

**COMPONENTS OF VARIABILITY IN BITUMINOUS
CONCRETE PAVEMENT CONSTRUCTION**

Volume 2: Field and Laboratory Evaluation

Final Report

by

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Prepared for

**OKLAHOMA DEPARTMENT OF TRANSPORTATION
in cooperation with the
FEDERAL HIGHWAY ADMINISTRATION**

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16. ABSTRACT <p>The objectives of phase-II of the project were: 1) to determine the components of the total variability in the measured quality attributes of acceptable bituminous concrete pavement construction in Oklahoma, 2) to assess the ODOT's specification tolerances for bituminous concrete pavement construction, 3) to evaluate the accuracy of the nuclear density gauge, and 4) to correlate the results of the nuclear test method for asphalt content determination with those obtained using the solvent extraction method. To meet these objectives, a research plan consisting of literature review, statistical experimental design, field sampling, and laboratory testing was adopted. Random sampling was conducted both at the production plant and the roadway independent of acceptance and job control sampling. Testing was performed in the materials laboratories of the different ODOT Divisions.</p> <p>ANOVA results indicated that sampling and testing variances represent a significant portion of the total observed variance in the measured quality attributes of bituminous concrete pavement construction. The computed percentages within QA/QC specification tolerances indicated that the present tolerances are practical and defensible. Correlations between density measurements obtained from the nuclear gauge and core samples ranged from 0.49 to 0.84. The use of calibrated relationships through regression analysis improved the estimation of core densities from nuclear measurements. Variability due to sampling and testing was larger in the core method than the nuclear gauge method. The correlation coefficient between individual asphalt content measurements using the extraction method and the nuclear gauge method was 0.63. No significant difference was found between the average asphalt content obtained from the extraction method and the average asphalt content obtained using the nuclear gauge method. Testing variability was less with the nuclear gauge method than the solvent extraction method.</p>			
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NOTICE

The opinions and conclusions expressed or implied in this report are those of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Oklahoma Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report.

EXECUTIVE SUMMARY

Variability in the quality attributes of highway construction products is due in part to materials and process variability, and in part to the variability in sampling and testing. Like any other statistical measure, the standard deviation -- an estimate of overall variability -- is computed from a set of numbers. These numbers are influenced by variation in the measurement process just as they are influenced by variations in the quality attribute being measured.

This report summarizes the findings of *phase-II* of ODOT research project 2179 -- *Evaluation of Components of Variability in Bituminous Concrete Pavement Construction*. The overall objective of this project was to develop a better understanding of the sources and relative magnitudes of variation in the measured properties of what is considered *acceptable* bituminous concrete pavement materials and construction in Oklahoma. The specific objectives of *phase-II* were as follows:

- Determine the components of the total variability (due to inherent variation in materials and processes, due to testing, and due to sampling) in the measured quality attributes of acceptable bituminous concrete pavements.
- Assess the ODOT's specification tolerances for bituminous concrete pavement construction and determine the 2-sigma and 3-sigma limits through a statistically-based field sampling and laboratory testing program.
- Evaluate the accuracy of the nuclear density gauge and calibrate the relationship between nuclear density measurements and core density measurements, and
- Correlate the results of the nuclear test method for asphalt content determination with those obtained using the solvent extraction method.

To meet the objectives of this project, a research plan consisting of literature review, statistical experimental design, field sampling, and laboratory testing was adopted. Random sampling was conducted both at the production plant and the roadway independent of acceptance and job control sampling. Testing was performed in the materials laboratories of the different ODOT Divisions.

The conclusions presented in this report are based on measurements of quality attributes obtained from one construction project. As called for in the sampling and testing program, data should be obtained from three additional projects to have a good representation of the variability in acceptable bituminous concrete pavement materials and construction in Oklahoma.

Nested analysis of variance results indicated that sampling and testing variances represent a significant portion of the total observed variance in the measured quality attributes of bituminous concrete pavement construction. It should be noted that combining the within-laboratory and between-laboratory testing variances increased the contribution of testing to the overall variance. Variation due to sampling and testing can be reduced by taking the average of several test results, improving sampling and testing methods, and proper training of personnel performing control and acceptance tests.

The computed percentages within JMF tolerances indicated lower percentages than expected for asphalt content, air voids, and in-place density. In addition, there was good as well as poor agreements between the computed percentages within tolerances for aggregate gradation using the cold feed samples and bituminous mixture samples. Values of the conformal indices were higher than expected, particularly for aggregate passing sieves 3/4", 1/2", and No. 4. This would normally be interpreted as a shift of the process average from the target value. Nevertheless, the large variances due to sampling and testing prevent a true evaluation of material and process variation.

In general, the computed percentages within QA/QC specification tolerances indicated that the present tolerances are practical and defensible. The percent within limits method outlined in the *AASHTO R9-90* is recommended for use by ODOT to establish the pay schedules.

Correlations between density measurements obtained from the nuclear gauge and core samples ranged from 0.49 to 0.84. A larger percentage of total variability due to sampling and testing was exhibited by the core method than the nuclear gauge method. Although the averages of density measurements using both methods were significantly different, the use of calibrated relationships through regression analysis improved the estimation of core densities from nuclear measurements.

The correlation coefficient between individual asphalt content measurements using the extraction method and the nuclear gauge method was 0.63. No significant difference was found between the average asphalt content obtained from the extraction method and the average asphalt content obtained using the nuclear gauge method. Variability due to testing was less with the nuclear gauge method than the solvent extraction method.

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CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT

Variability in highway construction materials and processes has always been a concern to the FHWA, state DOTs, and the construction industry. Nonconforming materials, poor workmanship, and lack of process control are common causes of the increase in variability beyond what is considered inherent or basic variability. Nevertheless, the overall observed variability is due in part to materials and process variability, and in part to the variability in sampling and testing. Like any other statistical measure, the standard deviation -- an estimate of overall variability -- is computed from a set of numbers. These numbers are influenced by variation in the measurement process just as they are influenced by variations in the quality attribute being measured.

The Oklahoma Department of Transportation (ODOT) recognizes that reliable data on the sources and magnitudes of variability that exist in the measured properties of *acceptable* bituminous concrete pavement construction are needed for the development of realistic and defensible specifications. This information is required to establish tolerances for the different quality attributes, develop control charts for process control, and devise a system of pay factors for acceptance purposes. The need for this research is emphasized by the recent decision made by ODOT management to adopt statistically-based quality assurance specifications in their highway construction program.

