QUALITY CONTROL AND QUALITY ASSURANCE OF HOT MIX ASPHALT CONSTRUCTION IN DELAWARE

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ABSTRACT

This report presents a study where the objective is the development of an appropriate statistical acceptance procedure for the Delaware Department of Transportation. DELDOT's modification of its specifications for the acceptance of Hot Mix Asphalt (HMA) in order to incorporate quality assurance concepts lead to requirements such as the emphasis laid on the HMA producer in terms of quality control activities such as performing component material tests, tracking test results on control charts and following the plan developed by DELDOT. The incorporation of new statistically based acceptance specifications used new criteria for acceptance rather than the previous methods of minimum test result requirements for numerous criteria. After the statistical acceptance procedure was reviewed and used for quantifying and evaluating the DELDOT's statistical plan, a comparative analysis between the developed procedure and the FAA and FHWA procedure was done for achieving the objective and providing recommendations and new composite pay factors were developed.

Chapter 1

INTRODUCTION

1.1 Background

Since the mid 60's the Federal Highway Administration began to encourage Departments of Transportation and Contractors toward the use of quality control and quality assurance (QA/QC) specifications, which are statistically based.

For example, a QA specification has become an important component in organization commitment to overall quality management. This consists of several activities including: process control, acceptance, and sometimes independent assurance of product (Buttlar and Harrell, 1998). These specifications must be designed to reward good quality, and penalize poor quality.

The QA specification, also called as the QA/QC specification, is a combination of end-result specifications and materials and methods specifications. The highway agency is responsible for the acceptance of the product that is produced by the contractor following or implementing quality control in order to produce a product that meets the specifications provided by the highway agency.

QA specifications typically are statistically based specifications that use methods such as random sampling in which the properties of the desired products or constructions are described by appropriate statistical parameters, and lot by lot testing. These methods

would help the contractor know whether or not the operations are producing the acceptable product.

Specifications for the construction of asphalt pavements can be classified into propriety specifications, method – related specifications (MRS), end – result specifications (ERS), performance – related specifications (PRS) or combination of these specifications.

- **Propriety Specification**

This type of specification refers to some specific product or its equivalent in its clauses; therefore, it limits the competition and often results in a cost increase. Since the buyer has to accept the product as a "black box", the buyer's risk is much higher than in the other three types of specifications

- **Method Specification**

This type of specification outlines a specific material selection and construction operation process to be followed by the contractor in providing a product. Since there is no explicit product specified, this type of specification allows competition among various suppliers and contractors; but, because the buyer sets the requirements for materials and methods, the owner has to bear the responsibility of the performance.

- **End-Result Specification**

The final characteristics of the product are stipulated in the end-result specification and the contractor is given considerable freedom in achieving those characteristics. It may specify a limit or range for any given material and/or construction characteristic. The risk for the contractor or agency depends on how the acceptance limits and processes are specified.

- **Performance Related Specification (PRS)**

This type of specification holds the contractor responsible for the finished product's performance; thus, the contractor assumes considerable risk for the performance of the finished product. This type of specification is often used in conjunction with some type of warranty. The challenge here is to use "true" performance indicators, which may not be available for all materials and processes.

Statistical acceptance specifications tend to provide a more defensible approach to specifying HMA construction than the previously used methods of specification (Muench and Mahoney, 2001).

```
                                              PRS
                              ERS        ┌──────────────
                   MRS    ┌──────────────┘
        ──────────┘
                    QUALITY IMPROVEMENT
        ──────────────────────────────────────────▶
```

Characteristic
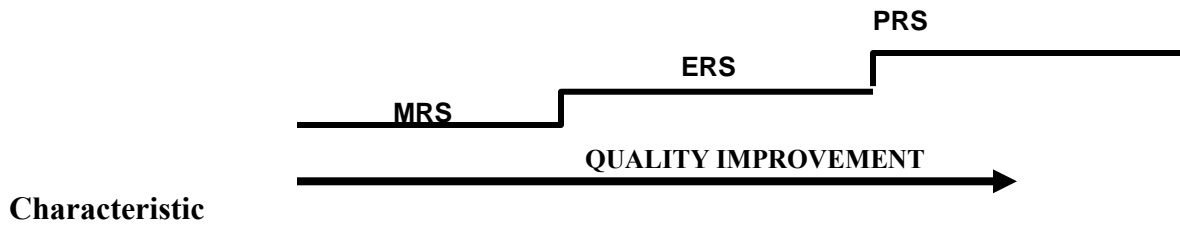
Specification Variables	Indirectly or directly related to performance	Indirectly or directly related to performance	Only those directly related to performance
Raw Materials	Agency	Agency	Contractor
Mix Design	Agency	Contractor	Contractor
Process Control	Agency/Contractor	Contractor	Contractor
Lots	No	Yes, uniform construction run	Yes, same for all characteristics
Sampling	"Representative" or arbitrary, frequency based on opinion	Random locations, frequency based on sampling theory	Random locations, frequency based on sampling theory
Pay Adjustments	Usually not used	Often used, based on judgments	Required. Based on performance and LCC analysis
Type of Acceptance Terms	May or may not be related to performance	May or may not be related to performance	Directly related to performance (prediction models)
Material Acceptance	By agency, often from a single sample	By agency, from samples obtained prior to placement or in-situ	By agency, from samples obtained in-situ
Equipment	Agency Specifies	Agency allows wider range of equipment usage	Few prescriptions

Figure 1.1: Evolution and advantages of end-result and performance-related specifications. From (Buttlar and Harrel, 1998)

End–result and performance- related specification require a contractor to achieve the final product that has a quality level equivalent to as- produced or as – constructed quality levels. This is directly linked to the attainment of a good future performance. These specifications shift most or all of the responsibility for producing a high quality product to the contractor. These offer the contractor freedom in the methods used to arrive at the quality levels. Performance-related is difficult to develop, but offers the ultimate means of compensation payment.

The main advantages of statistical acceptance specifications over method specification include (Muench and Mahoney, 2001):

1) Responsibility for material and construction quality resides with the party that can best control these factors: the contractor.

2) The contractor is allowed greater latitude in the choice of materials, equipment, and method which allows more control over material and construction quality as well as contractor profitability.

3) Acceptance/rejection decisions are objective, consistent and statistically defensible.

4) Quick inspection and pay calculations on relatively small subsections of materials/construction give contractors the opportunity to take corrective action before large quantities of out-of-specification material or construction is produced.

Under QA specifications, the quality level is typically presented in statistical terms such as the mean and standard deviation, percent within limits, average absolute,

etc., therefore QA specification effective of the quality wanted, the quality specified, and the quality delivered are the same (Figure 1) If any difference exists, the QA specification is not effective

Appendix A shows various US highway agencies in different states adopting end – results specifications and QA/QC management schemes.

1.2 Scope

The scope of the work includes a comprehensive literature review of the current state of practice of QA/QC in the United States with more emphasis on the state of Delaware, the development of an appropriate database structure for the QA statistical evaluation, estimation of the variability of Hot Mix Asphalt construction in Delaware, identifying statistical distribution of test results, developing compliance limits for selected HMA tests in Delaware, and developing a quantitative method for adjusting payments. The anticipated results of this project include sound technical guidelines for QA in Delaware. The results and conclusions of the study will be submitted to Delaware Department of Transportation in the form of a research report. The findings and recommendations will form the basis for papers that will be submitted to Transportation Research Board, peer review journals and used in conference presentations.

1.3 Objective

The main objective of this report is to develop and implement appropriate HMA statistical acceptance procedures for DELDOT. The main objective of this report will be achieved through the following sub-objectives:

a) To provide a general theoretical background on statistical acceptance procedures

b) To quantify and evaluate DELDOT's statistical acceptance plan

c) To perform a comparative analysis between the developed DELDOT procedure, and selected states and federal procedures.

1.4 Statement of Problem

In 2002, the Delaware Department of Transportation (DELDOT) modified its specifications for accepting Hot Mix Asphalt (HMA) so that they could incorporate Quality Assurance (QA) concepts. QA is all the planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.

The incorporated QA concepts involve emphasizing the HMA producer's responsibility for performing quality control (QC) activities – the producer must perform component material tests, track test results on a control chart, and develop and follow a QC plan approved by DELDOT. In addition, new statistically-based acceptance specifications were incorporated using new criteria for acceptance-result targets and tolerances, and incentives for selected material characteristics rather than minimum test result requirements for numerous criteria. Among other changes, DELDOT formalized the sampling procedure to require choosing specific random locations within defined lots in order to analyze the quality of the material and the placement of the HMA.

The protocol for the QC/QA program in DELDOT is as follows:
The contractor is responsible for the quality control process while DELDOT is responsible for quality assurance. In Delaware it involves a material component (about

70%) and an application component (about 30%). The material component involves plant production, while the application component involves density measurement during the HMA application.

For the HMA project, the quality control purposes are divided into lots, each equaling 2000 tons of mix (or three days production whichever comes first). These lots are further subdivided into four equal sub-lots comprised of 500 tons each. The current specifications require both the contractor and DELDOT engineers to randomly sample each of the sub lots within a given lot. The contractor's results represent quality control and DELDOT results represent quality assurance.

The five tests completed during QA were:

  I. Asphalt content

 II. Gradation

III. Bulk specific gravity of the sample

IV. Theoretical specific gravity

 V. Gyratory compaction

 In terms of the payment, the following were used:

  I. Asphalt content – 30% of 70%

 II. Sieve # 8 – 35% of 70%

III. Sieve # 200 – 35% of 70%

IV. Density – 30% - Application

 The maximum bonus allowed is 105%.

The acceptance and pay determination for HMA work is based on the average of the five tests performed on the lots (four contractor and one agency test). All the above

tests for each sub lot by the Department are the QA test and not the average of contractor and engineer results. The contractor result for QC is only for their tracking and judgment. The placement component involves final in-place compaction, as determined from contractor-drilled cores located and tested by DELDOT. For all test results, the statistical value of percent within limits is calculated and used toward calculating the final acceptance and payment decision.

Chapter 2

ACCEPTANCE PLANS

2.1 Acceptance Plan Basics

An acceptance procedure is a formal procedure used to decide whether work should be accepted, rejected, or accepted at a reduced payment (Muench and Mahoney, 2001). The procedure is therefore a form of quality assurance. Acceptance procedures should never be used as a method to control or improve quality.

Acceptance procedures can be divided into three forms (Montgomery, 1997).

1) Acceptance with no inspection

2) Acceptance with 100 percent inspection

3) Acceptance sampling

Accept with no inspection is an application where there is no economic justification to look for defective materials. The 100 percent inspection is generally used when materials are extremely critical and passing any defective materials would result in unacceptably high failure costs. Finally, the acceptance sampling method can be performed in a number of situations (Montgomery, 1985):

a)   When testing is destructive; otherwise all of the product will be lost

b)   When the cost of 100 percent inspection is very high in comparison to the cost of passing a non conforming item

c)   When there are many similar materials to be inspected

d)   When information concerning the producer's quality is not available

e)   When 100 percent is not feasible

f)   When the supplier has an excellent history of quality and some reduction in inspection is desired

g)   When the supplier has a satisfactory history of quality but, because of potential serious product liability the firm cannot forgo inspection

Of these approaches, HMA construction typically uses acceptance sampling. The acceptance sampling has several advantages; these include the following (Montgomery, 1985):

a) It is usually more economical because less inspection is required

b) It usually requires less handling therefore less damage will result

c) Fewer technicians are needed

d) It often reduces the amount of inspection error, since 100 percent inspection is often fatiguing and boring, resulting in a higher percentage of non conforming items being accepted

e) Rejection of entire lots provide strong motivation for suppliers to improve their quality

It also has some disadvantages:

a) There is always the risk of accepting a lot of poor quality and rejecting a lot of good quality

b) Developing acceptance plans requires time and effort in planning, as well as documentation of the different sampling plans

Two key concepts are involved in the effective use of acceptance sampling (Muench and Mahoney, 2001):

a) Acceptance sampling only estimates material properties

b) Acceptance sampling depends on random sampling

In acceptance sampling, the inspection is performed on a small random sample to draw conclusions about a large amount of material. The conclusions obtained are only estimates of actual lot properties and therefore the estimates involve some amount of uncertainty, so the characteristics the samples use for acceptance sampling must be random.

Muench and Mahoney, (2001), listed the following components that will aid in the proper implementation of acceptance sampling in HMA construction.

a) Acceptance sampling

b) Quality characteristics

c) Specification limits

d) Statistical model

e) Quality level goals

f) Risk

g) Pay factors

2.2 Acceptance Sampling

Acceptance sampling is used to determine whether to accept or reject a lot of material that has already been produced. A lot is defined as quantity of product accumulated under uniform conditions. The main purpose of acceptance sampling is to

decide whether or not the lot is likely to be acceptable, not to estimate the quality of the lot.

2.3 Types of Acceptance Sampling Plans

Sampling plans can be categorized in several forms:

1) Sampling by attributes as compared to sampling by variables.

2) When the item inspection leads to a binary result (either the item is confirming or nonconforming) or the number of nonconformities in an item are counted, then we are dealing with sampling by attributes. If the item inspection leads to a continuous measurement, then we are sampling by variables.

3) Incoming compared with outgoing inspection:

4) If the batches are inspected before the product is shipped to the consumer, it is called outgoing inspection. If the inspection is done by the consumer, after they are received from the supplier, it is called incoming inspection.

5) Rectifying compared with non-rectifying sampling plans.

6) Determines what is done to nonconforming items that were found during the inspection. When the cost of replacing faulty items with new ones, or reworking them is accounted for, the sampling plan is rectifying.

7) Single, double, and multiple sampling plans:

The sampling procedure may consist of drawing a single sample, or it may be done in two or more steps. A double sampling procedure means that if the sample taken from the batch is not informative enough, another sample is taken. In multiple sampling additional samples can be drawn after the second sample.

Acceptance is the responsibility of the state Department of Transportation. According to the definition of the Federal Aid Policy Guide (FHWA, 1995), *All factors that comprise the state highway agency's (SHA) determination of quality of the product as specified in the contract requirements. These factors include verification sampling, testing and inspection and may include the results of quality control sampling and testing.*

2.4 Quality Acceptance Plan

Among the quality assurance programs of the state DOT, the acceptance sampling is one of the important elements. The contractor is responsible for the quality control and quality acceptance testing but it is the responsibility of the Department to accept or reject the material. One of the most prevalent applications of acceptance sampling is the division of the materials in a highway project into specified numbers called "lots". These lots are used for taking a few samples and further using these samples for testing and based on the test results, the acceptance decisions are reached.

The purpose of acceptance sampling is to determine a course of action, not to estimate the true material quality of a lot (Duncan, 1986) (Montgomery, 1984). It is possible therefore that at times the DOT rejects materials with good quality and accepts materials with bad quality.

An acceptance sampling usually specifies acceptance-sampling procedures. It is crucial for the DOT and the contractor to have a proper understanding of the various components and relationships between components of the acceptance sampling plan since the acceptance sampling is the basis for making important decisions like the acceptance

and rejection of materials, pay adjustment and various kinds of risks involved in making these decisions. Mentioned below are a few topics addressed in an acceptance sampling plan:

1) The material/quality characteristics being evaluated in the acceptance sampling plan

2) Testing methods

3) The size of a lot and number of sub-lots per lot

4) Methods of locating samples within individual sub-lots

5) The number of samples or measurements per lot

6) Evaluation methods based on testing results

7) Specification limits

8) Acceptance criteria

9) Payment adjustments based on acceptance sampling results

All the above topics are related to the risk analysis of the acceptance sampling plan.

2.5 Attribute and Variable Acceptance Plans

There are two basic types of acceptance sampling plans, which are described below:

1) Attribute acceptance plan

2) Variable acceptance plan

Attribute acceptance plans grade the material as conforming or nonconforming. It means that every sample is tested or inspected for the presence or absence of quality characteristics. Instead of retaining the measurements pertaining to these quality

characteristics they are compared with a standard and then recorded as either conforming or nonconforming.

Unlike the attribute acceptance plan, in the variable acceptance plan the quality characteristics are measured and the values are retained. The quality characteristics thus measured are used as continuous variables; this helps in having better information about the sample as compared to the attribute acceptance plan. The variable acceptance plan is therefore one of the most preferred HMA statistical acceptance plans. The variable acceptance follows an important assumption, which is that the variable acceptance plan assumes normal distribution for the measured quality characteristics. This assumption is usually satisfied by the construction-related lot characteristics (Markey, Mahoney, and Gietz, 1994; Aurilio and Raymond, 1995; Cadicamo, 1999).

2.6 Quality Characteristics

A quality characteristic is the characteristic of a unit or product that is actually measured to determine its conformance with a given requirement. When the quality characteristic is measured for acceptance purposes, it is an acceptable quality characteristic (AQC). The selection of quality characteristics has to be done keeping in mind two important factors, that the quality characteristics should be selected because of their importance in determining the overall performance of the HMA pavements and also that they should be independent of each other.

The quality characteristics directly affect the long-term performance of HMA pavements. The HMA production and construction specifications require measurement of basic properties that are assumed to relate to HMA performance. These properties typically include air voids, the asphalt binder content and the aggregate gradation of the compacted mix. The pavement quality can then be defined by how closely the properties of HMA agree with the design requirements.

Important factors to be considered when choosing quality characteristics are the quality characteristics of the HMA should be measured to best predict the future performance of the pavement and also the most appropriate methods for the measurement of the quality characteristics. The test methods employed in measuring quality characteristics have to be;

1) Rapid,

2) Reliable and

3) Relatively inexpensive.

The most important of the above three is the rapid measurement of the quality characteristics. The primary focus of the contractor is to meet the "bottom line", which means the ability to quickly determine when the production and construction processes begin to go out of control. If these problems are not identified and corrected at the right time it will lead to the production and placement of material that does not meet the specification requirements.

2.7 Quality Level

As the quality characteristics are used for the payment determination, it becomes important to determine the relationship between the quality measure and the payment. There are several quality measures that can be used. The average or the average deviation from a target value was often used as the quality measure in past acceptance plans. The use of the average alone provides no measure of variability, which is a drawback as the variability is now recognized as an important predictor of performance.

Based on the FHWA report RD-02-095 by Burati, Weed, Hughes and Hill,(2003), it can be mentioned that the preferred quality measures over the recent years include percent defective (PD) and percent within limits (PWL). These quality measures are preferred over the rest as they simultaneously measure both the average level and the variability in a statistically efficient way. Other quality measures in use by certain agencies include the average absolute deviation (AAD), moving average and conformal index (CI). As some of the quality measures are more discriminating than others, they have to be carefully chosen. The reason behind this is that the most effective quality measure can translate directly into economic savings, because of a reduced inspection or the lesser probability of a poorer product being accepted, or sometimes both.

2.7.1 The PWL Quality Measure

The percentage of the lot falling above the lower specification limit, beneath the upper specification limit, or between the upper specification limit and lower specification limit is defined as percent within limits, (PWL), it may refer to either the population value or the sample estimate of the population value PWL = 100 – PD.

2.7.2 The PD Quality Measure

Also known as percent defective, (PD), it gives a measure of materials not meeting the requirements. As mentioned above, PD and PWL are related by the simple relationship, PWL = 100 – PD. There are certain advantages of using PD as a quality measure, especially with two-sided specifications, as the PD below the lower specification limit can simply be added to the PD above the upper specification limit to obtain the total PD value. The figure below shows the relation between PD and PWL.
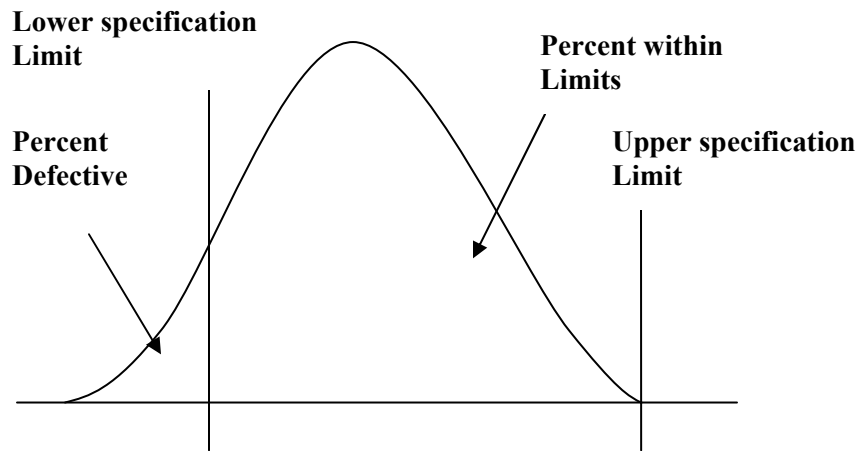
Figure 2.1: Relationship between PD and PWL. (Source: FHWA 2003)

PD and PWL are equivalent quality measures as one can be converted to another by a simple subtraction of 100. Most state agencies prefer the usage of PWL, i.e. measure of material meeting the requirement, as compared to the PD, i.e, measure of material not meeting the requirement. The FHWA also promotes the usage of PWL when compared to the PD.

2.7.3 The Average Deviation from the Target Quality Measure

The average deviation from the target has been used as a measure for accepting products at times. This kind of quality measure can encourage the contractor to

manipulate production processes of the lot. The contractor can increase the process variability by making frequent adjustments to the process mean, hence for the quality assurance acceptance plans the AAD quality measure is not used

2.7.4 The Conformal Index Quality Measure

It is often described as an alternative to the standard deviation approach to specifications. Similar to the standard deviation in function, the conformal index is a measure of variation. According to Lundy, (2001), in "Acceptance Procedures for Dense-Graded Mixes", CI is compared to the standard deviation and has been described as a measure of accuracy while standard deviation is a measure of precision.

A measure of the dispersion of a series of results around a target or specified value is expressed as the square root of the quantity obtained by summing the squares of the deviations from the target value and dividing by the number of observations.

