* 5th Edition. McGraw-Hill, Inc., New York.

Hudson, S. B. 1971. *Handbook of Applications of Statistical Concepts to the Highway Industry, Part I – Initial Computations and Applications*. Federal Highway Administration, Washington, DC.

Hudson, S. B. 1972. *Handbook of Applications of Statistical Concepts to the Highway Industry, Part III – Practical Application of Advanced Statistical Methods*. Federal Highway Administration, Washington, DC.

Hudson S. B., F. T. Higgins, and F. J. Bowery. 1972. *Determination of Statistical Parameters for Bituminous Concrete.* Pennsylvania Department of Transportation, Harrisburg, PA.

Hughes, Charles S. 1996. *Synthesis of Highway Practice 232—Variability in Highway Pavement Construction.* National Academy Press, Washington, DC.

Kandhal, Prithvi S., Ronald J. Cominsky, Dean Maurer, and John B. Motter. 1993. “Development and Implementation of Statistically Based End-Result Specifications for Hot-Mix Asphalt in Pennsylvania.” *Transportation Research Record No. 1389,* pp. 9-16.

Kerman, Mitchell C., and Ronald L. Brown. 2000. *Computer Programming Fundamentals with Applications in Visual Basic 6.0.* Addison Wesley Longman, Inc., New York.

McMahon, Thurmul F., and Woodrow J. Halstead. 1969. “Quality Assurance in Highway Construction Part 1 – Introduction and Concepts.” *Public Roads,* Vol. 35, No. 6, pp. 129-134.

Miller-Warden Associates. 1965. *NCHRP Report 17--Development of Guidelines for Practical and Realistic Construction Specifications*. National Research Council, Washington, DC.

Montgomery, Douglas C. 1996. *Design and Analysis of Experiments.* 4th Edition. John Wiley & Sons, Inc, New York.

National Institute of Standards and Technology. 2000. http://www.itl.nist.gov/div898/handbook/pmc/section3/pmc32.html, viewed on July 7, 2000.

Office of Materials and Research. 1977. *Implementation of Quality Assurance Specifications*. Florida Department of Transportation, Gainesville, FL.

Parker, Frazier Jr., E. Ray Brown, and Robert L. Vecellio. 1993. "Development of New Criteria for Control of Hot-mix Asphalt Construction." *Transportation Research Record No. 1389,* pp. 1-8.

Raheja, Dev G. 1991. *Assurance Technologies-Principles and Practices*. McGraw-Hill, Inc., New York.

Rao, P. V. 1998. *Statistical Research Methods in the Life Sciences*. Duxbury Press, Pacific Grove, CA.

Rilett, L. R. 1998a. "Identifying Component Variability of End Product Specification Tests." *Journal of Construction Engineering and Management*, March/April, pp. 133-138.

Rilett, L. R. 1998b. "Effect of Variability on End Product Specifications." *Journal of Construction Engineering and Management*, March/April, pp. 139-145.

Roberts, Freddy L., Prithvi S. Kandhal, E. Ray Brown, Dah-Yinn Lee, and Thomas W. Kennedy. 1996. *Hot Mix Asphalt Materials, Mixture Design, and Construction.* 2nd Edition, NAPA Research and Education Foundation, Lanham, MD.

Ryan, Thomas P. 1989. *Statistical Methods for Quality Improvement.* John Wiley & Sons, Inc., New York.

SAS Institute Inc. 1990. *SAS Procedures Guide, Version 6.* 3rd Edition. SAS Institute Inc., Cary, NC.

Schexnayder, Cliff, and L. Greg Ohrn. 1997. "Highway Specifications-Quality versus Pay." *Journal of Construction and Engineering Management,* December, pp. 437-443.

Schlotzhauer, Sandra D., and Ramon C. Littell. 1997. *SAS System for Elementary Statistical Analysis*. 2nd Edition. SAS Institute Inc., Cary, NC.

Schmitt, Robert L., Jeffrey S. Russell, Awed S. Hanna, Hussain U. Bahia, and Galadriel A. Jung. 1998. "Summary of Current Quality Control/ Quality Assurance Practices for Hot-Mix Asphalt Construction." *Transportation Research Record No. 1632*, pp. 22-31.

Shapiro, Samuel S., and Gross, Alan J. 1981. *Statistical Modeling Techniques*. Marcel Dekker, Inc., New York.

Taguchi, Genichi. 1986. *Introduction to Quality Engineering*. Asian Productivity Organization, Tokyo.

Transportation Research Board (TRB). 1976. *Synthesis of Highway Practice No.38--Statistically oriented end-result specification*. National Research Council, Washington, DC.

Transportation Research Board (TRB). 1979. *Synthesis of Highway Practice No.65--Quality Assurance*. National Research Council, Washington, DC.

Transportation Research Board (TRB). 1996. *Transportation Research Circular No.457--Glossary of Highway Quality Assurance Terms*. National Research Council, Washington, DC.

Vaughn, Richard C. 1990. *Quality Assurance*. Iowa State University Press, Ames, Iowa.

Vardeman, Stephen B., and J. Marcus Jobe. 1999. *Statistical Quality Assurance Methods for Engineers*. John Wiley & Sons, Inc., New York.

Wadsworth, Harrison M., Kenneth S. Stephens, and A. Blanton Godfrey. 1986. *Modern Methods for Quality Control and Improvement*. John Wiley & Sons, Inc., New York.

Wall III, James, and Michael R. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design*. Federal Highway Administration, Washington, DC.

Weed, Richard M. 1989. *Statistical Specification Development*. New Jersey Department of Transportation, Trenton, NJ.

Weed, Richard M. 1996a. *Managing Quality: Time for a National Policy*. New Jersey Department of Transportation, Trenton, NJ.

Weed, Richard M. 1996b. *Quality Assurance Software for the Personal Computer FHWA Demonstration Project 89, Quality Management*. New Jersey Department of Transportation, Trenton, NJ.

Weed, Richard M. 1997. *Highway Quality Assurance: The Need for Science-and-Knowledge-based Decision Making*. New Jersey Department of Transportation, Trenton, NJ.

Weed, Richard M. 1999. "Practical Framework for Performance-Related Specifications." *Transportation Research Board 1654,* pp. 81-87.

Wegman, Daniel E. 1996. "Minnesota's Quality Management Program: A Process for Continuous Improvement." *Quality Management of Hot Mix Asphalt, ASTM STP 1299*, Dale S. Decker, Ed., American Society for Testing and Materials, Philadelphia, PA.

Willenbrock, Jack H. 1975. *A Manual for Statistical Quality Control of Highway Construction*, Vols I and II. Federal Highway Administration, National Highway Institute, University Park, PA.

Willenbrock, Jack H., and Peter A. Kopac. 1976. *The Development of Tables for Estimating Percentage of Material within Specification Limits*. The Pennsylvania State University, University Park, PA.

BIOGRAPHICAL SKETCH

Sutharin Pathomvanich was born in March 1971, in Bangkok, Thailand. She received her bachelor's degree in civil engineering from Chulalongkorn University, Bangkok. After graduation she worked in a construction firm for a year. Then, she joined the University of Florida, where she received her master's degree in construction engineering and management in 1995. Afterward, she worked as a lecturer in the civil engineering department at Kasetsart University, Bangkok, and received a scholarship from the Thai government to pursue her studies for her Ph.D. degree. She entered the Ph.D. program in civil engineering department at the University of Florida in August 1996 and received her Ph.D. in December 2000.