OBJECTIVES AND SCOPE

This report summarizes the findings of *Phase-II* of ODOT research project 2179 -- "*Evaluation of Components of Variability in Bituminous Concrete Pavement Construction*" which was initiated in Fall, 1990. The overall objective of this project was to develop a better understanding of the sources and relative magnitudes of variation in the measured properties of what is considered acceptable bituminous concrete pavement materials and construction in Oklahoma. The specific objectives of the research were as follows:

- Evaluate the ODOT's quality assurance specifications in comparison with those developed by other states in terms of the quality attributes used for acceptance, allowable deviations for 100% pay, reported values of the standard deviation of acceptable construction, and forms of the overall pay factor.
- Determine the components of the total variability (due to inherent variation in materials and processes, due to testing, and due to sampling) in the measured quality attributes of acceptable bituminous concrete pavements.
- Assess the ODOT's specification tolerances for bituminous concrete pavement construction and determine the 2-sigma and 3-sigma limits through a statistically-based field sampling and laboratory testing program.

- Evaluate the accuracy of the nuclear density gauge and calibrate the relationship between nuclear density measurements and core density measurements, and
- Correlate the results of the nuclear test method for asphalt content determination with those obtained using the solvent extraction method.

RESEARCH APPROACH

To meet the objectives of this project, a research plan consisting of two phases was adopted. In phase-I, the following tasks were addressed:

Task 1. Literature Review - Review and document national and local experiences with determining the statistical parameters of acceptable construction materials and products.

Task 2. Evaluation of Existing Data on Variability - Using available data from the ODOT's Materials Division, determine the overall variability in the quality attributes of selected bituminous concrete pavement projects which were constructed in the past.

Task 3. Survey of Quality Assurance Specifications of Other States - Evaluate the ODOT's quality assurance specifications in comparison with the specifications developed by other states DOTs.

Phase-II tasks included the following:

Task 4. Planning and Executing Field Sampling Program - The objective of this task was to conduct a field sampling program to obtain measurements of the quality attributes of acceptable bituminous concrete pavement construction. Sampling was based on the principles of random sampling and statistical experimental design.

The sampling program called for obtaining samples from four construction projects to be selected in coordination with ODOT. Difficulties with locating projects of appropriate size have limited the sampling program to only one construction project.

Sampling was conducted both at the production plant and the roadway independent of acceptance sampling and job control sampling. Fifty sample units were obtained from a lot of 4,000 tons of bituminous concrete production. The lot was divided into 25 equal sublots, and two sample-units were obtained from each subplot at random. Sample-units of the aggregate were obtained from the cold feed conveyor belt. In addition, sample-units of the fresh bituminous mix were taken from delivery trucks at the plant. Nuclear density gauge measurements were made at randomly selected points on the finished pavement; two density measurements per subplot. At the conclusion of the nuclear gauge test, two cores were drilled at each sampling location.

Task 5. Field and Laboratory Testing - The sample-units obtained in Task 4 were forwarded to the materials laboratories in the different ODOT Divisions for testing. All sample-units were tested in duplicate by dividing each sample-unit into two test specimens using approved splitting and quartering

methods. Preparation of test specimens and testing methods were in accordance with the ODOT standard test methods.

Task 6. Analysis of Test results - Analysis of variance (ANOVA) procedures were applied to the test results obtained in Task 5 to determine the components of the overall variation in the measured quality attributes. The percent of measurements within the JMF tolerances, QA/QC Specification tolerances, and the 2-sigma and 3-sigma limits were computed. Results of the nuclear gauge test methods for asphalt content and in-place density were analyzed.

The results of Phase-I (Tasks 1, 2, and 3) were assembled in a companion report entitled "*Components of Variability in Bituminous Concrete Pavement Construction - Volume 1: Summary of Current State Practices*", June 1992.

OVERVIEW OF THE NEXT CHAPTERS

The results of *Phase-II* tasks form the basis for the findings and conclusions presented in this report. Chapter 2 presents background material on components of variability, measurement errors, and nested analysis of variance. In Chapter 3, details of the research methodology are described. Chapter 4 summarizes the results of analysis of variance and specifications compliance. Evaluations of the nuclear density gauge and the nuclear asphalt content gauge are discussed in Chapters 5 and 6. Finally, Chapter 7 presents an appraisal of the research findings and the conclusions of this study. The material presented in these chapters is supplemented by Appendices A through F.

CHAPTER 2

BACKGROUND

This chapter, primarily algebraic, presents the basic terminology and statistical concepts which are referred to throughout this report. The chapter is organized as follows. First, the sources of variation in the measured quality attributes of bituminous concrete pavement construction are introduced. Second, the nature of measurement errors is discussed briefly. Third, the techniques of analysis of variance and experimental design are explained with emphasis on the balanced, three-factor nested design. Throughout, enough theory is presented to make the discussion meaningful, but not so much as to obscure the practical applications of the methods described. The general theory of analysis of variance is discussed in more detail by Box & Hunter [6], Gates & Shive [7], and Gaylor & Hartwell [8].

COMPONENTS OF VARIABILITY

Variability in the measured quality attributes of *acceptable* highway construction materials and variables has its origin in three well known components: *material variation*, *sampling variation*, and *testing variation*. A brief discussion of these three components is given in the following sections.

Material Variation - This component represents the inherent, random variation of construction material and processes which meet specifications. When samples are taken from several sublots and tests are performed on these samples, there will be differences in the averages of the test results for the different sublots no matter how carefully the samples are taken, handled and tested. The component of variance caused by this unavoidable lack of uniformity is denoted by σ^2_M .

Sampling Variation - Every sampling procedure has certain variability associated with it. Samples taken from the same subplot will differ due to segregation and other causes [18]. The component of variance caused by the method of obtaining samples is denoted by σ^2_S .

Testing Variation - Testing variation is a function of the accuracy and precision of the test method, i.e., the reliability of test results obtained from test specimens that are nearly alike. In any test determination, variation exists in the measured values due to a number of reasons including the within-operator variation, between operators variation, test equipment variation, test procedure variation, and between laboratories variation [5]. The symbol σ^2_T is used to denote this component of variance.