The similarity between CI and AAD can be observed by noting that AAD uses the average of the absolute values of the individual deviations from the target values and CI uses the squares of the individual deviations from the target value. CI also has similar properties as the standard deviation. The standard deviation is the root mean square of differences from the mean and CI is the root mean square of differences from a target such as the job mix formula for Hot Mix Asphalt Concrete. As in case of AAD, the CI also discourages mid-lot process adjustments by not allowing positive and negative deviations from the target to cancel out one another.

2.7.5 The Moving Average Quality Measure

Few of the agencies use the moving average quality measure for acceptance procedures. For moving averages the first step is the selection of a sample size, say n = 4 is determined. The first average is then determined from the first four values. For the second moving average, the fifth value replaces the first value in the calculations, and for the third moving average the sixth value replaces the second value and so on.

The moving average has been mostly applied for process control purposes, and is mostly useful when continuous processes are involved. There are certain disadvantages in using this method such as lack of consistency, appearance of individual test results as multiple averages and some other disadvantages.

2.8 Recommended Quality Measure

During the characterization of a lot it is important to measure both the center and the spread of the lot. There are potential difficulties in using AAD and CI quality measures with most significant one being the lack of direct measurement of lot variability, which leads us to the interpretation that for a given lot the AAD and CI can come from a number of different populations. Even though the PWL and PD acceptance plans have some limitations, such as a given PWL can represent many different populations, there are lesser drawbacks due to the fact that both the sample mean and the standard deviation are determined in the PWL method. The FHWA recommends the use of the PWL approach and it is also the method used in the American Association of State Highway and Transportation Officials QA Guide Specification because the PWL method

can be used with both one-sided and two-sided acceptance properties, and it does not require different approaches for one-sided and two-sided cases.

2.9 Payment Quality Characteristics

- **Specification Limit** - The limiting values(s) placed on quality characteristics, established preferably by statistical analysis, for evaluating material or construction within specification requirements. The term can refer to either an individual upper or lower specification limit, called a single specification limit, USL or LSL; or to USL and LSL together, called double specification limits.

- **Acceptance Limit** - In a variable acceptance plan, the limiting upper or lower value, placed on a quality measure will permit acceptance of a lot. Unlike specification limits placed on a quality characteristic, an acceptance limit is placed on a quality measure. For example, in PWL acceptance plans, PWL refers to the specification limits placed on the quality characteristic and the minimum allowable PWL identifies the acceptance limit for the PWL quality measure.

The specification limits are based on engineering requirements and are expressed in the same units as those of the quality characteristic under consideration whereas the acceptance limits are expressed in statistical units such as mean, percent defective, percent within limits, average absolute deviation etc. A risk analysis is done for finding accept or reject acceptance plans. Establishing a specification requires defining the acceptable and unacceptable material based on engineering decisions. The AQL

(acceptable quality level) decision defines the acceptable material and RQL (rejectable quality level) decision defines the unacceptable material. According to the TRB Glossary:

- **AQL** That minimum level of actual quality at which the material or construction can be considered fully acceptable (for that quality characteristic). For example, when quality is based on PWL, the AQL is that actual (not estimated) PWL at which the quality characteristic can just be considered fully acceptable. Acceptance plans should be designed so that AQL material will receive a pay of 100 percent.

- **RQL** That maximum level of actual quality at which the material or construction can be considered unacceptable (rejectable). For example, when quality is based on the PD, the RQL is the actual (not estimated) PD at which the quality characteristic can be considered full rejectable. It is desirable to require removal and replacement, corrective action, or the assignment of a relatively low pay factor when RQL work is detected.

2.10 Risk

Since the lot disposition is based on sample results there is a probability of making an incorrect disposition of a lot.

Type –I (α): The probability that an acceptance plan will erroneously reject acceptable quality level (AQL) material or construction with respect to a single acceptance quality characteristic. It is the risk the contractor or producer takes when rejecting AQL material or construction. In simple terms the Type I risk is incorrectly rejecting a lot that is really acceptable.

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Type –II (β): The probability that an acceptable plan will erroneously fully accept (100% or greater) rejectable quality level (RQL) material or construction with respect to a single acceptance quality characteristic. It is the risk the highway agency takes when RQL material or construction is fully accepted. The probability of having RQL material or construction accepted (at any pay) may be considerably greater than the buyer's risk. In simple terms the Type II risk is incorrectly accepting a lot that is really unacceptable. This is called the consumer's risk.

2.11 Pay Factor

A multiplication factor, often expressed as a percentage, is used to adjust the contractor's bid price per unit of work based on the estimated quality of work. After the determination of the quality characteristics that are measured as a part of the acceptance decision, the next step is to decide if the quality characteristics measured will be used in determining the payment factor. The process is depicted in the flow chart given in figure 2.2.

```
                    ┌──────────────────────────────┐
                    │ Quality Characteristics selected for │
                    │ acceptance                   │
                    └──────────────────────────────┘
                                 │
                                 ▼
                         ◇ Use for pay ◇
                         ◇ determination ◇
                                 │
                                 ▼
                    ┌──────────────────────────────┐
                    │ Determine the quality        │
                    │ measure to use               │
                    │ e.g., PWL, PD, AAD           │
                    └──────────────────────────────┘
                                 │
                                 ▼
                    ┌──────────────────────────────┐
                    │ Determine specification      │
                    │ limits and decide on AQL     │
                    │ and RQL                      │
                    └──────────────────────────────┘
                                 │
                                 ▼
                    ┌──────────────────────────────┐
                    │ Decide pay relationships     │
                    └──────────────────────────────┘
```
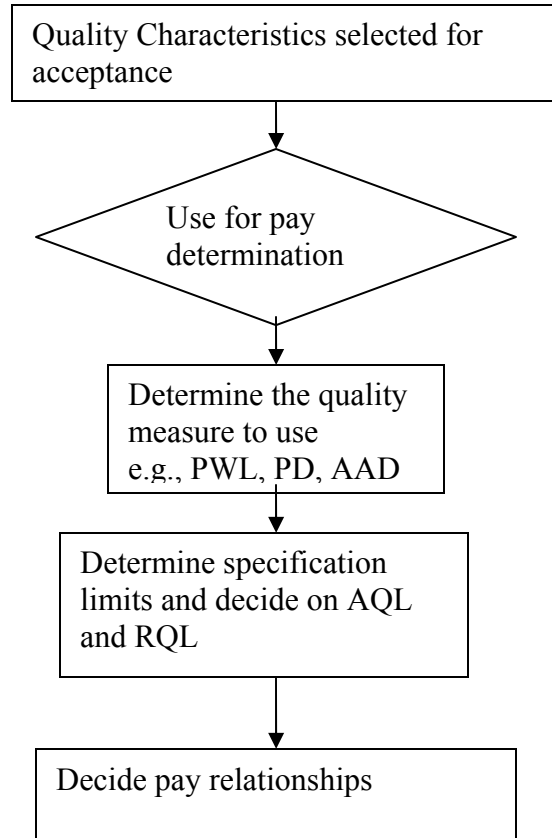
Figure 2.2: Flow chart representing various steps of acceptance sampling

The necessity of the pay factor is for the proper application pay adjustment for payment to the contractor in proportion to the level of quality of the pavement. The work of the contractor meeting the requirements of the level of quality in the specification is called acceptable and is eligible for 100 percent payment while the work done by the contractor that fails to meet the requirement of the level of service in the specification receives a certain degree of pay reduction in order to compensate for the money that needs to be spent by the agency for removal or replacement, and for the work that exceeds the level of service in the specification. The contractor receives monetary incentives based on the pay adjustment factor.

Chapter 3

CONTROL CHARTS

3.1 Introduction

According to Xie, Goh and Kuralmani, (2002), the control charts are essential to monitor the degree to which a product meets the required specifications. Deviations from the required specification and variability around the required specification are the major hindrances in achieving good quality products. The procedure to monitor starts with getting samples of a predetermined size and producing line charts for knowing the variability of the samples when compared to the required specifications. In case a trend is observed in the line charts or in case the samples fall out of the specified limits then it is concluded that the process is out of control. The next step is to take corrective action to remedy the problem encountered.

Based on Shewhart ideas of statistical control charts the statistical process control started in the early twenties. According to Xie, Goh and Kuralmani, (2002), the most common steps to set up control charts are as follows:

(1) Select the process characteristics through observation, with or without calculations;

(2) Calculate the process mean, which is used as the center line (CL) for the control chart;

(3) Calculate the standard deviation;

(4) Calculate the upper control limit (UCL) and the lower control limit (LCL) using the mean plus three times the standard deviation and the mean minus three times the standard deviation as shown below:
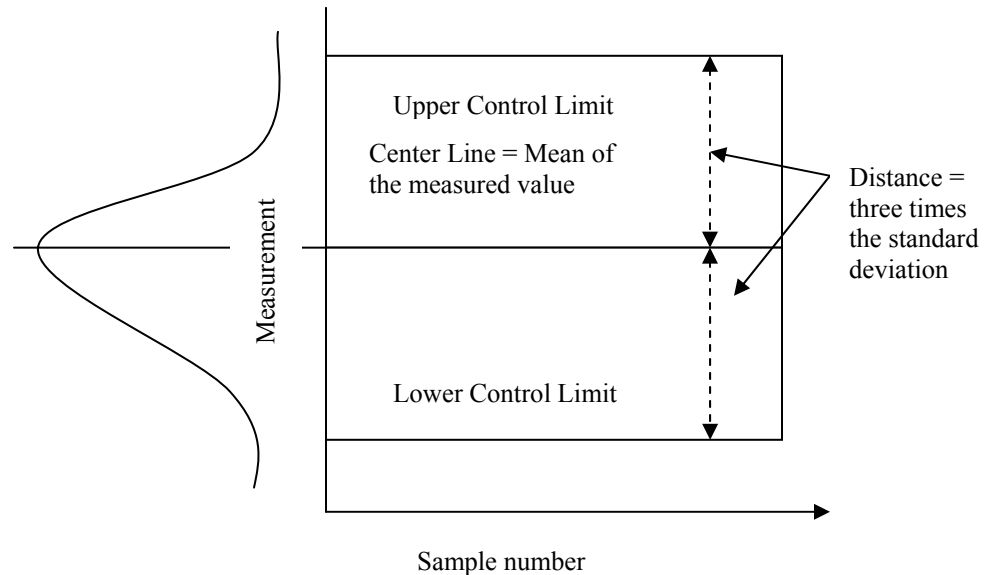
Figure 3.1: Basic principle of control chart with traditional 3-sigma limits. Source: Statistical Models and Control Charts for High-Quality Processes, Xie, Goh, Kuralmani, (2002).

(5) Plot the process characteristics on the chart and connect the consecutive points;

(6) Check for points that fall outside the limits and make a note of the reason and the required correction followed by the modification of the CL, UCL and LCL if needed.

3.2 Uses of Control Charts

1) Used as a technique for improving productivity

2) Used as an effective measure to prevent defects

3) Used to avoid unnecessary process adjustments

4) Used to provide diagnostic information

5) Used to provide information related to process capability.

3.3 Types of Control Charts

1) Control charts for attributes

2) Control charts for variables

3.3.1 Control Charts for Attributes

Based on the Statistical Models and Control Charts for High-Quality Processes by Xie, Goh, Kuralmani, (2002), for the control charts for attributes, the data is in the form of discrete counts. p- chart, c- chart and u- chart are the usual forms of attribute control charts.

- **p- charts**

This type of chart is usually used to monitor the proportion of nonconforming also called defectives in a sample.

- **c- charts**

This control chart shows the number of nonconforming or defective products of a process.

- **u- charts**

This control chart shows the nonconformities per unit produced by the process.

3.3.2 Control Charts for Variables

A measurable quality characteristic that can be expressed in numerical form is called a variable. The variable control charts are more extensively used compared to attribute control charts. The reason for their extensive use is their efficiency in controlling the process and their ability to provide more information per sample than the attribute control charts. According to Xie, Goh, Kuralmani, (2002), for the variable control charts, the process or quality characteristics take on continuous values. Control over the mean value and variability of the quality characteristic are essential when considering a quality characteristic that is a variable. X bar and R charts are the general forms of control charts for variables.

- **X bar chart**

This chart is also called control chart for means and is developed based on the average of the subgroup data. This chart helps in the control of process average or mean quality level.

- **R chart**

This chart is also called control chart for range and is developed based on ranges of each subgroup data. The range of subgroup data is calculated by subtracting the maximum and minimum value in each subgroup.

3.4 Comparison Between Attribute Control Charts and Variable Control Charts

The attribute control chart helps summarizing various aspects of the quality of the product faster therefore for an engineer it becomes easier to classify the products as acceptable or unacceptable. Also attribute control charts are inexpensive time efficient

and precise procedures. Variable control charts are more sensitive than attribute control charts (Montgomery, 1985) therefore they are helpful in pointing out the quality problems well before they happen.

Chapter 4

DATA ANALYSIS

4.1 Introduction

The data collected in the field was compiled into a usable format. The data was cleaned to delete inconsistencies, and then formatted. The raw data provided by the Delaware Department of Transportation in an Excel spreadsheet format, required some filtration to convert it into a more compatible format for the present study. Once a spreadsheet was compiled with all the pertinent data, it had to be cleaned for missing and inconsistent data.

The next step consisted of computing the density of core, air voids, voids in mineral aggregate and voids filled with asphalt content for 2898 rows of data. A sample spreadsheet containing data used in this study is located in the Appendix B. The upper and lower quality index was computed for the density of core, air voids, voids in mineral aggregate, voids filled with asphalt content, the No. 8 sieve and No. 200 sieve using the target value and upper and lower specification limits specified by DelDOT.

4.2 Types of Analyses

The various types of analyses performed on the data were normal probability plot analysis, correlation analysis, multiple regression analysis, box and whisker plots

analysis and individual, average and range control charts plot analysis for each quality characteristic.

4.3 Normal Probability Plot for Various Quality Characteristics

It can be seen from the normal probability plot for air voids that data shows normal probability distribution until the air voids approach 7.0 percent after which the data points show a deviation from the normal. In case of measured asphalt, the data points are scattered on either side of the normal while in the case of density of core an almost perfect normal probability distribution of the data can be observed. From the normal probability plot of voids filled with asphalt it can be seen that for data greater than 60 percent there is a normal probability distribution, whereas the voids filled with asphalt less than 60 percent show deviation. Similarly by the plot for voids filled with mineral aggregate, VMA, it can be inferred that the VMA data points less than 11 percent and data points 70 percent and above show a deviation while the rest of the values have a normal behavior.

Chart 4.1: Normal Probability Plot for Various Quality Characteristics

Normal Probability Plot — Air Voids
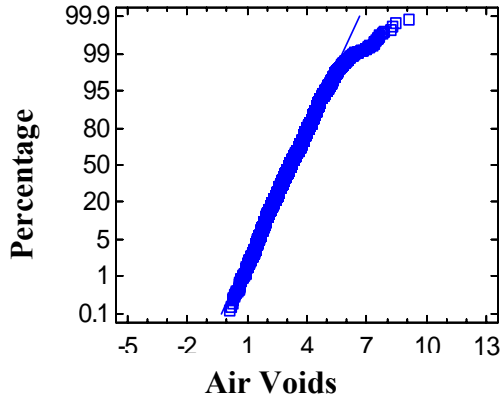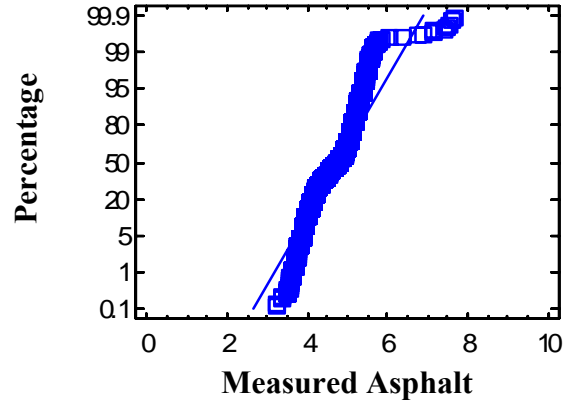
Normal Probability Plot — Measured Asphalt

Normal Probability Plot — Density of Core

Normal Probability Plot — Voids filled with Asphalt

Normal Probability Plot — Voids in Mineral Aggregate
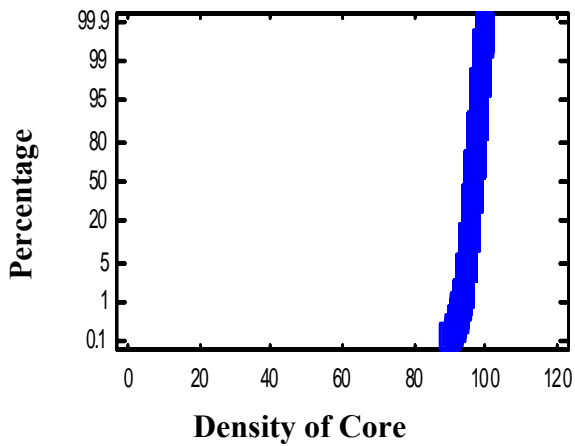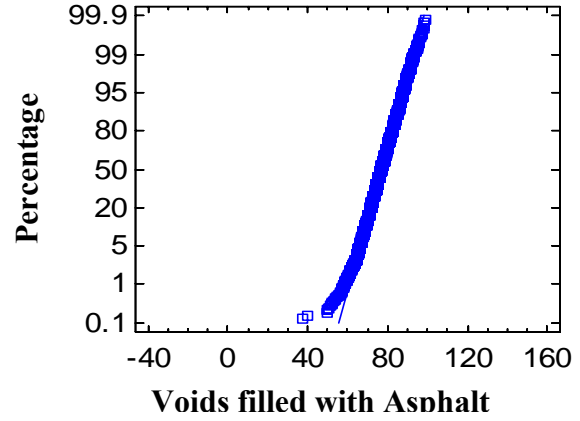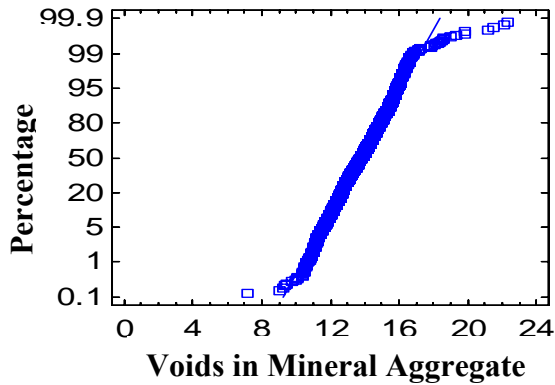
4.4 Box and Whisker Plots for Various Quality Characteristics

A box and whisker plot is known for its ability to compare similar distributions at a glance rather than showing distribution. The box and whisker plot helps us to know the center, spread and overall range and also helps in detecting symmetrical and skewed distribution.

For example based on the box and whisker plot of air voids it can observed that the minimum value of the data range lies between -4 and -5 percent, the lower quartile or the 25th percentile also called the median of the lower half of the data occurs between 2 and 3 percent and the median of all data range is approximate 3 percent. The upper quartile or the 75th percentile also known as the median of the upper half of the data occurs at 4 percent. The maximum value of the data range for air voids is observed to be approximate 12 percent.

Comparing the box and whisker plots to the individual control charts mentioned in the next section, it can be observed that the box and whisker plot can be tied in with the control chart. For example, it can be observed from the box and whisker plot (for density of core) there is one outlier between 0 and 5 percent; also a similar outlier can be noticed in the individual control chart for density of core.

Chart 4.2: Box and Whisker Plots for Various Quality Characteristics

Box and Whisker Plot
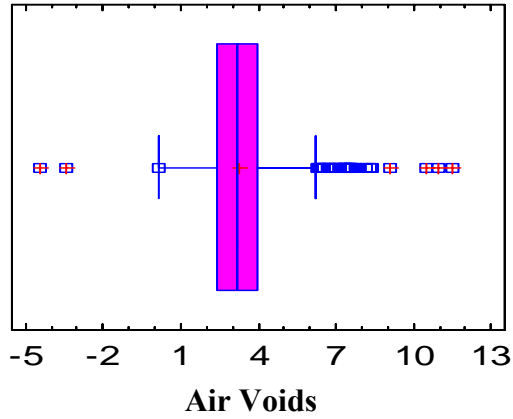
Air Voids

Box and Whisker Plot

Density of Core

Box and Whisker Plot

Measured Asphalt

Box and Whisker Plot

Voids filled with Asphalt

Box and Whisker Plot

Voids filled with Mineral Aggregate
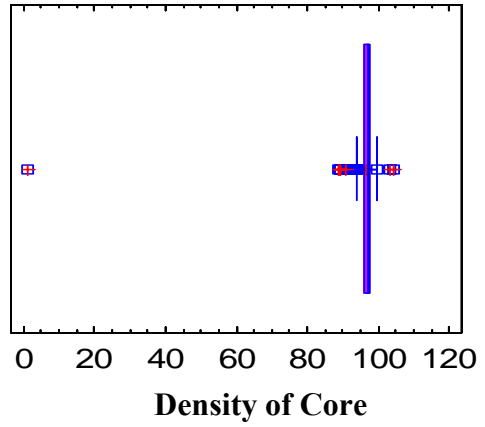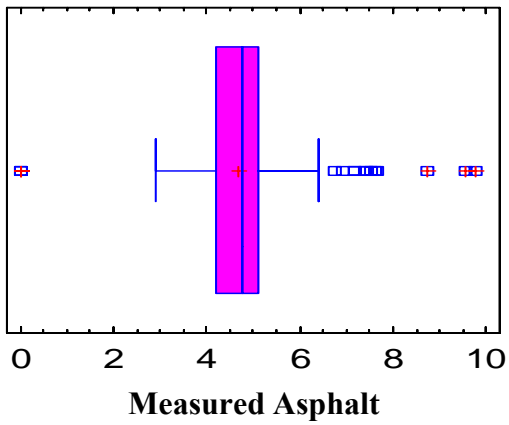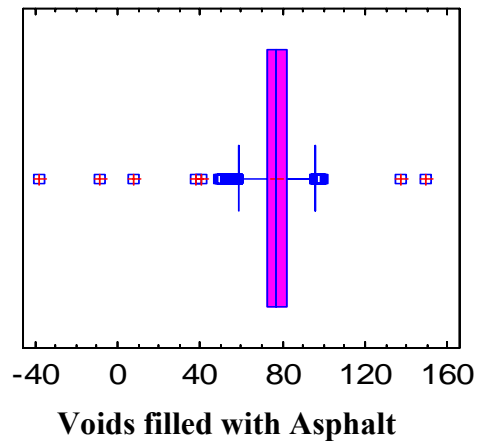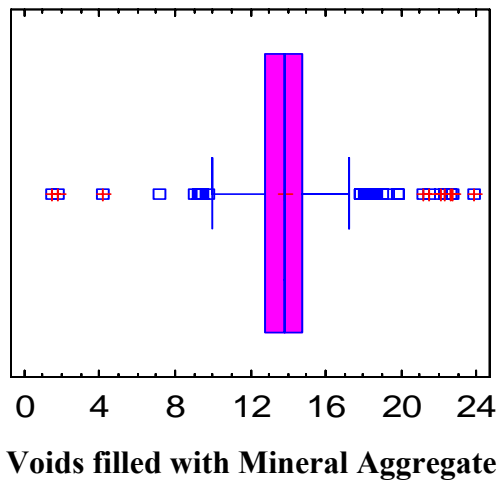
4.5 Individual Control Charts for Various Quality Characteristics

The HMA data is variable a type of data and based on the size of the subgroups of the kind of control chart to be used is decided upon. According to Wheeler, D. J., (1996), if the subgroup size is one then individual measurements chart, with or without a moving range chart be used. In case the subgroup size is between two and ten then X-bar and R-bar control charts are used. In case the subgroup size is over ten then X-bar and S chart are used.

Based on Raper, (2003), the moving range chart (MR) takes the moving range of the samples into consideration. The moving range has been defined as the absolute difference between two successive observations, which indicate possible shifts or changes in the process from one observation to the next. The X-chart has been defined as the plot of the individual observations. However, as the MR-chart plots data that are correlated with one another therefore the observation of trends is not very useful. For the same reason the MR-chart cannot provide information about variability of the process, but can be used to study the changes in the process between observations.

Chart 4.3: X and MR (2) - Initial Study for Air Voids

X Chart for Air Voids

UCL = 5.47
CTR = 3.23
LCL = 0.99

MR (2) Chart for Air Voids

UCL = 2.76
CTR = 0.84
LCL = 0.00
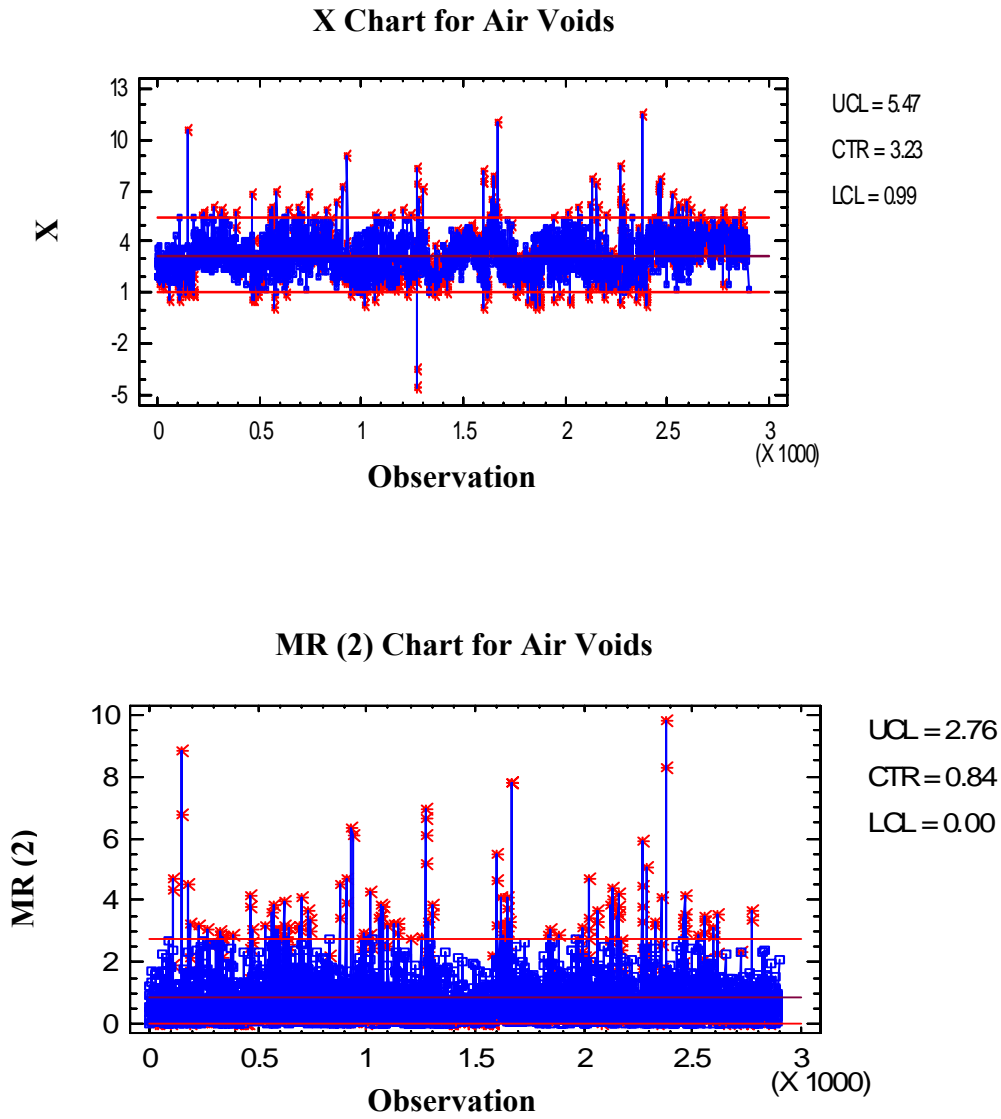
4.5.1 X and MR (2) - Initial Study for Air Voids

Number of observations = 2894; 0 observations excluded

X Chart:

UCL: +3.0 sigma = 5.47; Centerline = 3.23; LCL: -3.0; sigma = 0.98

121 beyond limits

MR (2) Chart: UCL: +3.0 sigma = 2.75; Centerline = 0.84; LCL: -3.0 sigma = 0.0; 115 beyond limits

Estimates: Process mean = 3.23; Process sigma = 0.75; Mean MR (2) = 0.84

The individual chart for air voids is designed to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 3.23 and standard deviation equals 0.75. These parameters were estimated from the data. Of the 2894 non-excluded points shown on the charts, 121 are beyond the control limits on the first chart while 115 are beyond the limits on the second chart. Since the probability of seeing 121 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.4: X and MR (2) - Control to Standard for Air Voids

X Chart for Air Voids

UCL = 6.74
CTR = 3.23
LCL = -0.28

MR (2) Chart for Air Voids

UCL = 4.31
CTR = 1.32
LCL = 0.00

4.5.2 X and MR (2) - Control to Standard for Air Voids

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 6.74; Centerline = 3.23; LCL: -3.0 sigma = -0.28; 26 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 4.31; Centerline = 1.32; LCL: -3.0 sigma = 0.0; 24 beyond limits

Estimates

Process mean = 3.23; Process sigma = 0.74; Mean MR (2) = 0.84

Standard

Process mean = 3.23; Process sigma = 1.17; Mean MR (2) = 1.32

The individual chart for air voids is designed to determine whether the data comes from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 3.23 and standard deviation equals 1.17. Of the 2894 non-excluded points shown on the charts, 26 are beyond the control limits on the first chart while 24 are beyond the limits on the second chart. Since the probability of seeing 26 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.5: X and MR (2) - Initial Study for Density of Core

X Chart for Density of Core

UCL = 99.06
CTR = 96.74
LCL = 94.41

MR (2) Chart for Density of Core

UCL = 2.8
CTR = 0.8
LCL = 0.0

4.5.3 X and MR (2) - Initial Study for Density of Core

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 99.06; Centerline = 96.74; LCL: -3.0 sigma = 94.41;

105 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 2.86; Centerline = 0.87; LCL: -3.0 sigma = 0.0

104 beyond limits

Estimates

Process mean = 96.74; Process sigma = 0.78; Mean MR (2) = 0.87

The individuals chart for density of core is designed to allow us to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 96.74 and standard deviation equals 0.78. These parameters were estimated from the data. Of the 2894 non-excluded points shown on the charts, 105 are beyond the control limits on the first chart while 104 are beyond the limits on the second chart. Since the probability of seeing 105 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.6: X and MR (2) - Control to Standard for Density of Core

X Chart for Density of Core

UCL = 100.28
CTR = 96.77
LCL = 93.26

MR (2) Chart for Density of Core

UCL = 4.31
CTR = 1.32
LCL = 0.00

4.5.4 X and MR (2) - Control to Standard for Density of Core

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 100.28; Centerline = 96.77; LCL: -3.0 sigma = 93.26; 27 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 4.31; Centerline = 1.32; LCL: -3.0 sigma = 0.0

25 beyond limits

Estimates

Process mean = 96.74; Process sigma = 0.78; Mean MR (2) = 0.87

Standard

Process mean = 96.77; Process sigma = 1.17; Mean MR (2) = 1.32

The individuals chart for density of core is designed to allow us to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 96.77 and standard deviation equals 1.17. Of the 2894 non-excluded points shown on the charts, 27 are beyond the control limits on the first chart while 25 are beyond the limits on the second chart. Since the probability of seeing 27 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.7: X and MR (2) - Initial Study for Measured Asphalt

X Chart for Measured Asphalt

UCL = 5.69
CTR = 4.68
LCL = 3.67

MR (2) Chart for Measured Asphalt

UCL = 1.25
CTR = 0.38
LCL = 0.00

4.5.5 X and MR (2) - Initial Study for Measured Asphalt

Number of observations = 2892; 0 observations excluded
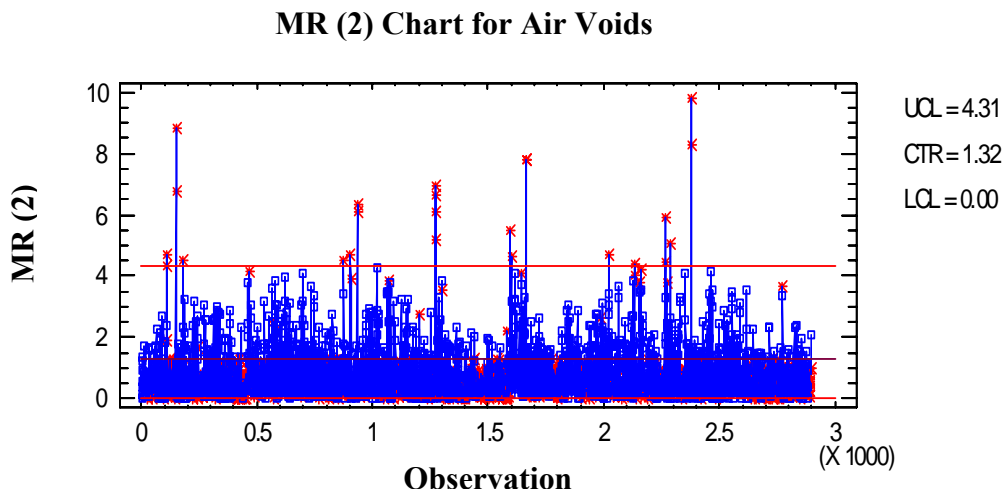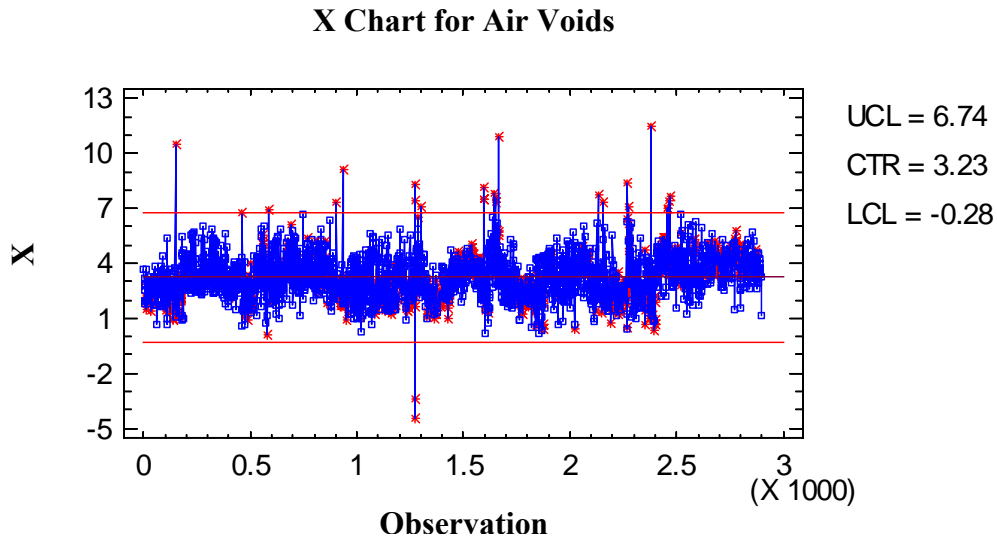
X Chart

UCL: +3.0 sigma = 5.69; Centerline = 4.68; LCL: -3.0 sigma = 3.67

58 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 1.25; Centerline = 0.38; LCL: -3.0 sigma = 0.0

139 beyond limits

Estimates

Process mean = 4.6796; Process sigma = 0.337809; Mean MR (2) = 0.381048

The individuals chart for measured asphalt is designed to determine whether the data comes from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 4.68 and standard deviation equals 0.34. These parameters were estimated from the data. Of the 2892 non-excluded points shown on the charts, 58 are beyond the control limits on the first chart while 139 are beyond the limits on the second chart. Since the probability of seeing 115 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.8: X and MR (2) - Control to Standard for Measured Asphalt

X Chart for Measured Asphalt

UCL = 6.42
CTR = 4.68
LCL = 2.94

MR (2) Chart for Measured Asphalt

UCL = 2.14
CTR = 0.65
LCL = 0.00
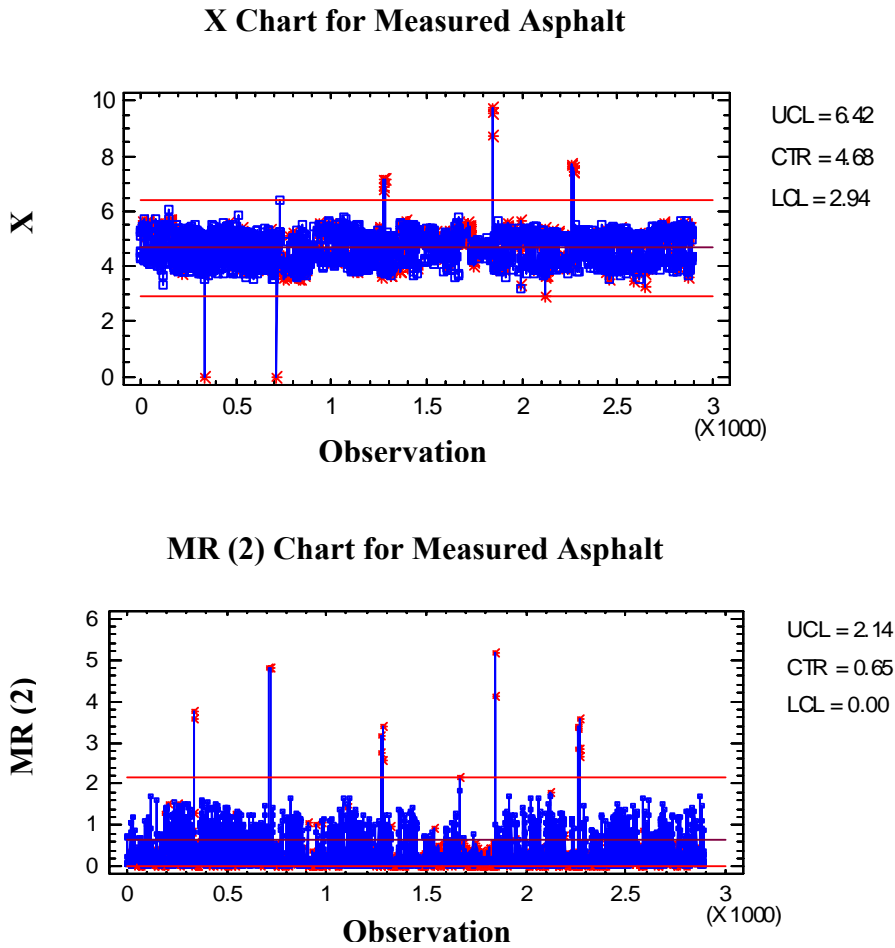
4.5.6 X and MR (2) - Control to Standard for Measured Asphalt

Number of observations = 2892; 0 observations excluded

X Chart

UCL: +3.0 sigma = 6.42; Centerline = 4.67; LCL: -3.0 sigma = 2.94

15 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 2.13; Centerline = 0.65; LCL: -3.0 sigma = 0.0
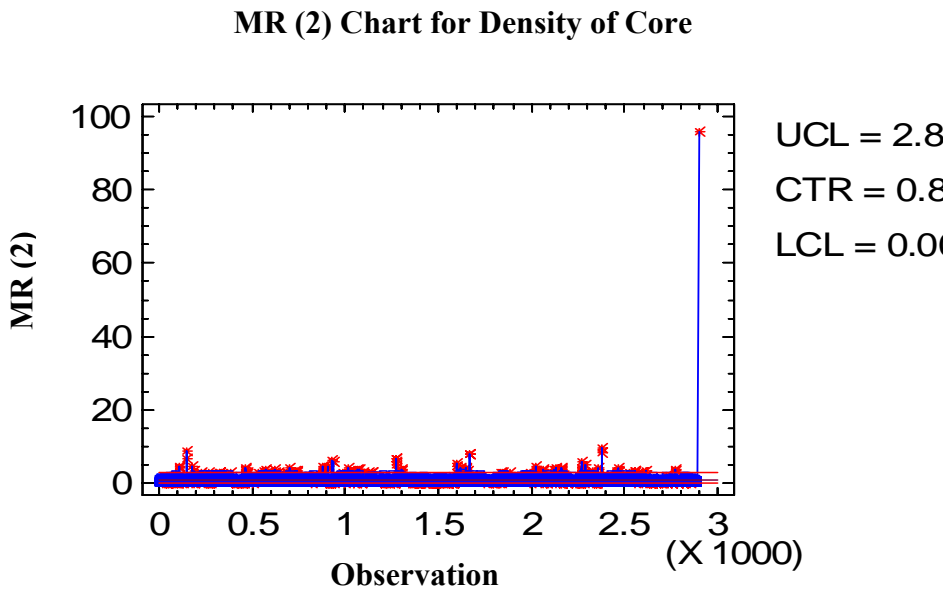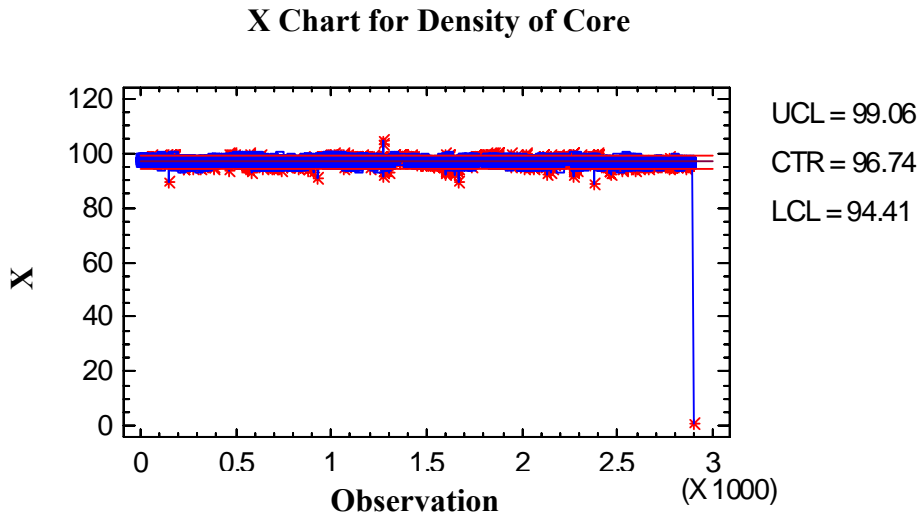
17 beyond limits

47

Estimates

Process mean = 4.68; Process sigma = 0.34; Mean MR (2) = 0.38

Standard

Process mean = 4.68; Process sigma = 0.58; Mean MR (2) = 0.65

The individuals chart for measured asphalt is designed to determine whether the data come from a process, which is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 4.68 and standard deviation equals 0.58. Of the 2892 non-excluded points shown on the charts, 15 are beyond the control limits on the first chart while 17 are beyond the limits on the second chart. Since the probability of seeing 15 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.9: X and MR (2) - Initial Study for Voids Filled with Asphalt