In drafting quality assurance specifications, the above components of variance should be taken into account in setting the allowable deviations from specified standards. The more serious deviations resulting from *assignable causes* in construction materials or processes can then be detected and penalized.

MEASUREMENT ERRORS

Measurements of the quality attributes of highway construction materials and products provide the quantitative information necessary for both process control and product acceptance. Obviously, any error in these measurements has a direct bearing on the ability to judge conformance.

In the discussion of measurements and their associated errors, the terms *accuracy* and *precision* are often used. *Accuracy* refers to the extent of the agreement between the average of numerous measurements on a given attribute and the true value of that attribute. The difference between the average and the true value is called the *error* or *bias*. *Precision* refers to the reproducibility of a measurement, i.e., the degree of nearness of individual measurements to each other when these measurements are obtained under prescribed like conditions [5].

A group of measurements can be precise without being accurate, i.e., the results may be clustered near each other but bear no relationship to the true value. Conversely, a group of measurements could be relatively accurate, in that their mean is very close to the true value, and yet the individual measurements be widely spread around this mean, indicating poor precision.

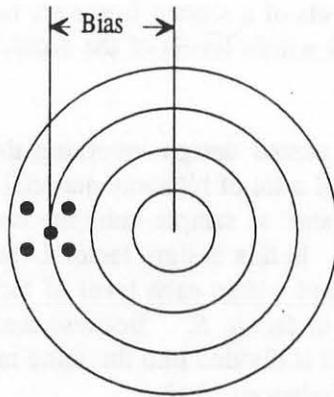
The relationship between accuracy and precision can be demonstrated by the example of three marksmen shooting at a target as depicted in Figure 1 [10]. The results of marksman A indicate good precision, but poor accuracy; the shots are spaced closely together near one spot some distance from the bull's eye. Marksman B has good accuracy because the shots are well distributed around the bull's eye, but his precision is poor because the shots are widely scattered on the target. Marksman C has good precision and good accuracy, i.e., he has shown good accuracy without bias because the shots are closely grouped inside the bull's eye.

With reference to Figure 1, the *reliability* of measurements can be explained by comparing marksman B and C. Both marksmen scored the same average, however marksman C has a better precision than marksman B. In terms of future performance, the probability that marksman C will perform without failure is greater than that for marksman B. Therefore, the shootings of marksman C are said to be more reliable than those of marksman B. In general, the reliability of measurements is a prediction of the accuracy and precision of measurements to be taken in the future based on the accuracy and precision of measurements which have already been taken.

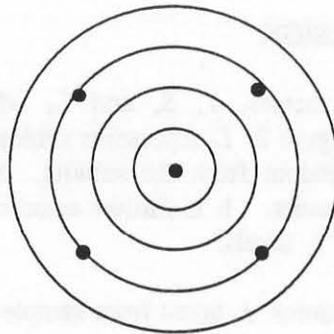
ANALYSIS OF VARIANCE

An important theorem of mathematical statistics states that the variance of the sum of any number of *independent factors* that contribute to the overall variability is equal to the sum of the component variances of the individual factors. This property of the variance is the basis of an analytical technique, known as analysis of variance (*ANOVA*), which can be utilized to compute the variance of the component factors and to test the statistical significance of each factor.

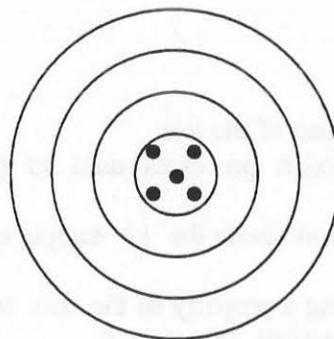
Application of the ANOVA requires a well designed statistical experiment that permits analyzing the different factors involved in the experiment. Designing a statistical experiment simply means



A
 Poor Accuracy
 Good Precision
 (Average off Center)



B
 Good Accuracy
 Poor Precision
 (Average on Center)



C
 Good Accuracy
 Good Precision
 (Average on Center)

Figure 1. Precision and Accuracy of Measurements

planning the experiment so that the information obtained will provide satisfactory answers to the questions that prompted the study without doing unnecessary work. A nested design is a form of statistical experiments which is useful in characterizing product variation and determining the contribution of each source of variability. In such a design, levels of a second factor are nested within levels of the main factor, and levels of a third factor are nested within levels of the second factor. Nesting can be continued to involve any desired number of factors.

Figure 2 illustrates a sampling plan for a nested design involving three sources of variation (factors) in measurements of some quality attribute of a lot of highway material or construction. The lot is divided into l different sublots of equal size, and s sample units are obtained from each subplot. Each sample unit is then split into t test portions. In this design, factor L (sublots) contains l levels. There are s levels of factor S (sample units) nested within each level of factor L , and t levels of factor T (test specimens) nested within each level of factor S . Because the same number of sample units is taken from each subplot, and each sample unit is divided into the same number of test specimens, the design is referred to as *completely nested* or *balanced* design.

THE BALANCED THREE-FACTOR NESTED DESIGN

Consider a statistical experiment with three factors, T , S , and L , where T is nested within S , and S is nested within L . With reference to Figure 2, L represents sublots of bituminous concrete pavement, S represents sample units taken at random from the sublots, and T represents tests performed on specimens prepared from the sample units. It is further assumed that factor L has l levels, factor S has s levels, and factor T has t levels.

Let y_{ijk} be a measurement made on test specimen k , taken from sample unit j in subplot i . The measurement y_{ijk} may be expressed as follows:

$$y_{ijk} = \mu + L_i + S_{ij} + T_{ijk} \quad (1)$$

where:

- μ = overall population mean, i.e., mean of the lot;
- L_i = effect of material and construction processes used to produce the i th subplot, ($i = 1, \dots, l$);
- S_{ij} = effect of sampling technique used to obtain the j th sample unit from the i th subplot; ($j = 1, \dots, s$);
- T_{ijk} = effect of test method on measuring a property of the k th test specimen taken from the j th sample unit in the i th subplot; ($k = 1, \dots, t$).

In addition, it is assumed that L_i , S_{ij} , and T_{ijk} are independent, normally distributed variables with zero means and variances of σ_M^2 , σ_S^2 , and σ_T^2 , respectively.