X Chart for Voids filled with Asphalt

MR (2) Chart for Voids filled with Asphalt
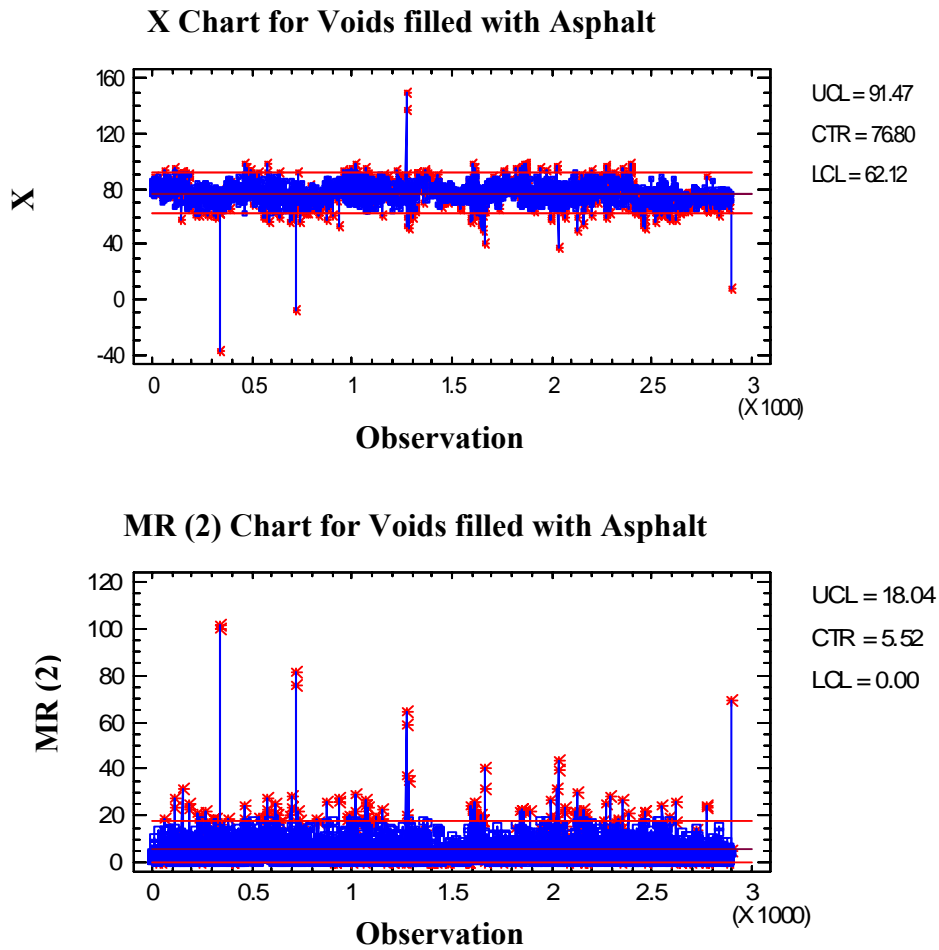
4.5.7 X and MR (2) - Initial Study for Voids filled with Asphalt

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 91.47; Centerline = 76.79; LCL: -3.0 sigma = 62.12

123 beyond limits

MR (2) Chart

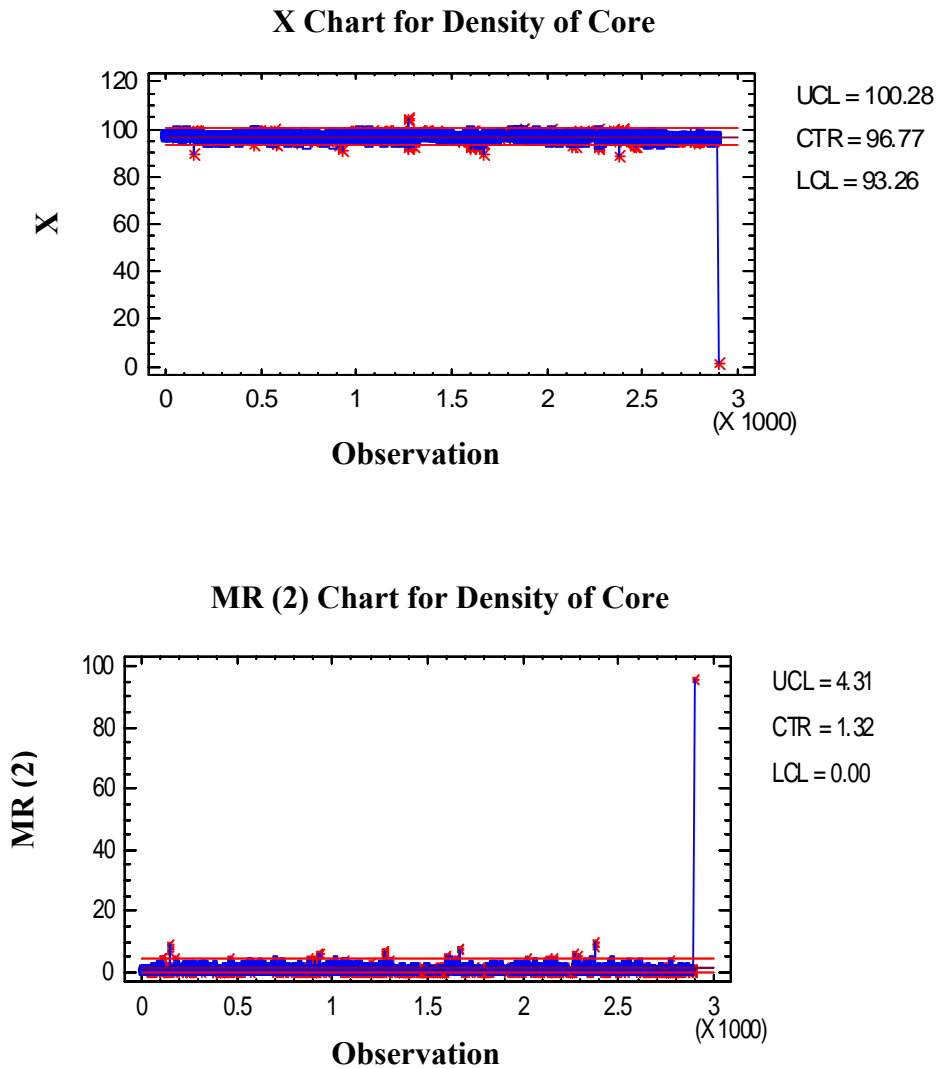UCL: +3.0 sigma = 18.04; Centerline = 5.52; LCL: -3.0 sigma = 0.0

100 beyond limits

Estimates

Process mean = 76.79; Process sigma = 4.89; Mean MR (2) = 5.52

The individuals chart for Voids filled with Asphalt is designed to allow us to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 76.79 and standard deviation equals to 4.89. These parameters were estimated from the data. Of the 2894 non-excluded points shown on the charts, 123 are beyond the control limits on the first chart while 100 are beyond the limits on the second chart. Since the probability of seeing 123 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.10: X and MR (2) - Control to Standard for Voids Filled with Asphalt

X Chart for Voids filled with Asphalt

MR (2) Chart for Voids filled with Asphalt
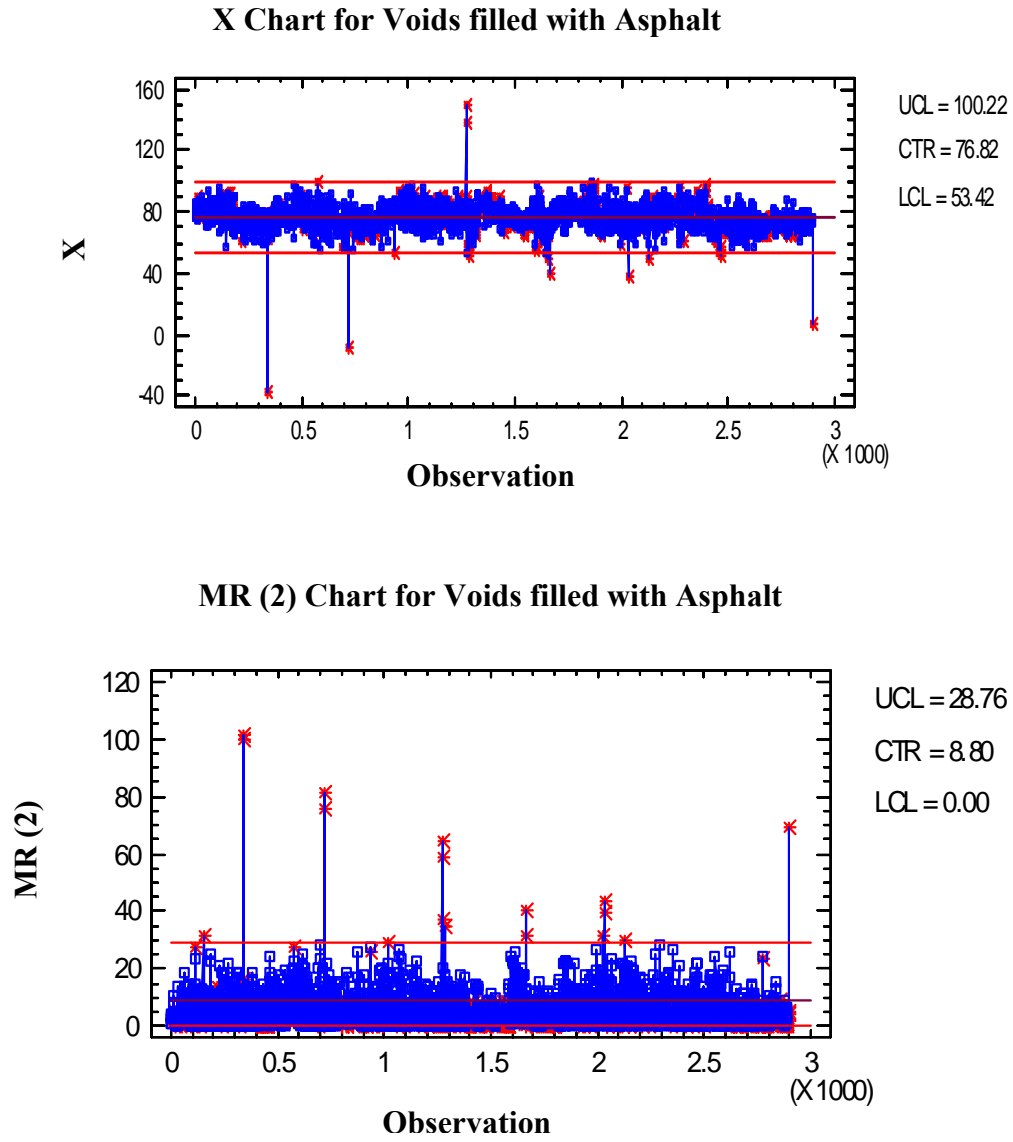
4.5.8 X and MR (2) - Control to Standard for Voids Filled with Asphalt

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 100.22; Centerline = 76.82; LCL: -3.0 sigma = 53.42

14 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 28.76; Centerline = 8.79; LCL: -3.0 sigma = 0.0

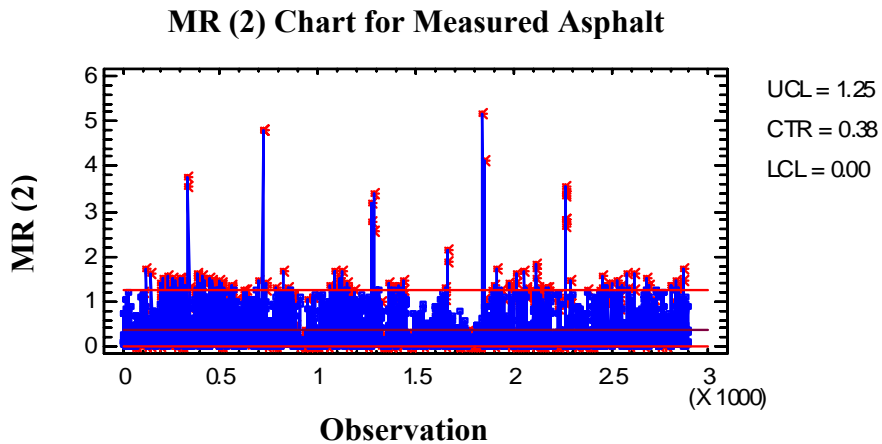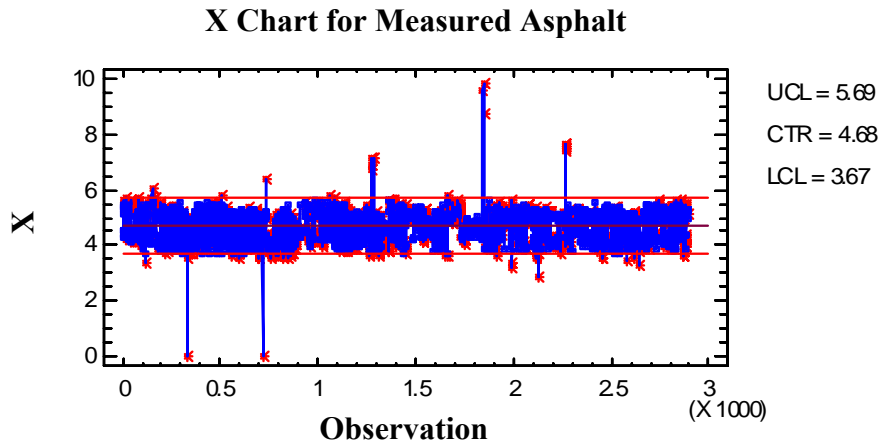17 beyond limits

Estimates

Process mean = 76.79; Process sigma = 4.89; Mean MR (2) = 5.52

Standard

Process mean = 76.82; Process sigma = 7.8; Mean MR (2) = 8.7984

The individual chart for voids filled with asphalt is designed to allow us determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 76.82 and a standard deviation equals 7.8. Of the 2894 non-excluded points shown on the charts, 14 are beyond the control limits on the first chart while 17 are beyond the limits on the second chart. Since the probability of seeing 14 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.11: X and MR (2) - Initial Study for Voids in Mineral Aggregate

X Chart for Voids in Mineral Aggregate

UCL = 16.47
CTR = 13.79
LCL = 11.11

MR (2) Chart for Voids in Mineral Aggregate

UCL = 3.29
CTR = 1.01
LCL = 0.00
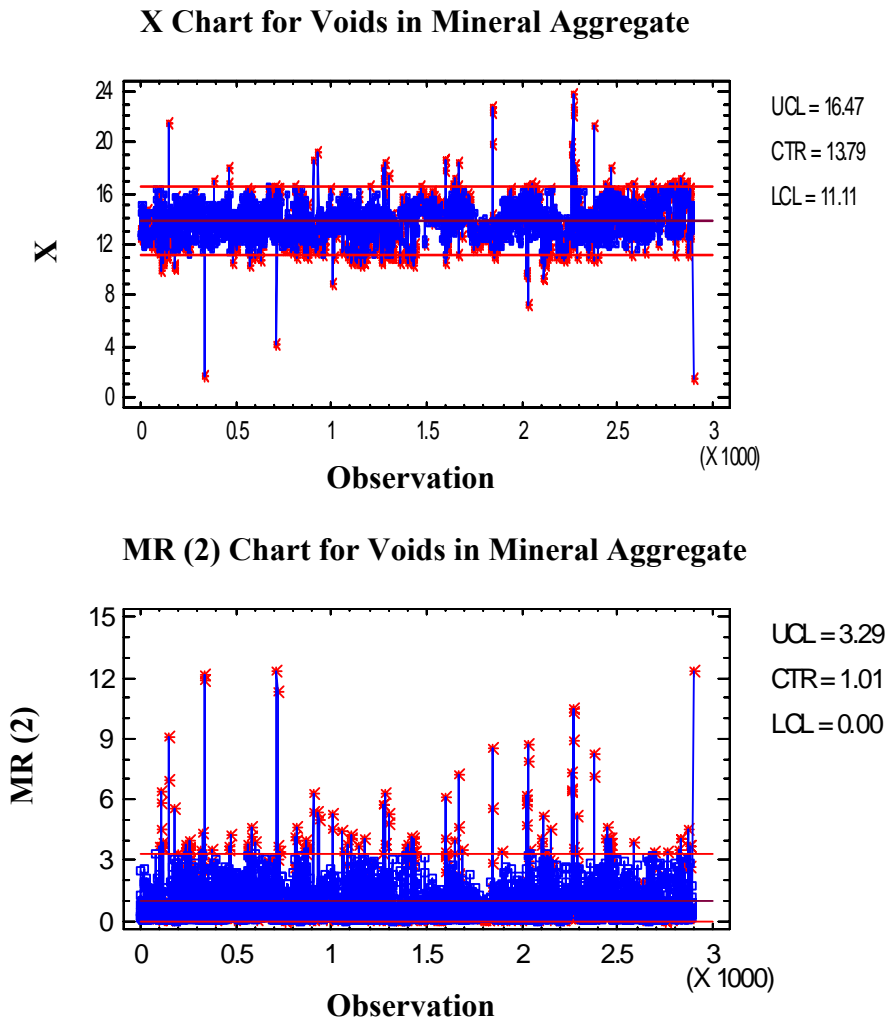
4.5.9 X and MR (2) - Initial Study for Voids in Mineral Aggregate

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 16.47; Centerline = 13.79; LCL: -3.0 sigma = 11.11; 132 beyond limits

53

MR (2) Chart

UCL: +3.0 sigma = 3.29321; Centerline = 1.00752; LCL: -3.0 sigma = 0.0

124 beyond limits

Estimates

Process mean = 13.79; Process sigma = 0.89; Mean MR (2) = 1.00

The individuals chart for voids in mineral aggregate is designed to allow us to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 13.79 and standard deviation equals 0.89. These parameters were estimated from the data. Of the 2894 non-excluded points shown on the charts, 132 are beyond the control limits on the first chart while 124 are beyond the limits on the second chart. Since the probability of seeing 132 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.12: X and MR (2) - Control to Standard for Voids in Mineral Aggregate

X Chart for Voids in Mineral Aggregate

MR (2) Chart for Voids in Mineral Aggregate
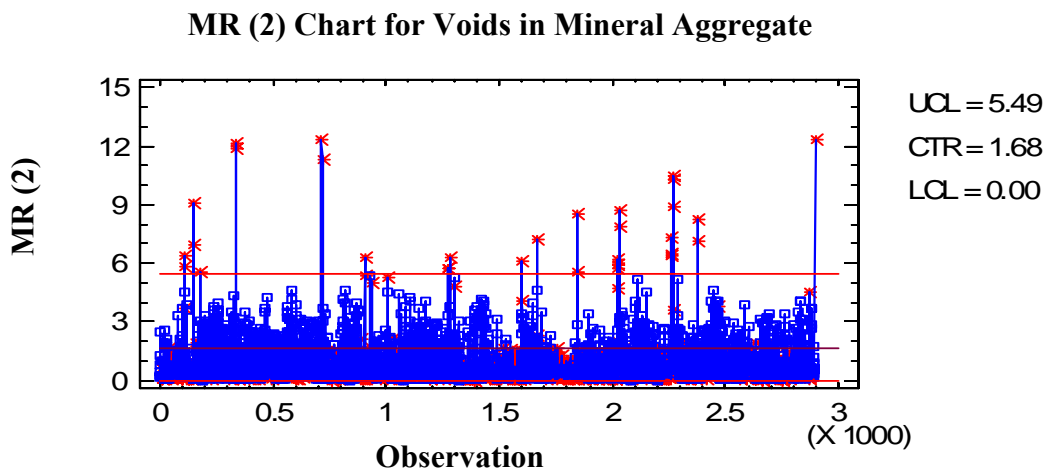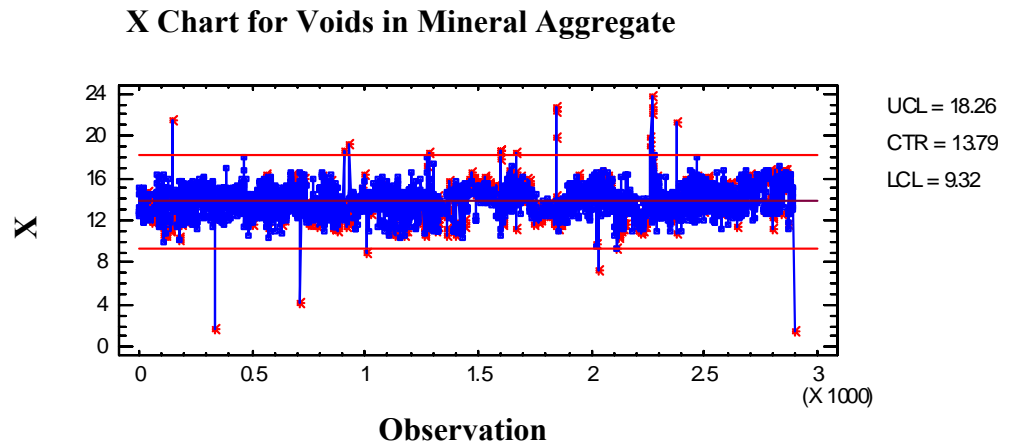
4.5.10 X and MR (2) - Control to Standard for Voids in Mineral Aggregate

Number of observations = 2894; 0 observations excluded

X Chart

UCL: +3.0 sigma = 18.26; Centerline = 13.79; LCL: -3.0 sigma = 9.32

22 beyond limits

MR (2) Chart

UCL: +3.0 sigma = 5.49; Centerline = 1.68; LCL: -3.0 sigma = 0.0; 31 beyond limits

55

Estimates

Process mean = 13.79; Process sigma = 0.89; Mean MR (2) = 1.00

Standard

Process mean = 13.79; Process sigma = 1.49; Mean MR (2) = 1.68

The individuals chart for Voids in Mineral Aggregate is designed to allow us to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 13.79 and a standard deviation equals 1.49. Of the 2894 non-excluded points shown on the charts, 22 are beyond the control limits on the first chart while 31 are beyond the limits on the second chart. Since the probability of seeing 23 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

4.6 Average and Range Control Charts; X-bar and R-bar Control Charts

Based on Juran and Gryna, (1993), in "Quality Planning and Analysis", it can be understood that X-bar, (mean) and R-bar, (range) charts are two of the most common control charts associated with statistical process control. X-bar is a word that represents mean or average and the R-bar represents range charts, the range that the sample lay between. The charts are compared with the upper and lower control limits.

To standardize the X-bar and R-bar control charts, the upper control limit, (UCL) and lower control limit, (LCL), are calculated using the formula in table 4.1 for the upper and lower most limits of the data.

Table 4.1: Computation of Upper and Lower Control Limits

	UCL	LCL
X-bar chart	$\overline{\overline{X}} + (A_2 * \overline{R})$	$\overline{\overline{X}} + (A_2 * \overline{R})$
R-bar chart	$D_4 * \overline{R}$	$D_3 * \overline{R}$
$\overline{\overline{X}}$ = Mean of the data; $\overline{R}$ = Range of the data; A_2, D_4, and D_3 factors for statistical control charts from Table 4.2		

Source: NCHRP Report 409, Annex 3, (1998).

Table 4.2: Factors for Statistical Control Charts

Sample Size, n	A_2	D_3	D_4
2	1.88	0	3.27
3	1.02	0	2.57
4	0.73	0	2.28
5	0.58	0	2.11
6	0.48	0	2.00
7	0.42	0.08	1.92

Source: NCHRP Report 409, Annex 3, (1998).

Chart 4.13: X-bar and Range - Initial Study for Density of Core

X –bar chart for Density of Core

UCL = 98.32
CTR = 96.74
LCL = 95.15

Range chart for Density of Core

UCL = 2.75
CTR = 0.84
LCL = 0.00
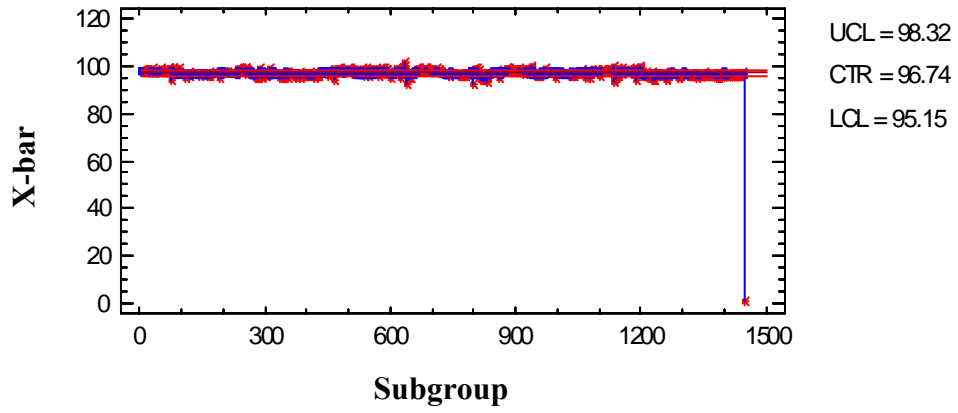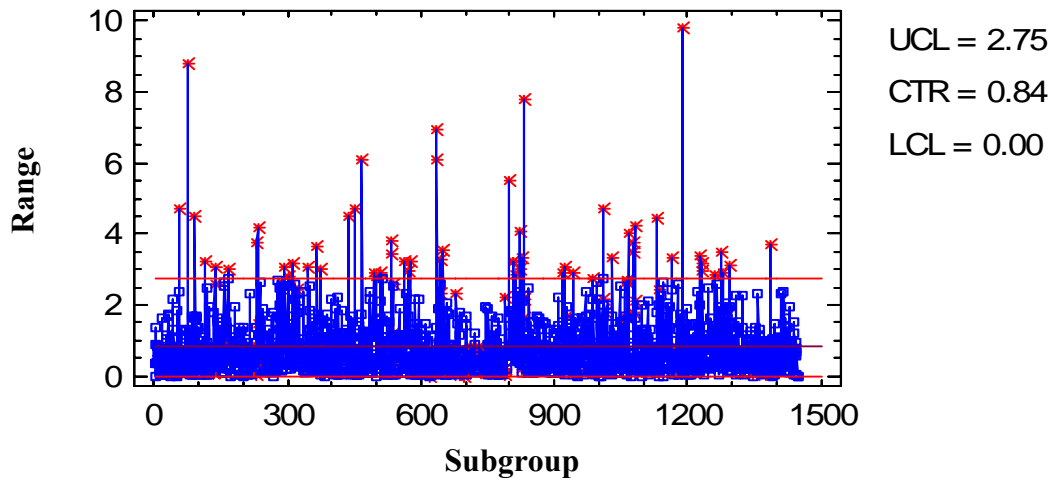
4.6.1 X-bar and Range - Initial Study for Density of Core

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 98.32; Centerline = 96.74; LCL: -3.0 sigma = 95.15

133 beyond limits

Range Chart

UCL: +3.0 sigma = 2.75; Centerline = 0.84; LCL: -3.0 sigma = 0.0

58 beyond limits

Estimates

Process mean = 96.74; Process sigma = 0.75; Mean range = 0.84

 X-Bar and R charts for density of core are designed to determine whether the data comes from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 96.74 and standard deviation equals 0.75. These parameters were estimated from the data. Of the 1448 non-excluded points shown on the charts, 133 are beyond the control limits on the first chart while 58 are beyond the limits on the second chart. Since the probability of seeing 133 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.14: X-bar and Range - Control to Standard for Density of Core

X –bar chart for Density of Core

UCL = 97.20
CTR = 96.80
LCL = 96.30

Range chart for Density of Core

UCL = 1.10
CTR = 0.40
LCL = 0.00

4.6.2 X-bar and Range - Control to Standard for Density of Core

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 97.2; Centerline = 96.8; LCL: -3.0 sigma = 96.3; 971 beyond limits

Range Chart

UCL: +3.0 sigma = 1.1; Centerline = 0.4; LCL: -3.0 sigma = 0.0

370 beyond limits

Estimates

Process mean = 96.74; Process sigma = 0.75; Mean range = 0.84

X-Bar and R charts for density of core are designed to determine whether the data come from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 96.74 and a standard deviation equals 0.75. Of the 1448 non-excluded points shown on the charts, 971 are beyond the control limits on the first chart while 370 are beyond the limits on the second chart. Since the probability of seeing 971 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.15: X-bar and Range - Initial Study for Air Voids

X –bar chart for Air Voids

UCL = 4.81
CTR = 3.23
LCL = 1.65

Range chart for Air Voids

UCL = 2.75
CTR = 0.84
LCL = 0.00

4.6.3 X-bar and Range - Initial Study for Air Voids

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 4.81; Centerline = 3.23; LCL: -3.0 sigma = 1.65; 130 beyond limits

Range Chart

UCL: +3.0 sigma = 2.75; Centerline = 0.84; LCL: -3.0 sigma = 0.0; 58 beyond limits

Estimates

Process mean = 3.23; Process sigma = 0.75; Mean range = 0.84

X-Bar and R charts for air voids are designed to determine whether the data comes from a process, which is in a state of statistical control. The control charts are constructed under the assumption that the data come from a normal distribution where mean equals 3.23 and standard deviation equals 0.75. These parameters were estimated from the data. Of the 1448 non-excluded points shown on the charts, 130 are beyond the control limits on the first chart while 58 are beyond the limits on the second chart. Since the probability of seeing 130 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.16: X-bar and Range - Control to Standard for Air Voids

X –bar chart for Air Voids

UCL = 3.70
CTR = 3.20
LCL = 2.80

Range chart for Air Voids

UCL = 1.10
CTR = 0.40
LCL = 0.00

4.6.4 X-bar and Range - Control to Standard for Air Voids

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 3.7; Centerline = 3.2; LCL: -3.0 sigma = 2.8; 971 beyond limits

Range Chart

UCL: +3.0 sigma = 1.1; Centerline= 0.4; LCL: -3.0 sigma = 0.0; 370 beyond limits

Estimates

Process mean = 3.23; Process sigma = 0.75; Mean range = 0.84

X-Bar and R charts for air voids are designed to determine whether the data comes from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 3.23 and standard deviation equals 0.75. Of the 1448 non-excluded points shown on the charts, 971 are beyond the control limits on the first chart while 370 are beyond the limits on the second chart. Since the probability of seeing 971 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.17: X-bar and Range - Initial Study for Voids in Mineral Aggregate

X –bar chart for Voids in Mineral Aggregate

UCL = 15.63
CTR = 13.79
LCL = 11.95

Range chart for Voids in Mineral Aggregate

UCL = 3.19
CTR = 0.98
LCL = 0.00

4.6.5 X-bar and Range - Initial Study for Voids in Mineral Aggregate

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 15.62; Centerline = 13.79; LCL: -3.0 sigma = 11.95

203 beyond limits

Range Chart

UCL: +3.0 sigma = 3.19; Centerline = 0.98; LCL: -3.0 sigma = 0.0

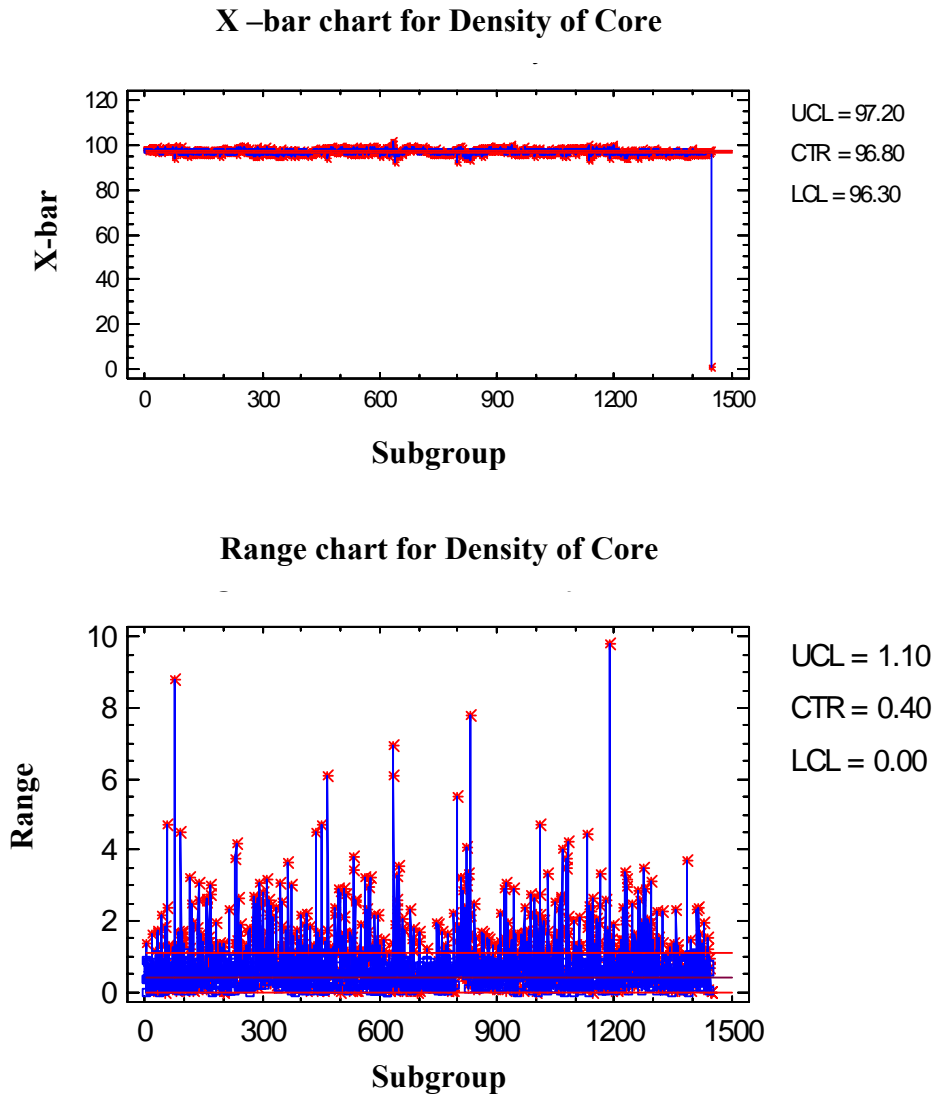68 beyond limits

Estimates

Process mean = 13.79; Process sigma = 0.86; Mean range = 0.98

X-Bar and R charts for voids in mineral aggregate are designed to determine whether the data comes from a process, which is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 13.79 and standard deviation equals 0.86. These parameters were estimated from the data. Of the 1448 non-excluded points shown on the charts, 203 are beyond the control limits on the first chart while 68 are beyond the limits on the second chart. Since the probability of seeing 203 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.18: X-bar and Range - Control to Standard for Voids in Mineral Aggregate

X –bar chart for Voids in Mineral Aggregate

UCL = 14.20
CTR = 13.80
LCL = 13.40

Range chart for Voids in Mineral Aggregate

UCL = 1.00
CTR = 0.40
LCL = 0.00
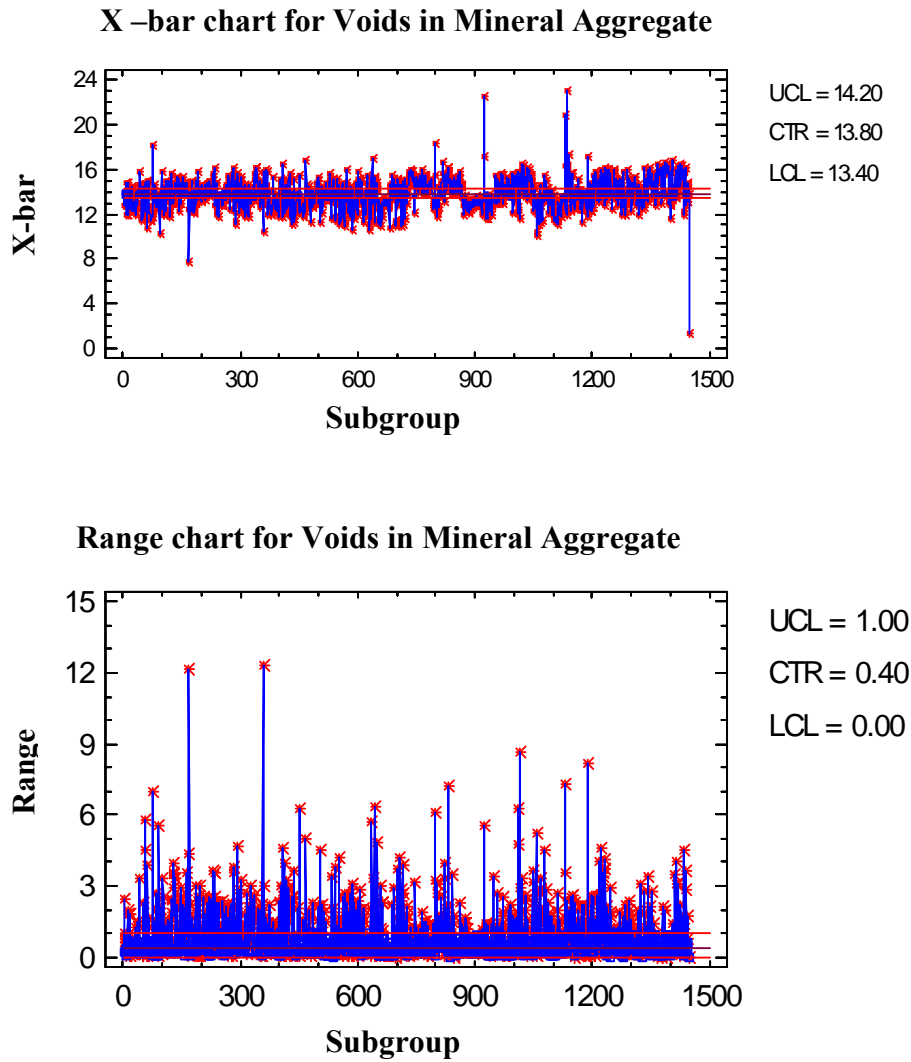
4.6.6 X-bar and Range - Control to Standard for Voids in Mineral Aggregate

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 14.2; Centerline = 13.8; LCL: -3.0 sigma = 13.4; 1112 beyond limits

Range Chart

UCL: +3.0 sigma = 1.0; Centerline = 0.4; LCL: -3.0 sigma = 0.0; 460 beyond limits
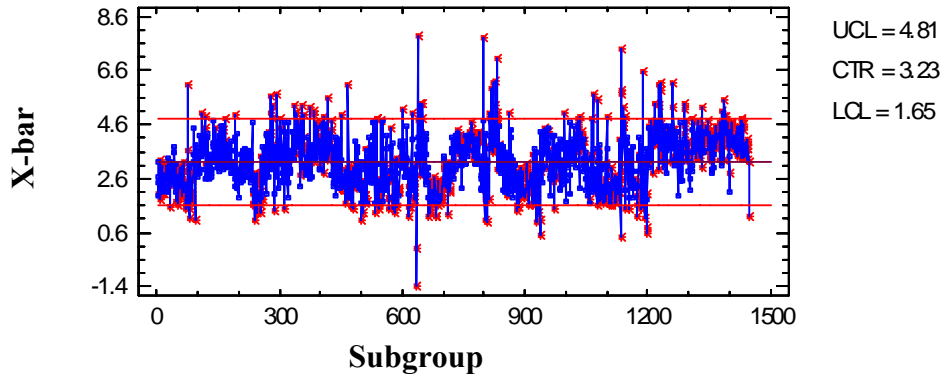
Estimates

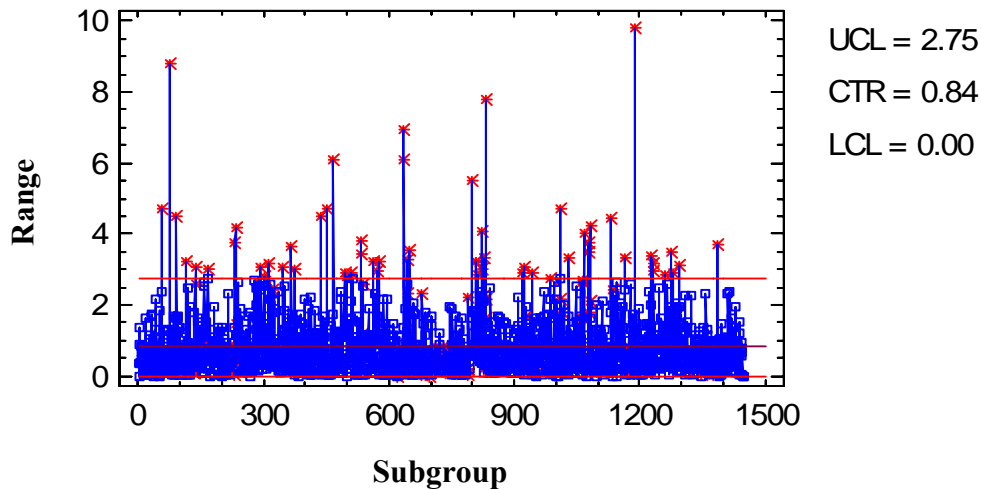Process mean = 13.79; Process sigma = 0.86; Mean range = 0.98

X-Bar and R charts for voids in mineral aggregate are designed to determine whether the data comes from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 13.79 and standard deviation equals to 0.87. Of the 1448 non-excluded points shown on the charts, 1112 are beyond the control limits on the first chart while 460 are beyond the limits on the second chart. Since the probability of seeing 1112 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.19: X-bar and Range - Initial Study for Voids Filled with Asphalt

X –bar chart for Voids Filled with Asphalt

UCL = 87.20
CTR = 76.80
LCL = 66.39

Range chart for Voids Filled with Asphalt

UCL = 18.08
CTR = 5.53
LCL = 0.00

4.6.7 X-bar and Range - Initial Study for Voids Filled with Asphalt

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 87.20; Centerline = 76.79; LCL: -3.0 sigma = 66.39;
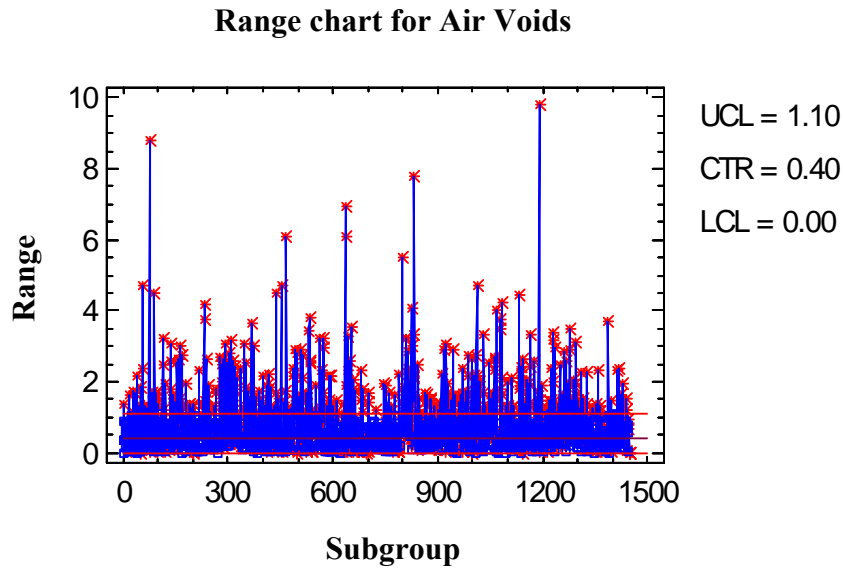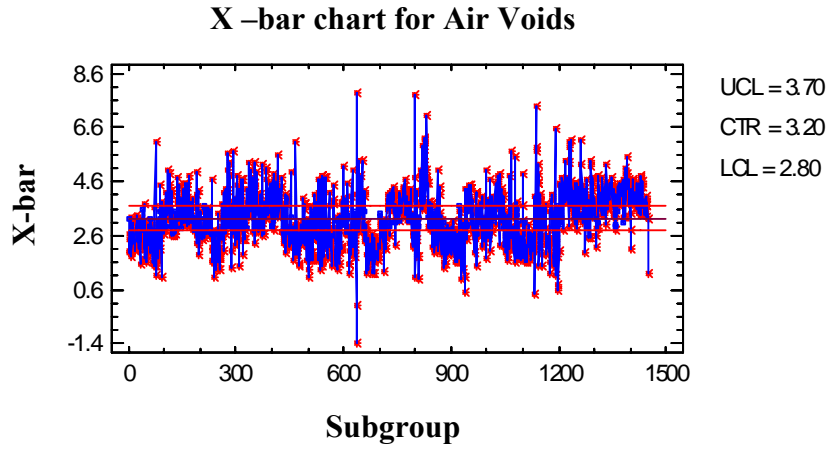
120 beyond limits