Sums of Squares

The model given by equation 1 involves three different sums of squares: *the between tests sum of squares* (SS_T), *the between sample units sum of squares* (SS_S), and *the between sublots sum of squares* (SS_L). These sum of squares are given by the following equations:

$$SS_T = \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t (y_{ijk} - y_{ij.})^2 \quad (2)$$

$$SS_S = \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t (y_{ij.} - y_{i..})^2 \quad (3)$$

$$SS_L = \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t (y_{i..} - y_{...})^2 \quad (4)$$

Since the sums of squares are additive, the total sum of squares (SS_{Total}) can be expressed as the sum of SS_L , SS_S and SS_T , that is,

$$\sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t (y_{ijk} - y_{...})^2 = SS_{Total} = SS_L + SS_S + SS_T \quad (5)$$

Table 1 describes the mathematical notation used in the above equations.

Mean Squares

To be useful in the analysis of variance, the sums of squares SS_L , SS_S and SS_T must be converted to mean squares (or variances). In this context, a mean square (MS) is defined by the equation:

$$MS = \frac{SS}{df} \quad (6)$$

where SS refers to the sum of squares and df represents the degrees of freedom associated with SS .

The degrees of freedom associated with a sum of squares is the number of measurements with independent information which enter into the calculation of the sum of squares. In general, the value of df can be computed using the following expression:

$$df = N - P \quad (7)$$

where N is the number of independent measurements and P is the number of population parameters estimated using the measurements. For instance, there are l measurements associated with SS_L , i.e., l different subplot means ($y_{i..}$'s). Since one population parameter ($y_{...}$) is required to compute SS_L , as shown by equation 4, the corresponding degrees of freedom are $(l - 1)$. Similarly, the degrees of freedom associated with SS_S and SS_T are $l(s - 1)$ and $ls(t - 1)$, respectively.

TABLE 1. MATHEMATICAL NOTATION

$$y_{ij} = \frac{1}{t} \sum_{k=1}^t y_{ijk}$$

$$y_{i..} = \frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t y_{ijk}$$

$$y_{...} = \frac{1}{lst} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t y_{ijk}$$

where:

y_{ij} = mean value of an attribute of the test specimens in the j th sample unit which is taken at random from subplot i ;

$y_{i..}$ = mean value of an attribute of the sample units in the i th subplot;

$y_{...}$ = mean of the subplot means (or grand mean of an attribute of a lot);

$y_{ijk} - y_{ij}$ = the deviation of the measurement y_{ijk} from the j th sample unit mean;

$y_{ij} - y_{i..}$ = the deviation of the j th sample unit mean from the i th subplot mean;

$y_{i..} - y_{...}$ = the deviation of the i th subplot mean from the grand mean.

Expected Mean Squares

Estimation of the three components of variance due to materials σ_M^2 , due to sampling σ_S^2 , and due to testing σ_T^2 requires the development of the expected values of the mean squares: $E[MS_T]$, $E[MS_S]$ and $E[MS_L]$. For reference, Table 2 lists important axioms of mathematical expectations which are used in the derivation of the expected mean squares. The following sections summarize these derivations.

TABLE 2. AXIOMS OF MATHEMATICAL EXPECTATIONS

If X_i is an independent, normally distributed random variable with zero mean and variance of σ_i^2 , and a_i is a constant, then:

$$E(a_i) = a_i$$

$$E(X_i) = 0$$

$$E(X_1 X_2) = E(X_1)E(X_2) = 0$$

$$V(a_i) = 0$$

$$V(X_i) = E(X_i^2) - [E(X_i)]^2 = E(X_i^2) = \sigma_i^2$$

$$V\left(\sum a_i X_i\right) = \sum a_i^2 V(X_i) = \sum a_i^2 \sigma_i^2$$

$$\text{Cov}(X_1, X_2) = E(XY) - E(X_1)E(X_2) = 0$$

Between-Tests Expected Mean Square

$$E[MS_T] = E\left[\frac{SS_T}{df_T}\right] = \frac{1}{ls(t-1)} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t E[y_{ijk} - y_{ij.}]^2$$

where,

$$\begin{aligned} y_{ijk} - y_{ij.} &= (\mu + L_i + S_{ij} + T_{ijk}) - \frac{1}{t} \left(\sum_{k=1}^t \mu + \sum_{k=1}^t L_i + \sum_{k=1}^t S_{ij} + \sum_{k=1}^t T_{ijk} \right) \\ &= (\mu + L_i + S_{ij} + T_{ijk}) - \frac{1}{t} \left(t\mu + tL_i + tS_{ij} + \sum_{k=1}^t T_{ijk} \right) \\ &= T_{ijk} - \frac{1}{t} \sum_{k=1}^t T_{ijk} \end{aligned}$$

Since T_{ijk} 's are assumed to be independent random variables with zero mean ($E(T_{ijk}) = 0$), their covariance is zero. Therefore,

$$\begin{aligned} E[y_{ijk} - y_{ij.}]^2 &= E\left[T_{ijk} - \frac{1}{t} \sum_{k=1}^t T_{ijk}\right]^2 = E[T_{ijk}]^2 - E\left[\frac{1}{t} \sum_{k=1}^t T_{ijk}\right]^2 \\ &= \sigma_T^2 - \frac{1}{t^2} E[T_{ij1} + \dots + T_{ijt}]^2 = \sigma_T^2 - \frac{1}{t^2} [E[T_{ij1}]^2 + \dots + E[T_{ijt}]^2] \\ &= \sigma_T^2 - \frac{1}{t^2} (t \sigma_T^2) = \sigma_T^2 - \frac{\sigma_T^2}{t} = \frac{t-1}{t} \sigma_T^2 \end{aligned}$$

and the value of $E[MS_T]$ would be given by:

$$E[MS_T] = \frac{1}{ls(t-1)} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t \left(\frac{t-1}{t} \sigma_T^2\right) = \left(\frac{lst}{ls(t-1)}\right) \left(\frac{t-1}{t}\right) \sigma_T^2 = \sigma_T^2$$