Range Chart

UCL: +3.0 sigma = 18.08; Centerline = 5.53; LCL: -3.0 sigma = 0.0; 51 beyond limits

Estimates

Process mean = 76.79; Process sigma = 4.90; Mean range = 5.53

X-Bar and R charts for voids filled with asphalt are designed to determine whether the data comes from a process, which is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 76.79 and standard deviation equals 4.90. These parameters were estimated from the data. Of the 1448 non-excluded points shown on the charts, 120 are beyond the control limits on the first chart while 51 are beyond the limits on the second chart. Since the probability of seeing 120 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.20 X-bar and Range - Control to Standard for Voids Filled with Asphalt

X –bar chart for Voids Filled with Asphalt

UCL = 79.38
CTR = 76.80
LCL = 74.25

Range chart for Voids Filled with Asphalt

UCL = 6.49
CTR = 2.50
LCL = 0.00
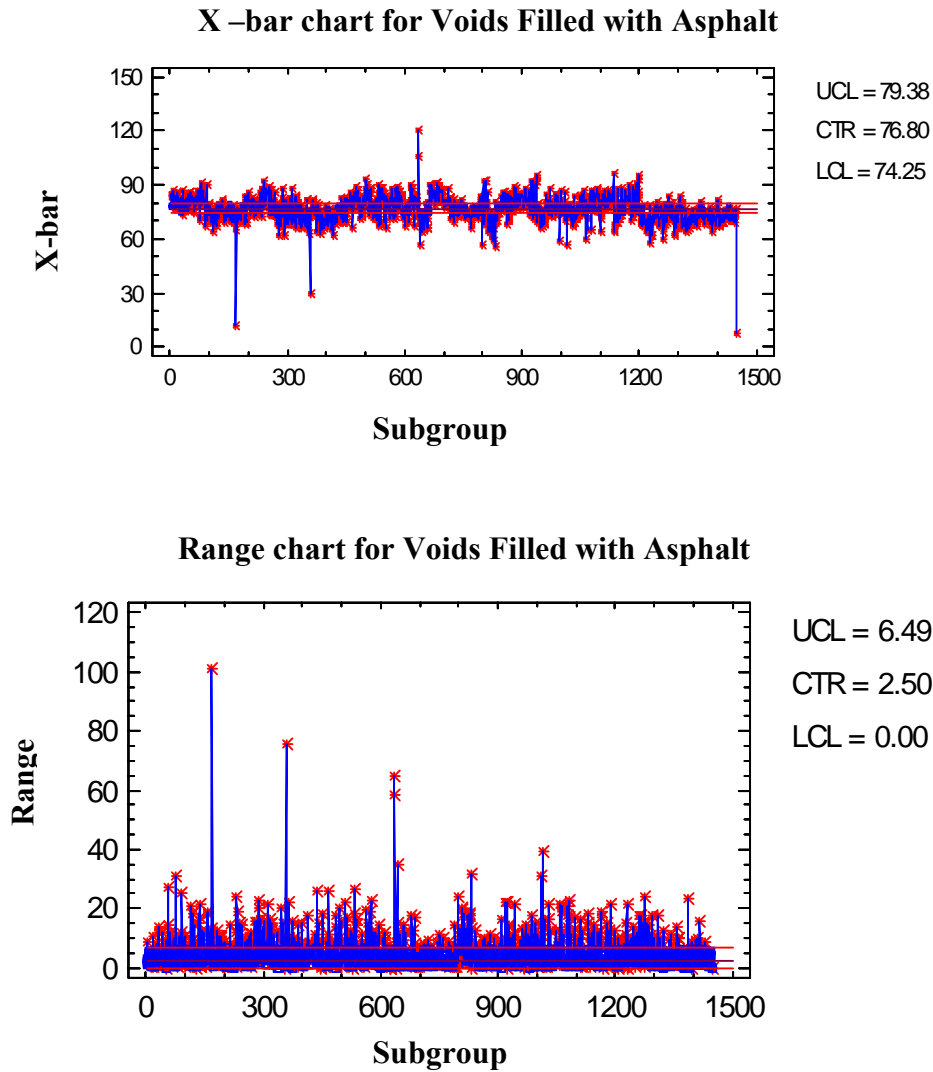
4.6.8 X-bar and Range - Control to Standard for Voids Filled with Asphalt

Number of subgroups = 1448; Average subgroup size = 1.99; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 79.38; Centerline = 76.8; LCL: -3.0 sigma = 74.25; 997 beyond limits
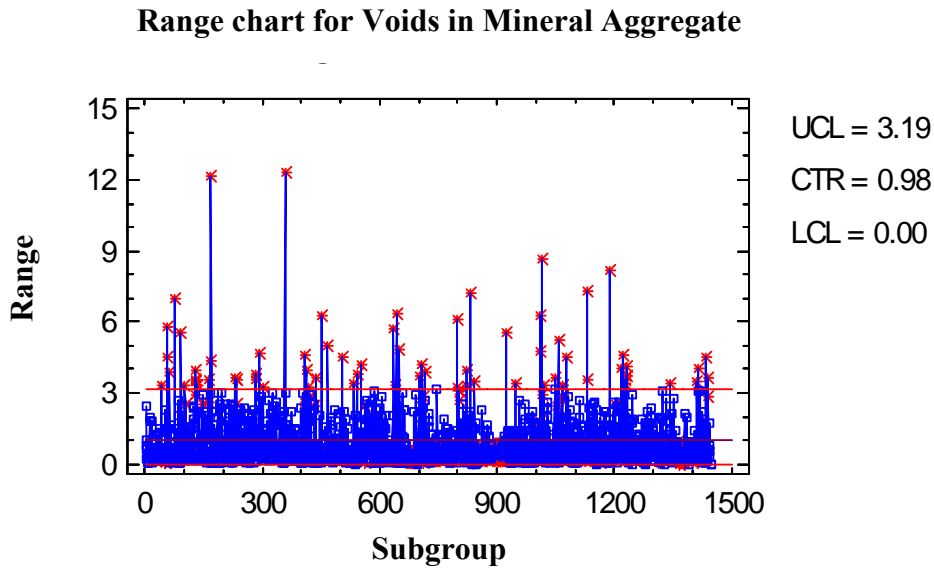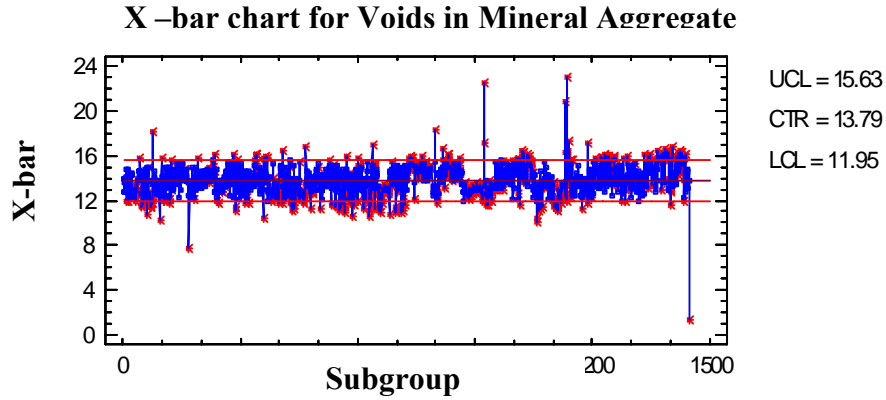
Range Chart

UCL: +3.0 sigma = 6.49; Centerline = 2.5; LCL: -3.0 sigma = 0.0; 419 beyond limits

Estimates

Process mean = 76.79; Process sigma = 4.90; Mean range = 5.53

X-Bar and R charts for voids filled with asphalt are designed to determine whether the data comes from a process, which is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 76.79 and standard deviation equals 4.9. Of the 1448 non-excluded points shown on the charts, 997 are beyond the control limits on the first chart while 419 are beyond the limits on the second chart. Since the probability of seeing 997 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.21: X-bar and Range - Initial Study for Measured Asphalt

X –bar chart for Measured Asphalt

UCL = 5.38
CTR = 4.68
LCL = 3.98

Range chart for Measured Asphalt

UCL = 1.21
CTR = 0.37
LCL = 0.00
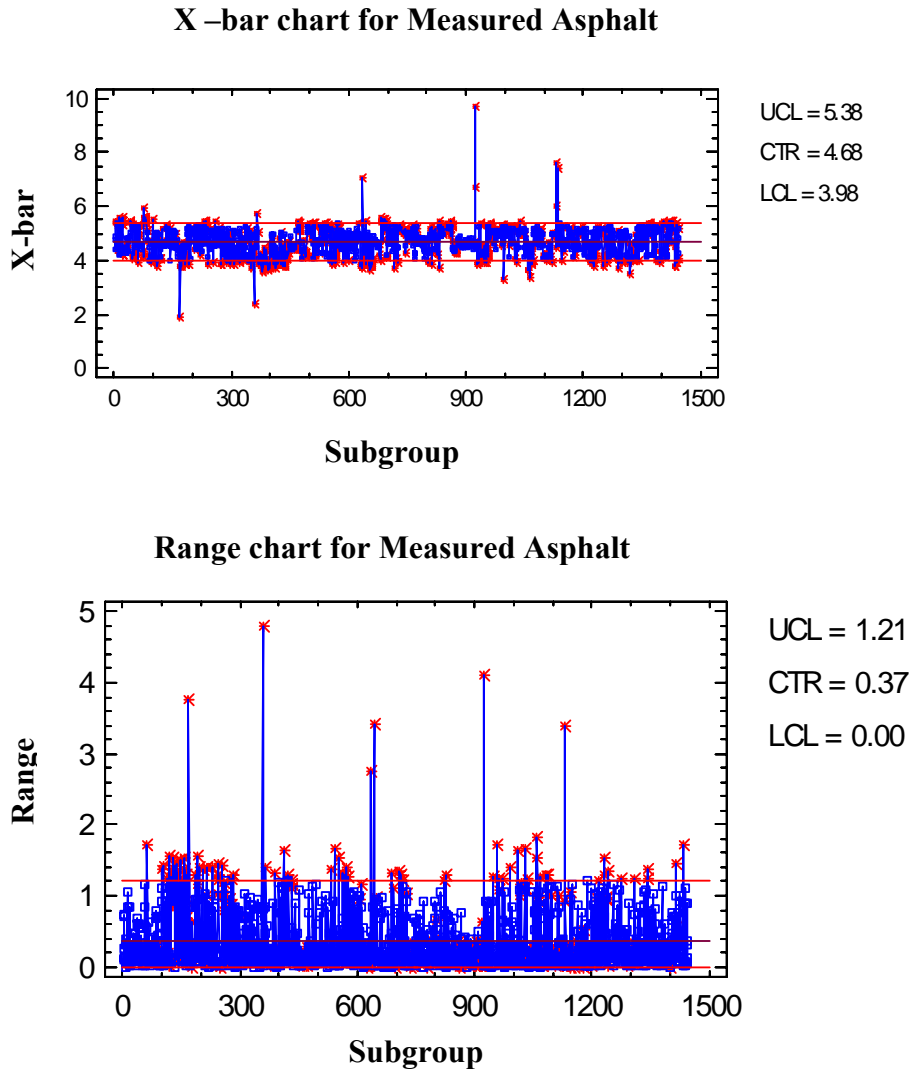
4.6.9 X-bar and Range - Initial Study for Measured Asphalt

Number of subgroups = 1446; Subgroup size = 2.0; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 5.38; Centerline = 4.68; LCL: -3.0 sigma = 3.98

177 beyond limits

Range Chart

UCL: +3.0 sigma = 1.21; Centerline = 0.37; LCL: -3.0 sigma = 0.0; 82 beyond limits

Estimates

Process mean = 4.68; Process sigma = 0.33; Mean range = 0.37

X-Bar and R charts for measured asphalt are designed to determine whether the data comes from a process, which is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 4.68 and standard deviation equals 0.33. These parameters were estimated from the data. Of the 1446 non-excluded points shown on the charts, 177 are beyond the control limits on the first chart while 82 are beyond the limits on the second chart. Since the probability of seeing 177 or more points beyond the limits just by chance is 0.0 if the data comes from the assumed distribution, we can declare the process to be out of control at the 99% confidence level.

Chart 4.22: X-bar and Range - Control to Standard for Measured Asphalt

X –bar chart for Measured Asphalt

UCL = 11.72
CTR = 4.68
LCL = -2.35

Range chart for Measured Asphalt

UCL = 17.80
CTR = 6.90
LCL = 0.00
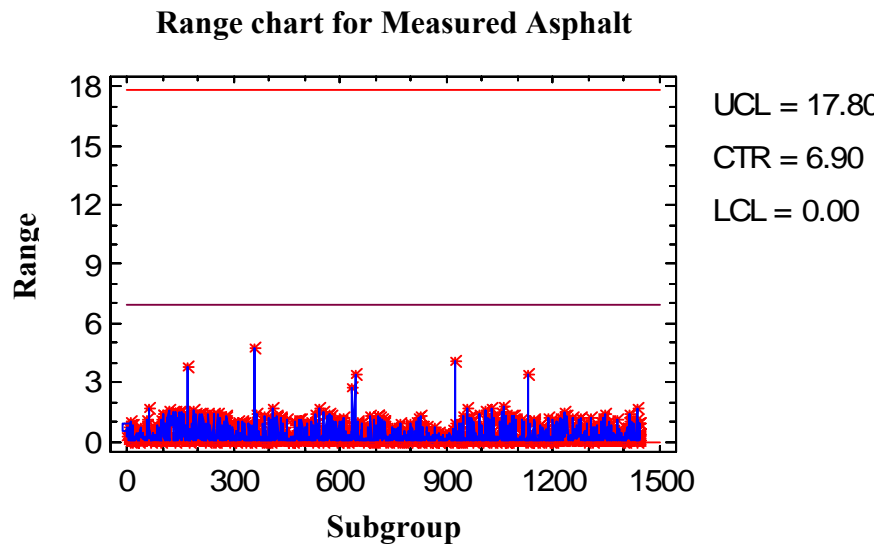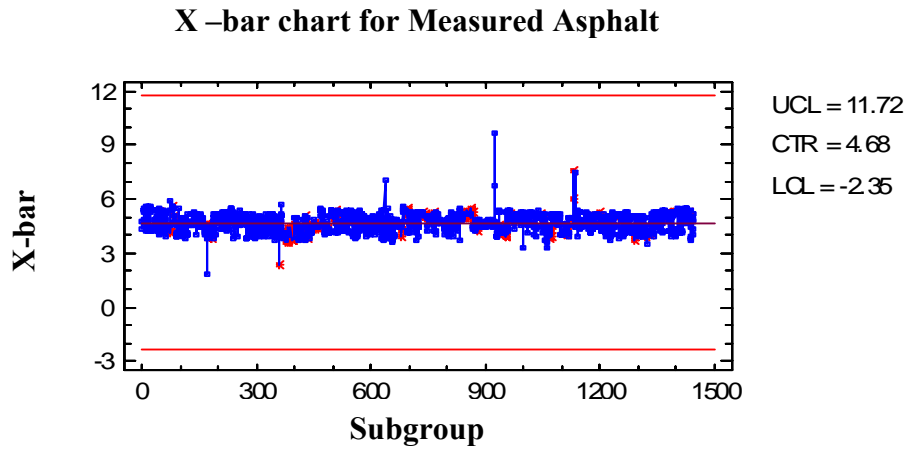
4.6.10 X-bar and Range - Control to Standard for Measured Asphalt

Number of subgroups = 1446; Subgroup size = 2.0; 0 subgroups excluded

X-bar Chart

UCL: +3.0 sigma = 11.72; Centerline = 4.68; LCL: -3.0 sigma = -2.35; 0 beyond limits

Range Chart
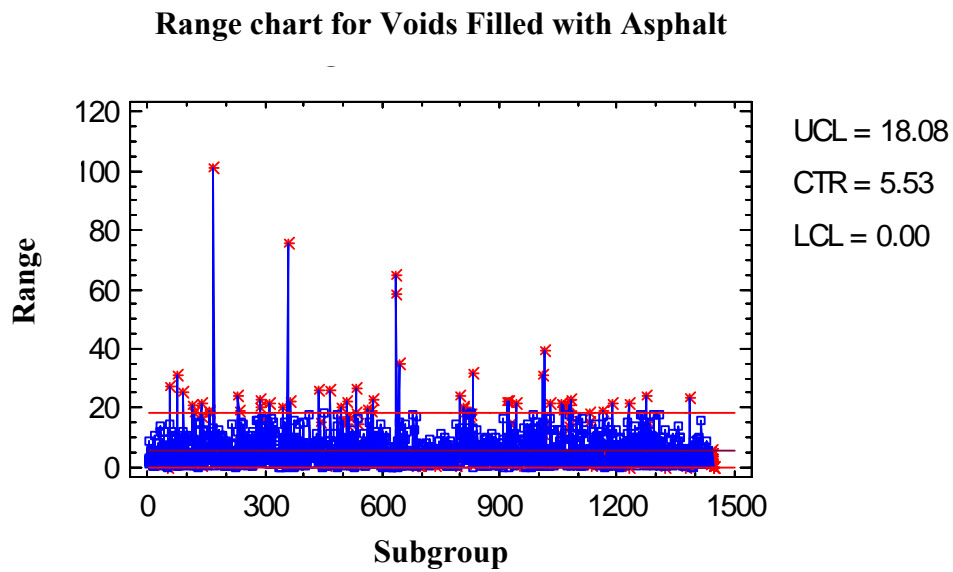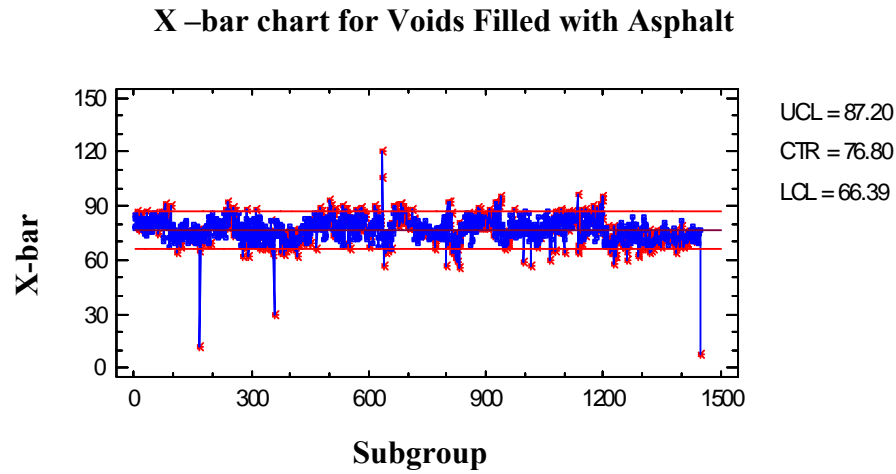
UCL: +3.0 sigma = 17.8; Centerline = 6.9; LCL: -3.0 sigma = 0.0; 0 beyond limits

Estimates

Process mean = 4.68; Process sigma = 0.33; Mean range = 0.37

X-Bar and R charts for Measured Asphalt are designed to determine whether the data comes from a process that is in a state of statistical control. The control charts are constructed under the assumption that the data comes from a normal distribution where mean equals 4.68 and standard deviation equals 0.33. Of the 1446 non-excluded points shown on the charts, 0 are beyond the control limits on the first chart while 0 are beyond the limits on the second chart. Since the probability of seeing 0 or more points beyond the limits just by chance is 1.0 if the data comes from the assumed distribution, we cannot reject the hypothesis that the process is in a state of statistical control at the 90% or higher confidence level.

4.7 Correlation Analysis

The correlation coefficient is described as a measure of the degree of linear relationship between two or more variables. In correlation, the emphasis is on the degree to which a linear model may describe the relationship between the variables.

The correlation analysis done on the quality characteristics density, asphalt content, voids in mineral aggregate and voids filled with asphalt and the results are tabulated in Table 4.3:

Table 4.3: Correlation Matrix

	Density of Core	Air Voids	Voids in Mineral Aggregate	Voids filled with Asphalt	Asphalt Content
Density of Core	1	-1	-0.56	0.89	0.17
Air Voids	-1	1	0.56	-0.89	-0.17
VMA	-0.56	0.56	1	-0.22	0.69
VFA	+0.89	-0.89	-0.22	1	0.46
Asphalt Content	0.17	-0.17	0.69	0.46	1

4.7.1 Density of Core and Air Voids

The direction of the relationship between the variables can be seen based on the signs of the correlation coefficient (+ or -). As seen in the table above, the density of core has a negative correlation with air voids which means that as the value of density variable increases the value of air voids variable decreases and as the value of density variable decreases the value of air voids variable increases. The correlation coefficient of -1 shows a perfect linear relationship but in the opposite direction.

4.7.2 Density of Core and Voids in Mineral Aggregate

As seen in the table above, the density of core has a negative correlation with voids in mineral aggregate which means that as the value of density of core variable increases, the value of the voids in mineral aggregate variable decreases; and as one decreases the other increases. The correlation coefficient of -0.56 shows a correlation in the opposite direction.

4.7.3 Density of Core and Voids filled with Asphalt

As seen in the table above, the density of core has a positive correlation with voids filled with asphalt. This means that as the value of density of core variable increases, the value of the voids filled with asphalt variable increases; as one decreases the other also decreases. The correlation coefficient of +0.89 shows a very strong correlation in the same direction.

4.7.4 Density of Core and Asphalt Content

Also seen in the table above, the density of core has a positive correlation with asphalt content. This means that as the value of density of core variable increases, the value of the asphalt Content variable increases; as one decreases the other also decreases. The correlation coefficient of +0.17 shows a weak correlation in the same direction.