Between-Sample-units Expected Mean Square

$$E[MS_S] = E\left[\frac{SS_S}{df_S}\right] = \frac{1}{l(s-1)} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t E[y_{ij.} - y_{i..}]^2$$

where,

$$\begin{aligned} y_{ij.} - y_{i..} &= \frac{1}{t} \left(\sum_{k=1}^t \mu + \sum_{k=1}^t L_i + \sum_{k=1}^t S_{ij} + \sum_{k=1}^t T_{ijk} \right) - \frac{1}{st} \left(\sum_{j=1}^s \sum_{k=1}^t \mu + \sum_{j=1}^s \sum_{k=1}^t L_i + \sum_{j=1}^s \sum_{k=1}^t S_{ij} + \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \\ &= \frac{1}{t} \left(t\mu + tL_i + tS_{ij} + \sum_{k=1}^t T_{ijk} \right) - \frac{1}{st} \left(st\mu + stL_i + t \sum_{j=1}^s S_{ij} + \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \\ &= \left(S_{ij} - \frac{1}{s} \sum_{j=1}^s S_{ij} \right) + \left(\frac{1}{t} \sum_{k=1}^t T_{ijk} - \frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \end{aligned}$$

therefore,

$$\begin{aligned} E[y_{ij.} - y_{i..}]^2 &= E\left[\left(S_{ij} - \frac{1}{s} \sum_{j=1}^s S_{ij} \right) + \left(\frac{1}{t} \sum_{k=1}^t T_{ijk} - \frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \right]^2 \\ &= E[S_{ij}]^2 - E\left[\frac{1}{s} \sum_{j=1}^s S_{ij} \right]^2 + E\left[\frac{1}{t} \sum_{k=1}^t T_{ijk} \right]^2 - E\left[\frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right]^2 \\ &= \sigma_S^2 - \frac{\sigma_S^2}{s} + \frac{\sigma_T^2}{t} - \frac{\sigma_T^2}{st} = \left(\frac{s-1}{s}\right) \sigma_S^2 + \left(\frac{s-1}{st}\right) \sigma_T^2 \end{aligned}$$

and the value of $E[MS_s]$ would be given by:

$$\begin{aligned} E[MS_s] &= \frac{1}{l(s-1)} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t \left(\left(\frac{s-1}{s} \right) \sigma_s^2 + \left(\frac{s-1}{st} \right) \sigma_T^2 \right) \\ &= \left(\frac{lst}{l(s-1)} \right) \left(\frac{s-1}{s} \right) \sigma_s^2 + \left(\frac{lst}{l(s-1)} \right) \left(\frac{s-1}{st} \right) \sigma_T^2 \\ &= t \sigma_s^2 + \sigma_T^2 \end{aligned}$$

Between-Sublots Expected Mean Square

$$E[MS_L] = E \left[\frac{SS_L}{df_L} \right] = \frac{1}{(l-1)} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t E[y_{i..} - y_{...}]^2$$

where,

$$\begin{aligned} y_{i..} - y_{...} &= \frac{1}{st} \left(\sum_{j=1}^s \sum_{k=1}^t \mu + \sum_{j=1}^s \sum_{k=1}^t L_i + \sum_{j=1}^s \sum_{k=1}^t S_{ij} + \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \\ &\quad - \frac{1}{lst} \left(\sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t \mu + \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t L_i + \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t S_{ij} + \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \\ &= \frac{1}{st} \left(st\mu + stL_i + t \sum_{j=1}^s S_{ij} + \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) - \frac{1}{lst} \left(lst\mu + st \sum_{i=1}^l L_i + t \sum_{i=1}^l \sum_{j=1}^s S_{ij} + \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \\ &= \left(L_i - \frac{1}{l} \sum_{i=1}^l L_i \right) + \left(\frac{1}{s} \sum_{j=1}^s S_{ij} - \frac{1}{ls} \sum_{i=1}^l \sum_{j=1}^s S_{ij} \right) + \left(\frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t T_{ijk} - \frac{1}{lst} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \end{aligned}$$

therefore,

$$\begin{aligned} E[y_{i..} - y_{...}]^2 &= E \left[\left(L_i - \frac{1}{l} \sum_{i=1}^l L_i \right) + \left(\frac{1}{s} \sum_{j=1}^s S_{ij} - \frac{1}{ls} \sum_{i=1}^l \sum_{j=1}^s S_{ij} \right) + \left(\frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t T_{ijk} - \frac{1}{lst} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right) \right]^2 \\ &= E \left[L_i^2 \right] - E \left[\frac{1}{l} \sum_{i=1}^l L_i \right]^2 + E \left[\frac{1}{s} \sum_{j=1}^s S_{ij} \right]^2 - E \left[\frac{1}{ls} \sum_{i=1}^l \sum_{j=1}^s S_{ij} \right]^2 + E \left[\frac{1}{st} \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right]^2 \\ &\quad - E \left[\frac{1}{lst} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t T_{ijk} \right]^2 \\ &= \sigma_M^2 - \frac{\sigma_M^2}{l} + \frac{\sigma_s^2}{s} - \frac{\sigma_s^2}{ls} + \frac{\sigma_T^2}{st} - \frac{\sigma_T^2}{lst} = \frac{l-1}{l} \sigma_M^2 + \frac{l-1}{ls} \sigma_s^2 + \frac{l-1}{lst} \sigma_T^2 \end{aligned}$$

and the value of $E[MS_L]$ would be given by:

$$\begin{aligned} E[MS_L] &= \frac{1}{(l-1)} \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t \left[\frac{l-1}{l} \sigma_M^2 + \frac{l-1}{ls} \sigma_s^2 + \frac{l-1}{lst} \sigma_T^2 \right] \\ &= \left(\frac{lst}{l-1} \right) \left(\frac{l-1}{l} \right) \sigma_M^2 + \left(\frac{lst}{l-1} \right) \left(\frac{l-1}{ls} \right) \sigma_s^2 + \left(\frac{lst}{l-1} \right) \left(\frac{l-1}{lst} \right) \sigma_T^2 \\ &= st \sigma_M^2 + t \sigma_s^2 + \sigma_T^2 \end{aligned}$$