4.7.5 Air Voids and Voids in Mineral Aggregate

As seen in the table above, the air voids have a positive correlation with voids in mineral aggregate. This means that as the value of air voids variable increases, the value of the voids in mineral aggregate variable increases; as one decreases the other also decreases. The correlation coefficient of +0.56 shows a strong correlation in the same direction.

4.7.6 Air Voids and Voids filled with Asphalt

As seen in the table above, the air voids have a negative correlation with voids filled with asphalt. This means that as the value of air voids variable increases, the value of the voids filled with asphalt variable decreases; and as one decreases the other increases. The correlation coefficient of -0.89 shows a correlation in opposite direction.

4.7.7 Air Voids and Asphalt Content

As seen in the table above, the air voids have a negative correlation with asphalt content. This means that as the value of air voids variable increases, the value of the asphalt content variable decreases; and as one decreases the other increases. The correlation coefficient of -0.17 shows a weak correlation in opposite direction.

4.7.8 Voids in Mineral Aggregate and Voids filled with Asphalt

As seen in the table above, the voids in mineral aggregate have a negative correlation with voids filled with asphalt. This means that as the value of voids in mineral aggregate variable increases, the value of the voids filled with asphalt variable decreases; and as one decreases the other increases. The correlation coefficient of -0.22 shows a relatively weak correlation in opposite direction.

4.7.9 Voids in Mineral Aggregate and Asphalt Content

Also seen in the table above, the voids in mineral aggregate have a positive correlation with asphalt content. This means that as the value of voids in mineral aggregate variable increases, the value of the asphalt content variable increases; as one

decreases the other decreases. The correlation coefficient of +0.69 shows a strong correlation in the same direction.

4.7.10 Voids filled with Asphalt and Asphalt Content

As seen in the table above, the voids filled with asphalt have a positive correlation with asphalt content. This means that as the value of air voids variable increases, the value of the voids in mineral aggregate variable increases; as one decreases the other also decreases. The correlation coefficient of +0.46 shows a relatively weak correlation in the same direction.

4.8 Multiple Regression Analysis of various Quality Characteristics

Chart 4.23: Dependent Variable-Air Voids with Independent Variable- Measured Asphalt

Plot of Fitted Model
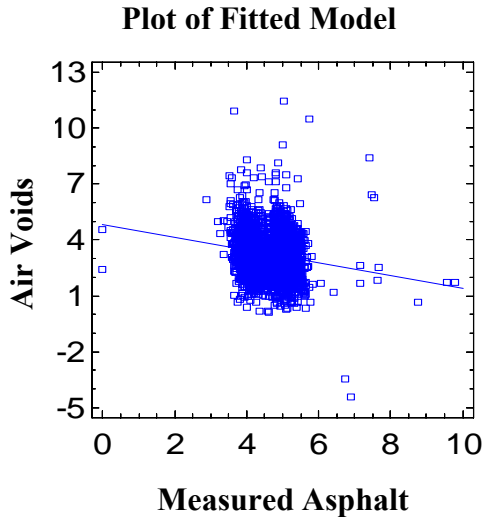
Parameter	Estimate	Error	Statistic	P Value
Constant	4.85	0.18	27.66	0.00
Measured Asphalt	-0.35	0.04	-9.29	0.00

R-squared = 2.90 percent; R-squared (adjusted for d.f.) = 2.86 percent

Standard Error of Est. = 1.15; Mean absolute error = 0.89

The output shows the results of fitting a multiple linear regression model to describe the relationship between air voids and measured asphalt content. The equation of the fitted model is:

Air Voids = 4.85 - 0.34*Measured Asphalt   (4.1)

Since the P-value in the analysis of variance, (ANOVA), table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 2.90 % of the variability in air voids. The adjusted R-squared statistic, which is more suitable for

comparing models with different numbers of independent variables, is 2.86 %. The

standard error of the estimate shows the standard deviation of the residuals to be 1.15.

In determining whether the model can be simplified, notice that the highest P-value on

the independent variables is 0.00, belonging to measured asphalt. Since the P-value is

less than 0.01, the highest order term is statistically significant at the 99% confidence

level. Consequently, it is ideal not to remove any variables from the model.

Chart 4.24: Dependent Variable-Air Voids with Independent Variable- Voids filled with Asphalt

Plot of Fitted Model
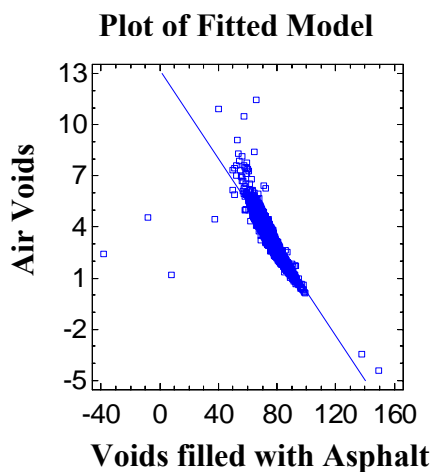
Parameter	Estimate	Error	Statistic	P Value
Constant	13.15	0.11	124.53	0.00
Voids filled with AC	-0.13	0.00	-94.45	0.00

R-squared = 75.52 percent; R-squared (adjusted for d.f.) = 75.51 percent

Standard Error of Est. = 0.58; Mean absolute error = 0.31

The output shows the results of fitting a multiple linear regression model to

describe the relationship between air voids and voids filled with asphalt. The equation of

the fitted model is:

Air Voids = 13.15 - 0.13*VFA   (4.2)

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 75.52 % of the variability in air voids. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 75.51 %. The standard error of the estimate shows the standard deviation of the residuals to be 0.58.

In determining whether the model can be simplified, notice that the highest P-value on the independent variables is 0.00, belonging to Voids filled with asphalt content. Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level. Consequently, it is ideal not to remove any variables from the model

Chart 4.25: Dependent Variable-Air Voids with Independent Variable- Voids in Mineral Aggregate

Plot of Fitted Model
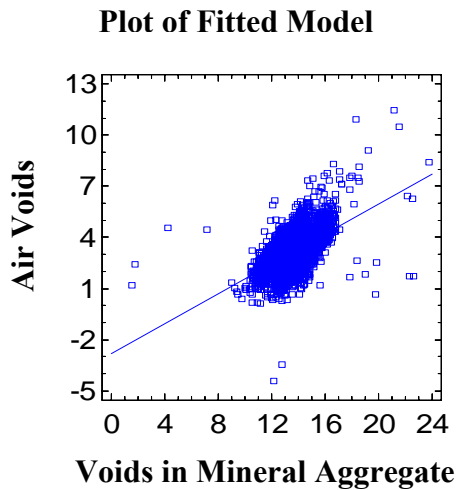
Parameter	Estimate	Error	Statistic	P Value
Constant	-2.84	0.17	-17.04	0.00
Voids filled with Mineral Aggregate	0.43	0.01	36.67	0.00

R-squared = 31.74 percent; R-squared (adjusted for d.f.) = 31.71 percent

Standard Error of Est. = 0.97; Mean absolute error = 0.73

The output shows the results of fitting a multiple linear regression model to describe the relationship between air voids and voids in mineral aggregate. The equation of the fitted model is:

Air Voids = -2.84 + 0.44 * VMA   (4.3)

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 31.74 % of the variability in Air Voids. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 31.71 %. The standard error of the estimate shows the standard deviation of the residuals to be 0.97.

In determining whether the model can be simplified, notice that the highest P-value on the independent variables is 0.00, belonging to voids in mineral aggregate. Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level. Consequently, it is ideal not to remove any variables from the model

Chart 4.26: Dependent Variable-Air Voids with Independent Variable- Density

Plot of Fitted Model
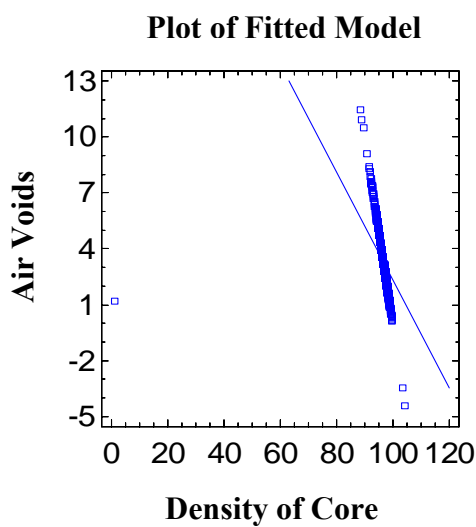
Parameter	Estimate	Error	Statistic	P Value
Constant	31.17	0.84	36.88	0.00
Density	- 0.29	0.00	-33.06	0.00

R-squared = 27.43 percent; R-squared (adjusted for d.f.) = 27.41 percent

Standard Error of Est. = 1.00; Mean absolute error = 0.65

The output shows the results of fitting a multiple linear regression model to describe the relationship between air voids and density. The equation of the fitted model is:

Air Voids = 31.17 - 0.29 *Density of Core   (4.4)

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 27.43 % of the variability in air voids. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 27.41 %. The standard error of the estimate shows the standard deviation of the residuals to be 1.00. In determining whether the model can be simplified, notice that the highest P-value on the independent variables is 0.00, belonging to density. Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level. Consequently, it is ideal not to remove any variables from the model

Chart 4.27: Component Residual Plot for Air Voids

Component Residual Plot for Air Voids
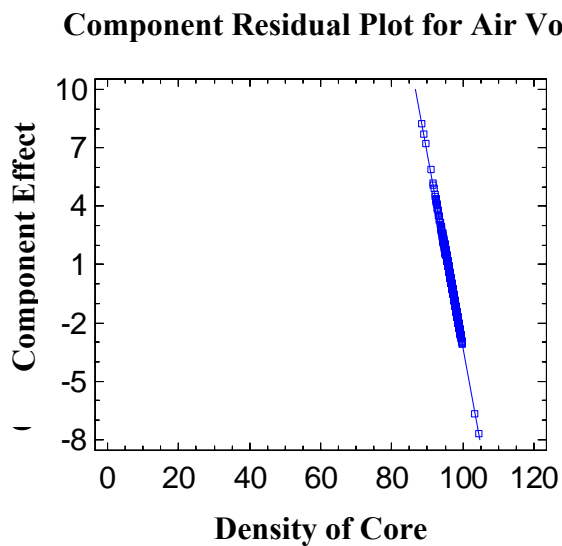
R-squared = 100.0 percent; R-squared (adjusted for d.f.) = 0.0 percent

Standard Error of Est. = 0.00; Mean absolute error = 0.00

The output shows the results of fitting a multiple linear regression model to describe the relationship between air voids and the four variables. The equation of the fitted model is:

Air Voids = 100.0 - 1.0*Density of Core - 8.71E-12*Measured Asphalt + 3.84E-14*VFA
+ 3.76E-12*VMA   (4.5)

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant

relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 100.0 % of the

variability in air voids. The adjusted R-squared statistic, which is more suitable for

comparing models with different numbers of independent variables, is 0.0 %.   The

standard error of the estimate shows the standard deviation of the residuals to be 1.00.

Since the P-value is less than 0.05, there is an indication of possible serial correlation.

Chart 4.28: Component Residual Plot for Density of Core

Component Residual Plot for Density of Core
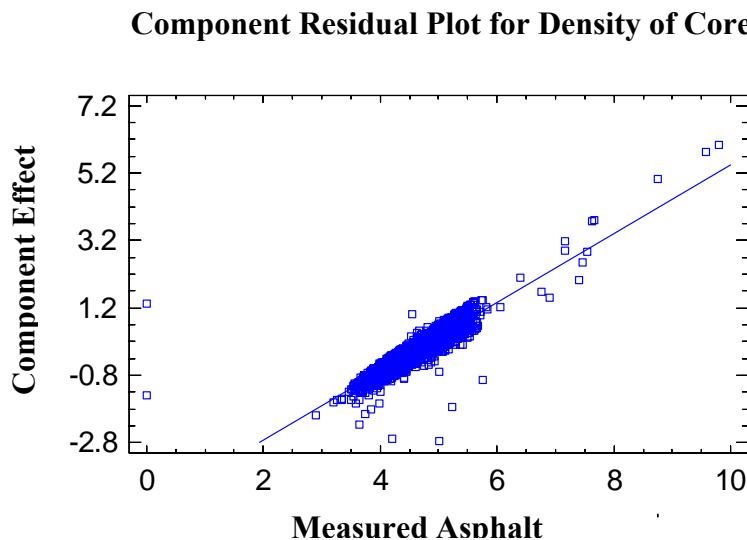
R-squared = 95.92 percent; R-squared (adjusted for d.f.) = 95.92 percent

Standard Error of Est. = 0.24; Mean absolute error = 0.14

The output shows the results of fitting a multiple linear regression model to describe the relationship between density of Core and 3 independent variables. The equation of the fitted model is

Density of Core = 95.29 + 1.02*Measured Asphalt + 0.07*VFA - 0.63*VMA   (4.6)

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level relationship. The R-Squared statistic indicates that the model as fitted explains 95.92 % of the variability in density. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 95.92 %. The standard error of the estimate shows the standard deviation of the residuals to be 0.24. Since the P-value is less than 0.05, there is an indication of possible serial correlation. In determining whether the model can be simplified, notice that the highest P-value on the independent variables is 0.00, belonging to measured asphalt. Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level. Consequently, it is ideal not to remove any variables from the model.

4.9 Pay Factor Analysis

For data related to each of the quality characteristics the average and standard deviation are computed. The quality index, Q_U, is found by subtracting the average of the measurements from the upper specification limit, and dividing the result by the standard deviation. In a similar way the lower quality index is computed by subtracting the lower specification limit from the average of the measurements, and

dividing the result by the standard deviation of the measurements. The upper and lower

specification limits for the computation is given by the state as given in the Table 4.4:

Parameter	UL and LL
No. 8 Sieve	Target Value -/+ 7.0%
No. 50 Sieve	Target Value -/+ 4.0%
No. 200 Sieve	Target Value -/+ 2.0%
Asphalt Binder Content	Target Value +/- 0.4%
VMA	Target Value -1.2% to +2.0%
Density	In place density >/= 92% (not more than 96%)
VFA	65.0 % to 75.0 %
AG = Aggregate Gradation; AC= Asphalt Content; AV = Air Voids; VMA = Voids in Mineral Aggregate; VFA = Voids filled with Asphalt Content	

Table 4.4: Upper and Lower Limit Determination

The next step will be to estimate the percentage of material that will fall within

the upper tolerance limit by using the table given in Appendix C. The table gives the

relationship between PWL, Q_U and Q_L for various sample sizes. The total percent within

limits, PWL $_{Total}$, is computed using the PWL_U and PWL_L and substituting in the

equation:

PWL $_{Total}$ = PWL_U + PWL_L − 100.00 (4.7)

The final step is to compute the pay factor for each of the quality characteristics.

Based on the table given below, the equation PF = 55 + 0.5 * PWL that has been

recommended by the AASHTO Quality Assurance Guide Specification has been used for

this report.

Table 4.5: Pay Factor Equations

State	Pay Equation	Test Property	Sample Size, n	RQL, PWL
New Jersey	PF =102-0.2 x PD PF = 10+1.0 x PWL[a]	Density	5	50
New Mexico	PF = 55+0.5 x PWL	AG, AC, AV, Density	3(minimum)	60
New York	PF = 21.7 + 0.833 x PWL (PWL$\geq$94) PF = 57.8 + 0.499 x PWL (PWL<94)	Density	4	5[b]
South Dakota	PF = 55+0.5 x PWL	AG, AC, AV, VMA, Density	5	60
Vermont	PF = 83 + 0.2 x PWL	AV	3(minimum)	50
Virginia	PF = 55+0.5 x PWL	AC, AV, VMA	4	40
Washington State	PF = (105 – 0.0182* ((100-PWL*100)^1.8163))/100	AC, AG, In-place Density	5	41
Delaware	PF = 55+0.5 x PWL	AG, AC	4	38
AG = Aggregate Gradation; AC= Asphalt Content; AV = Air Voids; VMA = Voids in Mineral Aggregate				
[a] Equation given as an example in the specification only; [b] Remove and replace for material PWL < 5				

Source: Equations from the NCHRP Report 447, Testing and Inspection Levels for Hot-Mix Asphaltic Concrete Overlays, (Russell,

Hanna, Nordheim and Schmitt, 2001).

The pay factor computations for all the quality characteristics have been shown below:

Table 4.6: Pay Factor Computations

Computed Parameters	Quality Characteristics						
	Density	**Air Voids**	**VMA**	**Voids filled with AC**	**AC**	**# 8 Sieve**	**# 200 Sieve**
Average	96.8	3.2	13.8	76.8	4.6	35.17	5.51
Standard Deviation	1.2	1.2	1.5	7.8	0.56	6.59	0.93
Upper Specification Limit, USL	96.0	5.5	15.0	75.0	5.0	42.35	7.35
Lower Specification Limit, LSL	92.0	2.5	12.0	65.0	4.2	28.35	3.35
Upper Quality Index, Q_U =(USL-Avg)/Stdev	-0.7	0.92	0.80	-0.23	0.5	1.09	1.97
Lower Quality Index, Q_L =(Avg-LSL)/Stdev	4.0	0.58	1.20	1.51	0.83	1.04	2.33
PWL_U corresponding to Q_U	26.67	80.67	76.67	42.33	66.67	86.67	100.0
PWL_L corresponding to Q_L	100.00	69.33	90.00	100.0	76.67	84.67	100.0
PWL_{total} $= PWL_U + PWL_L$ -100.0	26.67	50	66.67	42.33	43.34	71.34	100
Pay Factor, PF (%) = 55+0.5*(PWL_{total})	68.34	80	88.3	76.2	76.7	97.34	105.0

The PWL and independent pay factor are summarized in a tabular form given below:

Table 4.7: PWL and Pay Factors for Various Quality Characteristics

Quality Characteristics Parameter	Density	Air Voids	VMA	VFA	AC	Sieve 8	Sieve 200
PWL	26.67	50.0	66.67	42.33	43.34	71.34	100.0
Pay Factor	0.68	0.80	0.88	0.76	0.77	0.97	1.05

As described in this section, for each of the asphalt material property pay factor is computed using the equation PF = 55 + 0.5 * PWL, where PWL is the percent within limits. As can be seen above the calculation of PWL is a complicated process involving the determination of upper and lower quality indexes using the look-up tables for various quality characteristics. It can be observed from the pay factor equation that a pay factor of 100 percent corresponds to a 90 PWL and for the specification greater than 90 PWL the contractor will be paid more than 100 percent payment and 105 percent with a five percent bonus would be maximum pay factor that would occur for a PWL of 100. Also according to the equation the pay factor for zero percent of material falling within specification limits will be 55 percent. But for such a case when zero percent of material falls within the specification the state has clauses that deal with the low pay factor material.

4.10 Composite Pay Factor

Once the individual pay factors are computed for all the quality characteristics a composite pay factor (CPF) is computed. The CPF is computed by multiplying the respective weights of each of the quality characteristics by their respective individual pay factors. In terms of payment DelDOT uses the following:

Table 4.8: Payment Weightings

Quality Characteristic	Payment
Asphalt Content	30 % of 70%
Sieve No. 8	35% of 70%
Sieve No. 200	35% of 70%
Density	30%

Hence the CPF equation used by the DelDOT is:

CPF = {0.70 [0.35(PF of No. 8 sieve) + 0.35(PF of No. 200 sieve) + 0.30(PF of AC)] +

0.30 (PF of Density)}   (4.8)

And the computation yields:

CPF = 0.70[0.35(0.9734) + 0.35(1.05) + 0.30(0.767)] + 0.30(0.68) = 0.8608 %

The CPF can have a maximum of 105 percent, which is similar to the individual pay factors. The contractor can work on reducing the difference between the mean and target values. Working on reducing the variability of the test results can also help in increasing

the PWL and hence increase the PF. Based on "QA Specification Practices", by Mahoney and Backus, (1999), the minimum pay factor can range from 0.50 percent to 0.75 percent.

Table 4.9 compares the CPF equations that are used by various states. The values of CPF in the table below are computed by substituting the individual PF values in the various CPF equations used by different states. Table 4.10 summarizes the findings of the research and a comparative analysis of the findings with that of the Washington State Department of Transportation QC/QA research, FHWA research and FAA research.

Table 4.9: Composite Pay Factor Computations

Composite Pay Factor Equation	Composite Pay Factor using the Independent Pay Factor Values for DelDOT HMA Data	Composite Pay Factor	Remarks
0.20* Gradation + 0.30 * AC + 0. 50 * Density	0.20* (0.97+1.05)/2 + 0.30 * 0.77 + 0.50 * 0.68 = 0.773	0.77	Equation used by Colorado
0.40 * PF of Density + 0.30* PF of Asphalt + 0.30 * PF of Aggregate	0.40* 0.68 + 0.30 * 0.77 + 0.30 * (0.97+1.02)/2 = 0.806	0.81	Equation used by Idaho
0.20 * AC + 0.35 * Mat Density + 0.35 * AV + 0.10 * VMA	0.20 * 0.77 + 0.35 * 0.68 + 0.35 * 0.8 + 0.10 * 0.88 = 0.76	0.76	Equation used by Indiana
0.10 * AC + 0.25 * AV + 0.25 * VMA + 0.40 * Density	0.10 * 0.77 + 0.25 * 0.8 + 0.25 * 0.88 + 0.40 * 0.68 = 0.769	0.77	Equation used by Kentucky
0.60 * Density + 0.20 * Voids + 0.10 * VMA + 0.10 * AC	0.60 * 0.68 + 0.20 * 0.8 + 0.10 * 0.88 + 0.10 * 0.77 = 0.733	0.73	Equation used by Maine
0.25 * (Density + AC + VMA + Air Voids)	0.25 * (0.68 + 0.77 + 0.88 + 0.8) = 0.783	0.78	Equation used by Missouri
{ 3* (AC + AV + Density) + Gradation}/10	{ 3 * (0.77 + 0.8 + 0.68) + (0.97+ 1.05)/2} /10 = 0.776	0.78	Equation used by Oklahoma
0.20 * PF of AC + 0.35 * PF of AV + 0.10 * PF of VMA + 0.35* PF of Density	0.20 * 0.77 + 0.35 * 0.8 + 0.10 * 0.88 + 0.35 * 0.68 = 0.76	0.76	Equation used by South Carolina

Source: Pay Factor equations for various states from MPC Report No. 03-146, Evaluating the Impact of QC/QA Programs on Asphalt

Mixture Variability, by Khaled Ksaibati and Nathan Butts, 2003.