For convenience, the derived expressions for *expected mean squares* are summarized as follows:

$$E(MS_T) = \sigma_T^2 \quad (8)$$

$$E(MS_S) = t \sigma_s^2 + \sigma_T^2 \quad (9)$$

$$E(MS_L) = st \sigma_M^2 + t \sigma_s^2 + \sigma_T^2 \quad (10)$$

In theoretical statistics, $\hat{\theta}$ is an *unbiased* estimator of θ if $E(\hat{\theta}) = \theta$. Equations 8, 9, and 10 indicate that MS_T , MS_S , and MS_L are unbiased estimators of σ_T^2 , $(t \sigma_s^2 + \sigma_T^2)$, and $(st \sigma_M^2 + t \sigma_s^2 + \sigma_T^2)$, respectively. Therefore, estimates of σ_T^2 , σ_s^2 , and σ_M^2 can be derived by equating the *computed mean squares* to their corresponding expectations, that is,

$$MS_T = \sigma_T^2 \quad (11)$$

$$MS_S = t \sigma_s^2 + \sigma_T^2 \quad (12)$$

$$MS_L = st \sigma_M^2 + t \sigma_s^2 + \sigma_T^2 \quad (13)$$

The simultaneous solution of equations 11, 12, and 13 yields the following expressions of the components of variance:

$$\hat{\sigma}_T^2 = MS_T \quad (14)$$

$$\hat{\sigma}_s^2 = \frac{MS_S - MS_T}{t} \quad (15)$$

$$\hat{\sigma}_M^2 = \frac{MS_L - MS_S}{st} \quad (16)$$

Since the above estimates are obtained by subtraction, it is possible that their values can be negative.

Using the additive property of variances shown in Table 2, it can be shown that the total variance of the measurements is the sum of the component variances, that is,

$$\sigma_{Total}^2 = V(y_{ijk}) = V(\mu) + V(L_i) + V(S_{ij}) + V(T_{ijk}) = 0 + \sigma_M^2 + \sigma_s^2 + \sigma_T^2$$

and an estimate of the total variance is:

$$\hat{\sigma}_{Total}^2 = \hat{\sigma}_M^2 + \hat{\sigma}_S^2 + \hat{\sigma}_T^2 \quad (17)$$

For reference, the foregoing analysis of variance is summarized in Table 3.

TABLE 3. ANALYSIS OF VARIANCE TABLE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Expected Mean Square
Between Sublots	SS_L	$l - 1$	MS_L	$\sigma_T^2 + t\sigma_S^2 + st\sigma_M^2$
Between Sample units	SS_S	$l(s - 1)$	MS_S	$\sigma_T^2 + t\sigma_S^2$
Between Tests	SS_T	$ls(t - 1)$	MS_T	σ_T^2
Total	SS_{Total}	$lst - 1$		

Hypothesis Testing

Test for Sublot to Sublot Variation

$$\begin{aligned} \text{To test the hypothesis: } H_o: \sigma_M^2 &= 0 \\ H_1: \sigma_M^2 &> 0 \end{aligned}$$

the appropriate test statistics is given by:

$$F_M = \frac{MS_L}{MS_S} = \frac{\sigma_T^2 + t\sigma_S^2 + s t\sigma_M^2}{\sigma_T^2 + t\sigma_S^2} \quad (18)$$

When H_o is true (i.e. $\sigma_M^2 = 0$), the above test statistic is distributed as an *F-distribution* with $(l - 1)$ degrees of freedom for the numerator, and $l(s - 1)$ degrees of freedom for the denominator. The *computed- F_M* given by equation 18 is compared with a *tabulated- F* value for a given level of significance α . The decision rule for the above hypothesis is as follows:

$$\begin{aligned} \text{If } F_M > F_{Tabulated} & \dots \text{ Reject } H_o \\ \text{If } F_M \leq F_{Tabulated} & \dots \text{ Accept } H_o \end{aligned}$$

Rejecting H_o indicates that "sublot to sublot" variation exists, i.e., the material used to construct

the lot is not uniform. On the other hand, accepting H_o means that there is no variation between sublots, i.e., the material is uniform across the lot.

Test for Sample-Unit to Sample-Unit Variation

To test the hypothesis: $H_o: \sigma_s^2 = 0$
 $H_1: \sigma_s^2 > 0$

the appropriate test statistics is given by:

$$F_s = \frac{MS_s}{MS_T} = \frac{\sigma_T^2 + t\sigma_s^2}{\sigma_T^2} \tag{19}$$

When H_o is true (i.e., $\sigma_s^2 = 0$), the distribution of the above test statistics is the *F-distribution* with $l(s - 1)$ degrees of freedom for the numerator and $ls(t - 1)$ degrees of freedom for the denominator. For a given level of significance α , the decision rule for the above hypothesis is as follows:

If $F_s > F_{Tabulated}$ Reject H_o
 If $F_s \leq F_{Tabulated}$ Accept H_o

Rejecting H_o indicates that "sample-unit to sample-unit" variation exists, i.e., the contribution of sampling to the overall variation is significant. On the other hand, accepting H_o means that there is no variation between sample units, i.e., the contribution of sampling is not significant.

F-Ratios That are Less Than Unity

With reference to equations 18 and 19, it is possible that the computed values of F_M and F_s be less than 1.0, i.e., σ_M^2 and σ_s^2 are negative! Ostle [15], suggested two possible solutions to this problem. The first solution is to assume that σ_M^2 (or σ_s^2) equals zero. The second solution is to calculate the inverse of F_M (or F_s), denoted as F'_M (or F'_s), and test its significance. Note that the degrees of freedom have to be interchanged. If F'_M (or F'_s) turns out to be significant, one should consider rejecting the *postulated statistical model*.

Computational Formulas

Computations of the sums of squares can be made less tedious by utilizing the following expression:

$$\sum (X_i - \bar{X})^2 = \sum X_i^2 - \frac{1}{n} \left(\sum X_i \right)^2 \quad (20)$$

Application of the above equation to the sums of squares defined earlier yields the following formulas:

$$SS_T = \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t y_{ijk}^2 - \frac{1}{t} \sum_{i=1}^l \sum_{j=1}^s \left(\sum_{k=1}^t y_{ijk} \right)^2 \quad (21)$$

$$SS_S = \frac{1}{t} \sum_{i=1}^l \sum_{j=1}^s \left(\sum_{k=1}^t y_{ijk} \right)^2 - \frac{1}{st} \sum_{i=1}^l \left(\sum_{j=1}^s \sum_{k=1}^t y_{ijk} \right)^2 \quad (22)$$

$$SS_L = \frac{1}{st} \sum_{i=1}^l \left(\sum_{j=1}^s \sum_{k=1}^t y_{ijk} \right)^2 - \frac{1}{lst} \left(\sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t y_{ijk} \right)^2 \quad (23)$$

$$SS_{Total} = \sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t y_{ijk}^2 - \frac{1}{lst} \left(\sum_{i=1}^l \sum_{j=1}^s \sum_{k=1}^t y_{ijk} \right)^2 \quad (24)$$

CHAPTER 3

RESEARCH METHODOLOGY

This chapter summarizes the methods and procedures which were used to obtain unbiased data on the variability of acceptable bituminous concrete pavement materials and construction in Oklahoma. The field sampling program required by task 4 and the field and laboratory test methods required by task 5 are briefly described.