Table 4.10: Report Summary

Table 4.10: Report Summary (continuation)

Component	General Background	DELDOT Statistical Acceptance Plan	Evaluation and Comparison	
			WSDOT	FHWA and FAA
Sampling Type	Two types: Attribute and Variable	Uses variable sampling for those quality characteristics evaluated by statistical acceptance.	Uses variable sampling for	Typical of almost all acceptance plans and consistent with FHWA and FAA.
Quality Characteristics	Should be selected such that their quality accurately reflects overall project quality and they are independent of one another	Uses in-place density, asphalt content and gradation of aggregates.	Uses in-place density, asphalt content and aggregate gradation	Relative independent and similar to the FHWA. FAA uses more quality characteristics, some of which are highly correlated.
Specification Limits	Should be tight enough to detect manufacturing and construction variability, but loose enough to allow a reasonable amount of testing, sampling, and inherent material variability	a)In place density $\geq$ to 92% b)Asphalt content = JMF ±0.4 % c)Gradation: Passing the # 8 = ±7.0% Passing the # 200 = ±2.0%	Typical Class A/B specifications are: a)In-place density≥91 % b)Asphalt content=JMF ±0.5% c) Gradation: Passing the # 1/4 = ±6% Passing the # 10 = ±5% Passing the # 40 = ±4% Passing the #200 = ±2%	DELDOT specification bands are tight enough to detect manufacturing and construction variability, but loose enough to allow a reasonable amount of testing, sampling, and inherent material variability
Statistical Model	Several statistical models can be used	Estimates lot average and variation then uses quality indexes to compute PWL and Pay Factors	Estimates lot average and variation then uses the non-central t distribution to calculate lot quality (expressed as PWL)	Is most descriptive and makes the fewest assumptions of several common practices. FHWA and FAA use the same model

Component	General Background	DELDOT Statistical Acceptance Plan	Evaluation and Comparison	
			WSDOT	**FHWA and FAA**
Quality Level Goals	AQL and RQL relate the fraction of acceptable material within a lot to whether or not it will be accepted at full pay (AQL) or rejected at zero pay (RQL)	AQL = 95 PWL regardless of sample size C = 74 PWL varies with sample size (from 68 PWL up to 93 PWL) RQL = 38 PWL varies with sample size (from 33 PWL up to 65 PWL).	a)AQL = 95 PWL regardless of sample size b)C = 78 PWL varies with sample size(from 68 PWL up to 93 PWL) c)RQL = 41 PWL varies with sample size(from 33 PWL up to 65 PWL)	a)AQL is higher than average contractor quality b)RQL is low but adequate considering additional specification clauses c)FHWA AQL = 95 PWL d)FAA AQL = 90 PWL
Risk	All statistical acceptance plans involve risk to both the contractor and the contracting agency. This risk can be quantified	Primary α risk = 2.25% Secondary α risk = 0 % Primary β risk = 2.94% Secondary β risk = 50%	Primary α risk = 2.55% Secondary α risk = 0 % Primary β risk = 1.27 % Secondary β risk = 50%	a)Small α risk, which is typical and similar to FHWA b)Secondary β risk of 50% is typical c)Expected pay better describes the plan than risk
Pay Factors	Pay factors relate lot quality to actual pay. Expected pay is different from contractual pay and should be near 1.00 for AQL material	Maximum PF = 1.05 Minimum PF = 0.50 to 0.75 Expected Pay at AQL = 0.86	Uses a set of roughly parabolic equations Maximum PF= 1.05 Minimum PF= 0.75 Expected Pay at AQL = 1.03	a)Undocumented basis b)PF > 1.00 for AQL materials but this is largely correct by market forces c)Expected pay best describes the plan

Chapter 5

CONCLUDING REMARKS

This report attempted to develop a QC/QA procedure for hot mix asphalt construction in Delaware. The analysis is based on the field, laboratory and in-service data collected by DelDOT in the past five years.

5.1 Conclusions

The following conclusions can be drawn:

(a) The acceptance and payment for HMA used by the state can be based on the following quality characteristics

- Asphalt Content

- Gradation: No. 8 sieve; No. 200 sieve

- In-Place Density

(b) A composite pay factor was developed that is comparable to pay factors used by different states.

(c) It appears that there is a strong correlation between some of the quality characteristics used by the state.

(d) Based on the analysis it can be seen that

(1) The specification limits for the State of Delaware are as follows:

- In place density $\geq$ to 92%

- Asphalt content = JMF ± 0.4 %

- Gradation: Passing the No. 8 = ±7.0%; Passing the No. 200 = ±2.0%

(2) It can be noted from the analysis that the quality level goals used by the Delaware Department of Transportation are as follows:

- AQL = 95 PWL regardless of sample size

- The acceptance value C, varies with sample size and may vary from 68 PWL up to 93 PWL based on the sample size. C = 74 PWL for sample size 4.

- The rejectable quality level value varies with sample size from 33 PWL up to 65 PWL. RQL = 38 PWL for sample size 4.

(3) The α risks and β risks are computed for the Hot Mix Asphalt data. The computed risk values are as follows:

- Primary α risk = 2.28%; Secondary α risk = 0 %

- Primary β risk = 2.94%; Secondary β risk = 50%

(4) The Pay Factors for the Hot Mix Asphalt data has been computed and the results are as follows:

- Maximum PF = 1.05 for a PWL of 100 percent.

- Minimum PF can range from 0.50 to 0.75 percent.

- Expected Pay at AQL = 0.86

A comparative analysis between DelDOT, Washington State, FAA and FHWA shows a consistent pattern.

(5) This report illustrates the use and functioning of control charts for quality control of hot mix asphalt. The individual test results that have been plotted on the control charts show the job mix formula or target value, upper and lower control limits and the behavior of data points or observations in the process. The individual, X-bar and R control charts

for each of the quality characteristics provide evidence that all of the processes show variability.

Prompt and directed action at all levels can ensure better control and less economic waste by replacing variability with consistency. Hence, there is a need to maintain quality control charts in order to identify the reason behind variability as it can lead to hot mix asphalt being produced and used in construction to be out of the specified tolerance limits.

5.2 Future Research

There is a need to conduct a sensitivity analysis on the composite pay factor equation for a better understanding on how different weights of individual pay factors of the selected quality characteristics can affect the overall composite pay factor.

The pay factors developed should be field-tested and adjusted to reflect both the cultural and objective data within Delaware contractors.

Appendix A

FWHA of various US highway agencies adopting end – results specifications and QA/QC management schemes

State DOT	With Formal QC/QA System	Without Formal QC/QA	QC/QA in Development
Alabama		X	
Alaska		X	
Arizona	X		
Arkansas	X		
California		X	
Colorado	X		
Connecticut		X	
Delaware		X	
District of Columbia			X
Florida			X
Georgia	X		
Hawaii			X
Idaho		X	
Illinois	X		
Indiana	X		
Iowa			X
Kansas	X		

Kentucky	X		
Louisiana	X		
Maine		X	
Maryland	X		
Massachusetts		X	
Michigan	X		
Minnesota	X		
Mississippi		X	
Missouri		X	
Montana	X		
Nebraska			X
Nevada			X
New Hampshire		X	
New Jersey	X		
New Mexico			X
New York			X
North Carolina		X	
North Dakota		X	
Ohio		X	
Oklahoma			X
Oregon	X		
Pennsylvania	X		
Puerto Rico	X		

Rhode Island		X	
South Carolina			X
South Dakota			X
Tennessee	X		
Texas			X
Utah			X
Vermont		X	
Virginia		X	
Washington			X
West Virginia	X		
Wisconsin	X		
Wyoming	X		

APPENDIX B

Example Data Sheet for HMA Data provided by DelDOT

Density of Core	Air Voids	Voids in Mineral Aggregate	Voids filled with AC	Measured Asphalt
96.34	3.66	15.16	75.85	5.11
97.25	2.75	12.72	78.36	4.37
97.12	2.88	12.57	77.13	4.25
97.49	2.51	12.77	80.35	4.51
98.07	1.93	12.35	84.35	4.55
98.06	1.94	13.15	85.25	5.26
96.85	3.15	14.45	78.20	5.34
98.21	1.79	13.46	86.72	5.44
98.13	1.87	13.26	85.88	5.37
97.78	2.22	13.84	83.95	5.49
98.50	1.50	13.63	88.96	5.64
97.85	2.15	13.72	84.31	5.25
97.13	2.87	14.74	80.58	5.4
96.29	3.71	14.80	74.90	5.1
98.03	1.97	13.99	85.90	5.45
97.56	2.44	14.25	82.90	5.37
98.18	1.82	11.73	84.45	4.32
97.82	2.18	12.07	81.91	4.32
97.92	2.08	12.01	82.64	4.33
98.05	1.95	13.83	85.91	5.38
97.41	2.59	15.17	82.93	5.72
97.46	2.54	14.44	82.43	5.41
96.71	3.29	14.39	77.13	5.09
97.12	2.88	12.46	76.91	4.24
97.43	2.57	12.08	78.74	4.21
97.96	2.04	11.69	82.57	4.25
97.93	2.07	12.45	83.35	4.55
97.15	2.85	12.77	77.69	4.38

APPENDIX C

Quality Index Values for Estimating PWL

Upper Quality Index QU or Lower Quality Index QL														
PU or PL PWL for positive values of QU or QL	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=18	n=19 to n=25	n=26 to n=37	n=38 to n=69	n=70 to n=200	n=201 to ∞
100	1.16	1.50	1.79	2.03	2.23	2.39	2.53	2.65	2.83	3.03	3.20	3.38	3.54	3.70	3.83
99	-	1.47	1.67	1.80	1.89	1.95	2.00	2.04	2.09	2.14	2.18	2.22	2.26	2.29	2.31
98	1.15	1.44	1.60	1.70	1.76	1.81	1.84	1.86	1.91	1.93	1.96	1.99	2.01	2.03	2.05
97	-	1.41	1.54	1.62	1.67	1.70	1.72	1.74	1.77	1.79	1.81	1.83	1.85	1.86	1.87
96	1.14	1.38	1.49	1.55	1.59	1.61	1.63	1.65	1.67	1.68	1.70	1.71	1.73	1.74	1.75
95	-	1.35	1.44	1.49	1.52	1.54	1.55	1.56	1.58	1.59	1.61	1.62	1.63	1.63	1.64
94	1.13	1.32	1.39	1.43	1.46	1.47	1.48	1.49	1.50	1.51	1.52	1.53	1.54	1.55	1.55
93	-	1.29	1.35	1.38	1.40	1.41	1.42	1.43	1.44	1.44	1.45	1.46	1.46	1.47	1.47
92	1.12	1.26	1.31	1.33	1.35	1.36	1.36	1.37	1.37	1.38	1.39	1.39	1.40	1.40	1.40
91	1.11	1.23	1.27	1.29	1.30	1.30	1.31	1.31	1.32	1.32	1.33	1.33	1.33	1.34	1.34
90	1.10	1.20	1.23	1.24	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28	1.28	1.28
89	1.09	1.17	1.19	1.20	1.20	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.22	1.22	1.23
88	1.07	1.14	1.15	1.16	1.16	1.16	1.16	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.13	1.13
86	1.04	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
84	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
83	1.00	0.99	0.98	0.97	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.95	0.95	0.95
82	0.97	0.96	0.95	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
81	0.96	0.93	0.91	0.90	0.90	0.89	0.89	0.89	0.89	0.88	0.88	0.88	0.88	0.88	0.88
80	0.93	0.90	0.88	0.87	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84

Source: Specification Conformity Analysis, FHWA Technical Advisory T5080.12, June 23, 1989

Quality Index Values for Estimating PWL (Continuation)

PU or PL PWL for positive values of QU or QL	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=18	n=19 to n=25	n=26 to n=37	n=38 to n=69	n=70 to n=200	n=201 to ∞
79	0.91	0.87	0.85	0.84	0.83	0.82	0.82	0.82	0.82	0.81	0.81	0.81	0.81	0.81	0.81
78	0.89	0.84	0.82	0.80	0.80	0.79	0.79	0.79	0.78	0.78	0.78	0.78	0.77	0.77	0.77
77	0.87	0.81	0.78	0.77	0.76	0.76	0.76	0.75	0.75	0.75	0.75	0.74	0.74	0.74	0.74
76	0.84	0.78	0.75	0.74	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.71	0.71	0.71	0.71
75	0.82	0.75	0.72	0.71	0.70	0.70	0.69	0.69	0.69	0.68	0.68	0.68	0.68	0.68	0.67
74	0.79	0.72	0.69	0.68	0.67	0.66	0.66	0.66	0.66	0.65	0.65	0.65	0.65	0.64	0.64
73	0.76	0.69	0.66	0.65	0.64	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.62	0.61	0.61
72	0.74	0.66	0.63	0.62	0.61	0.60	0.60	0.60	0.59	0.59	0.59	0.59	0.59	0.58	0.58
71	0.71	0.63	0.60	0.59	0.58	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.55	0.55
70	0.68	0.60	0.57	0.56	0.55	0.55	0.54	0.54	0.54	0.53	0.53	0.53	0.53	0.53	0.52
69	0.65	0.57	0.54	0.53	0.52	0.52	0.51	0.51	0.51	0.50	0.50	0.50	0.50	0.50	0.50
68	0.62	0.54	0.51	0.50	0.49	0.49	0.48	0.48	0.48	0.48	0.47	0.47	0.47	0.47	0.47
67	0.59	0.51	0.47	0.47	0.46	0.46	0.46	0.45	0.45	0.45	0.45	0.44	0.44	0.44	0.44
66	0.56	0.48	0.45	0.44	0.44	0.43	0.43	0.43	0.42	0.42	0.42	0.42	0.41	0.41	0.41
65	0.52	0.45	0.43	0.41	0.41	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.39	0.39
64	0.49	0.42	0.40	0.39	0.38	0.38	0.37	0.37	0.37	0.36	0.36	0.36	0.36	0.36	0.36
63	0.46	0.39	0.37	0.36	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.33
62	0.43	0.36	0.34	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.31
61	0.39	0.33	0.31	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.28	0.28	0.28	0.28	0.28
60	0.36	0.30	0.28	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25
59	0.32	0.27	0.25	0.25	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.23	0.23

Source: Specification Conformity Analysis, FHWA Technical Advisory T5080.12, June 23, 1989

Quality Index Values for Estimating PWL (Continuation)

	Upper Quality Index QU or Lower Quality Index QL														
PU or PL PWL for positive values of QU or QL	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=18	n=19 to n=25	n=26 to n=37	n=38 to n=69	n=70 to n=200	n=201 to ∞
58	0.29	0.24	0.23	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20
57	0.25	0.21	0.20	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
56	0.22	0.18	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15
55	0.18	0.15	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
54	0.14	0.12	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
53	0.11	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
52	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
51	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source: Specification Conformity Analysis, FHWA Technical Advisory T5080.12, June 23, 1989

APPENDIX D

Percent Defective Estimation Table for Sample Size 4

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.67	49.33	49.00	48.67	48.33	48.00	47.67	47.33	47.00
0.1	46.67	46.33	46.00	45.67	45.33	45.00	44.67	44.33	44.00	43.67
0.2	43.33	43.00	42.67	42.33	42.00	41.67	41.33	41.00	40.67	40.33
0.3	40.00	39.67	39.33	39.00	38.67	38.33	38.00	37.67	37.33	37.00
0.4	36.67	36.33	36.00	35.67	35.33	35.00	34.67	34.33	34.00	33.67
0.5	33.33	33.00	32.67	32.33	32.00	31.67	31.33	31.00	30.67	30.33
0.6	30.00	29.67	29.33	29.00	28.67	28.33	28.00	27.67	27.33	27.00
0.7	26.67	26.33	26.00	25.67	25.33	25.00	24.67	24.33	24.00	23.67
0.8	23.33	23.00	22.67	22.33	22.00	21.67	21.33	21.00	20.67	20.33
0.9	20.00	19.67	19.33	19.00	18.67	18.33	18.00	17.67	17.33	17.00
1.0	16.67	16.33	16.00	15.67	15.33	15.00	14.67	14.33	14.00	13.67
1.1	13.33	13.00	12.67	12.33	12.00	11.67	11.33	11.00	10.67	10.33
1.2	10.00	9.67	9.33	9.00	8.67	8.33	8.00	7.67	7.33	7.00
1.3	6.67	6.33	6.00	5.67	5.33	5.00	4.67	4.33	4.00	3.67
1.4	3.33	3.00	2.67	2.33	2.00	1.67	1.33	1.00	0.67	0.33
1.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source:

Values in body of table are estimates of Percent Defective corresponding to specific values of Q = (Average-Lower Limit)/ (Standard Deviation) or Q = (Upper Limit-Average)/ (Standard Deviation). For negative Q values, the table must be subtracted from 100.

APPENDIX E

PWL Estimation Table for Sample Size 4

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	50.33	50.67	51.00	51.33	51.67	52.00	52.33	52.67	53.00
0.1	53.33	53.67	54.00	54.33	54.67	55.00	55.33	55.67	56.00	56.33
0.2	56.67	57.00	57.33	57.67	58.00	58.33	58.67	59.00	59.33	59.67
0.3	60.00	60.33	60.67	61.00	61.33	61.67	62.00	62.33	62.67	63.00
0.4	63.33	63.67	64.00	64.33	64.67	65.00	65.33	65.67	66.00	66.33
0.5	66.67	67.00	67.33	67.67	68.00	68.33	68.67	69.00	69.33	69.67
0.6	70.00	70.33	70.67	71.00	71.33	71.67	72.00	72.33	72.67	73.00
0.7	73.33	73.67	74.00	74.33	74.67	75.00	75.33	75.67	76.00	76.33
0.8	76.67	77.00	77.33	77.67	78.00	78.33	78.67	79.00	79.33	79.67
0.9	80.00	80.33	80.67	81.00	81.33	81.67	82.00	82.33	82.67	83.00
1.0	83.33	83.67	84.00	84.33	84.67	85.00	85.33	85.67	86.00	86.33
1.1	86.67	87.00	87.33	87.67	88.00	88.33	88.67	89.00	89.33	89.67
1.2	90.00	90.33	90.67	91.00	91.33	91.67	92.00	92.33	92.66	93.00
1.3	93.33	93.67	94.00	94.33	94.67	95.00	95.33	95.67	96.00	96.33
1.4	96.67	97.00	97.33	97.67	98.00	98.33	98.67	99.00	99.33	99.67
1.5	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source:

Values in body of table are estimates of PWL corresponding to specific values of QL = (Average-Lower Limit)/Standard Deviation or QU= (Upper Limit-Average)/Standard Deviation. For negative Q values, the table values must be subtracted from 100.

APPENDIX F

Calculation of α and β risks of the DELDOT statistical acceptance specification at a sample size of four (n = 4)

1) Select the sample size for which risk is to be calculated.

   Sample size = 4

2) Determine AQL, RQL, and the acceptance value (c, the PD that exactly receives a pay factor of 1.00). Determine the rejection value (r, the PD at which material is considered rejectable) if it is different than RQL. PWL and PD are expressed as a percent.

AQL = 95 PWL = 0.95 (DELDOT's specification uses an AQL of 95 PWL)

RQL = 38 PWL = 0.38 (From Section 1-06.2, Table 2 using the n-4 column at a pay factor of 0.75)

c = 74 PWL = 0.74 (From Section 1-06.2, Table 2 using the n-4 column at a pay factor of 1.00)

r = 38 PWL = 0.38 (r = RQL in DELDOT specification)

3) Determine the standard normal values associated with AQL, RQL, c, and r (Z_{AQL}, Z_{RQL}, Z_c, and Z_r). This can be done on Microsoft Excel using the NORMSINV function.

$Z_{AQL} = Z_{0.95} = 1.645$

$Z_{RQL} = Z_{0.38} = -0.355$

$Z_c = Z_{0.74} = 0.643$

$Z_r = Z_{0.38} = -0.355$ (same as Z_{RQL} since r = RQL in the DELDOT specification)

<u>Primary α risk</u>: $Z(\alpha_c) = \dfrac{Z_{AQL} - Z_c}{1/(n)^{1/2}} = \dfrac{1.645 - 0.643}{1/(4)^{1/2}} = 2.004$

<u>Secondary α risk</u>: $Z(\alpha_c) = \dfrac{Z_{AQL} - Z_r}{1/(n)^{1/2}} = \dfrac{1.645 - (-0.355)}{1/(4)^{1/2}} = 4.00$

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Primary β risk: $Z(\beta_c) = \dfrac{Z_c - Z_{RQL}}{1/(n)^{1/2}} = \dfrac{0.643 - (-0.355)}{1/(4)^{1/2}} = 1.996$

Secondary β risk: $Z(\beta_c) = \dfrac{Z_r - Z_{RQL}}{1/(n)^{1/2}} = \dfrac{-0.355 - (-0.355)}{1/(4)^{1/2}} = 0$

5. Determine the probabilities associated with the standard normal values calculated for α and β risks. This can be done on Microsoft Excel using the NORMSDIST function.

Primary α risk: $1 - P(Z > z(\alpha_c)) = 1 - 0.9775 = 0.0225$

Secondary α risk: $1 - P(Z > z(\alpha_r)) = 1 - 0.9999 = 0.00001$

Primary β risk: $1 - P(Z > z(\beta_c)) = 1 - 0.97703 = 0.02297$

Secondary β risk: $1 - P(Z > z(\beta_r)) = 1 - 0.5000 = 0.5000$

Primary α risk = 2.25 %

Secondary α risk = 0 %

Primary β risk = 2.297 %

Secondary β risk = 50%

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