FIELD PROJECT DESCRIPTION

Project MAF-398(82) was selected by ODOT for conducting the statistically designed experiment. This project involved the construction of new four-lane alignment of highway US-412, Delaware County, Oklahoma. Estimated average daily traffic was greater than 5,000. The paving material was an asphalt concrete type-F produced by Cummins Construction Company using a fully automated, drum mix plant. Table 4 summarizes the types and sources of materials. The job mix formula for this project is shown in Table 5.

TABLE 4. TYPES AND SOURCES OF MATERIALS, US-412 PROJECT

Material	Source	% Used
Aggregate:		
1) #57 Arkhola	Arkhola Sand & Gravel, Zeb Quarry	50
2) 3/4" Arkhola Chips	Arkhola Sand & Gravel, Zeb Quarry	12
3) Mine Run Chat	Pioneer Rock & Chat, Commerce, Oklahoma	23
4) Fine Sand	Sooner Sand, Sallisaw, Oklahoma	10
5) Screenings	Sooner Rock, Jay, Oklahoma	5
Asphalt Cement (AC-20)	Sinclair Oil Company, Tulsa, Oklahoma	
Anti-Strip Agent (Perma-Tac+)	ScamRoad, Inc., Waco, Texas	

FIELD SAMPLING

Sampling was conducted at the production plant as well as the roadway independent of acceptance sampling and job control sampling. Stratified random sampling plans were designed to obtain the required sample-units according to *ASTM D3665-82* [2]. The @RAND function of *LOTUS 1-2-3@* was used to generate the sampling plans in the field. For the purpose of this research project, the production of 4,000 tons of bituminous concrete was considered a lot. The lot was divided into 25 equal sublots of equal size, and two sample-units were obtained from each subplot at random.

TABLE 5. JOB MIX FORMULA, US-412 PROJECT

Percent Passing	Source					Combined Aggregate	JMF	JMF Tolerances
	1	2	3	4	5			
1 1/2"	100					100	100	0
1"	97					98	98	± 7
3/4"	73	100				87	87	± 7
1/2"	39	80	100			67	70	± 7
No. 4	4	5	74		89	34	34	± 7
No. 10	2	4	47	100	63	25	25	± 4
No. 40	2	3	23	80	31	16	16	± 4
No. 80	1	2	15	23	21	8	8	± 4
No. 200	1	2	10	1.9	15	4	4	± 2
% Asphalt Cement (AC-20)							4.1	± 0.4
Mix Temperature, °F ⁽¹⁾							305	± 20
Anti-Strip Additive ⁽²⁾							0.5%	

Tests on Aggregates			Tests on Asphalt Cement		
	Found	Required		Found	Required
Sand Equivalent	68	45 Min.	Specific Gravity @ 25°	1.0241	
L.A. Abrasion, (% Wear)	27.7	40 Max.			
Durability (DC)	73	40 Min.			
Fractured Faces	100	75 w/2			
BISG	2.648				
Hveem Weight	1210				

Tests on Compressed Mixtures								
Percent Asphalt	Spec. Grav. Specimen	Max. Theor. Spec. Grav.	Dens. % of Max. Theor.	Dens. % Req'd. of Max. Theor.	V.M.A. %	V.M.A. (Min. %)	Hveem Stab.	Hveem Stab. (Min. %)
3.5	2.342	2.508	93.4		14.6		46	
4.0	2.357	2.490	94.6	94-96	14.6	13.0 +	44	40
4.5	2.379	2.472	96.2		14.2		44	

Recommended 4.1% Asphalt Cement (AC-20)
 Compacted Wt. 109.4 lbs/yd²/1" thickness
 Max. Theoretical Specific Gravity @ 4.1% Asphalt Cement is 2.486 (155.1 pc f)

- 1 At discharge from mixer
- 2 By weight of Asphalt Cement

Sampling at the Plant

At the plant, samples were obtained from two different locations as depicted in Figure 3. The first sampling point yielded samples from the aggregate stream prior to the drum mixer according to *AASHTO T2-84* [1]. A sampling platform was installed to facilitate intercepting the entire cross section of the material from the belt discharge. Two sample-units, each having a mass of at least 90 lb (40 kg), were obtained from each subplot at random. The sample-units were identified by labels, placed in cloth sacks, and stored.

Sample-units of the freshly mixed bituminous concrete were obtained from the hauling trucks containing the preselected random tonnage according to *AASHTO T168-90* [1]. Two sample-units, each having a minimum mass of 90 lb (40 kg), were selected from each subplot. The sample-units were identified by labels, placed in sacks, and stored.

Sampling at the Roadway

Sampling of the compacted mixture was conducted at random using a system of coordinates designed for this purpose. Two sampling locations per subplot were identified by spray paint markings on the pavement. At each sampling location, duplicate density measurements were made using a thin-lift nuclear gauge according to *ASTM D2950-82* [4]. Three types of gauges were used: Troxler Model 4640, Toxler Model 3440, and Seaman Model C-200. Each gauge was calibrated for the bituminous mix used in this project. At the conclusion of the nuclear gauge test, two cores were drilled at each sampling location according to *AASHTO T168-82* [1]. The cores were identified by labels and stored in boxes.

Figures 4 through 11 show photographs of the production plant, the aggregate sampling platform, and other photographs taken during the field sampling.

LABORATORY TESTING

Test determinations were performed in the ODOT materials laboratories around the state in coordination with the ODOT Research Division and Materials Division. All sample-units obtained from the plant were tested in duplicate. Each sampling-unit was split into two test specimens of approximately equal size using approved splitting and quartering methods according to *AASHTO T248-89* [1].

In all cases, standard testing procedures, used in routine testing work, were followed. These procedures were in accordance with the ASTM and AASHTO standard test methods, except as noted in the ODOT Standard Specifications for Highway Construction [14]. Samples taken from the aggregate stream at the belt discharge were tested for gradation according to *AASHTO T27-88 and T11-90* [1]. The test determinations performed on the bituminous mixture were: 1) asphalt content, nuclear method (*OHD L-26*) [3]; 2) asphalt content, extraction method (*OHD L-26*); 3) gradation of extracted aggregate (*AASHTO T30-87*) [1]; 4) density of lab-molded specimens (*OHD L-8 and L-14*); and 5) Hveem stability (*OHD L-16*). Cores taken from the finished pavement were tested for density according to *OHD L-14*. Results of all test determinations are presented in Appendices A and E.

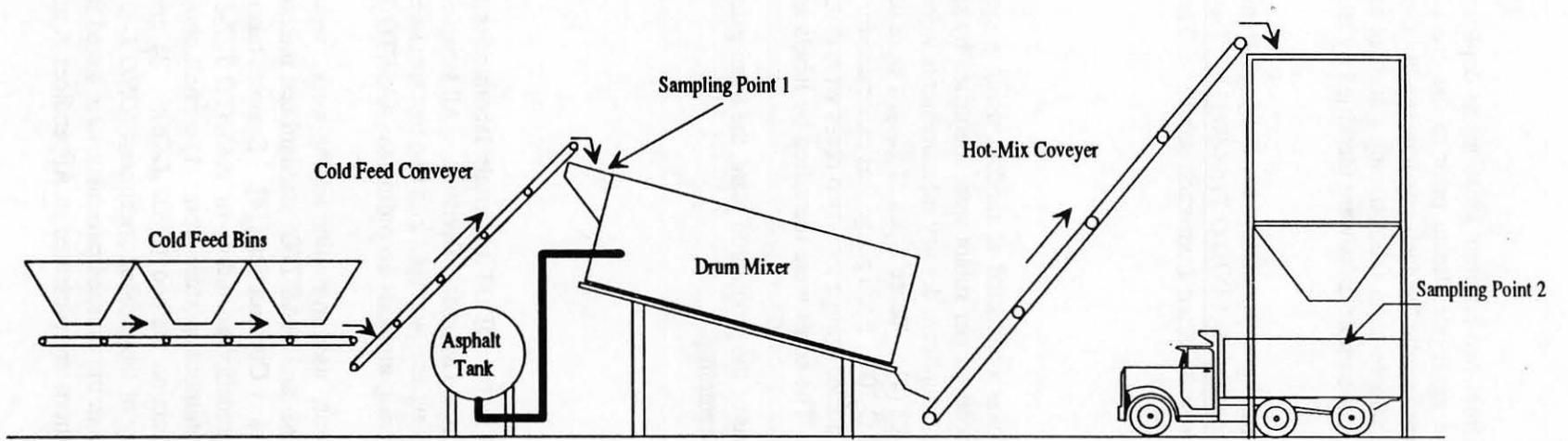


Figure 3. Location of Sampling Points at Production Plant



Figure 4. Bituminous Mixture Production Plant

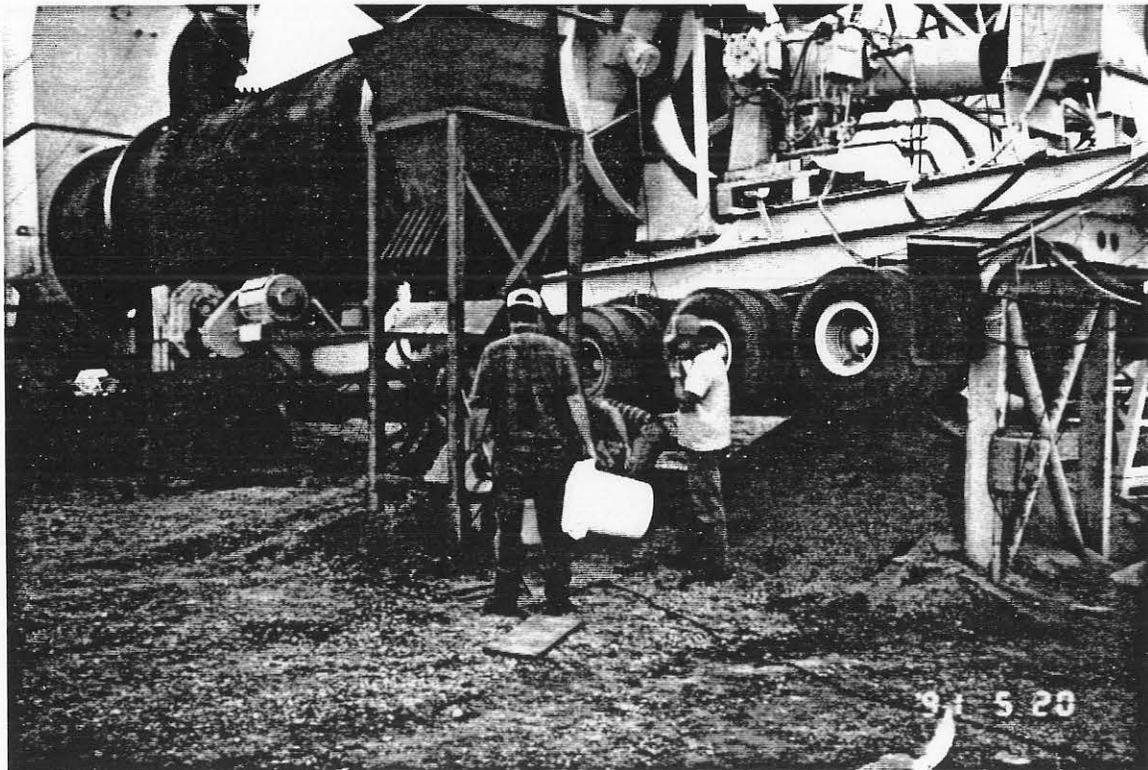


Figure 5. Aggregate Sampling Platform



Figure 6. Sampling Fresh Mixture from Hauling Truck



Figure 7. Another Photograph of Sampling Fresh Mixture

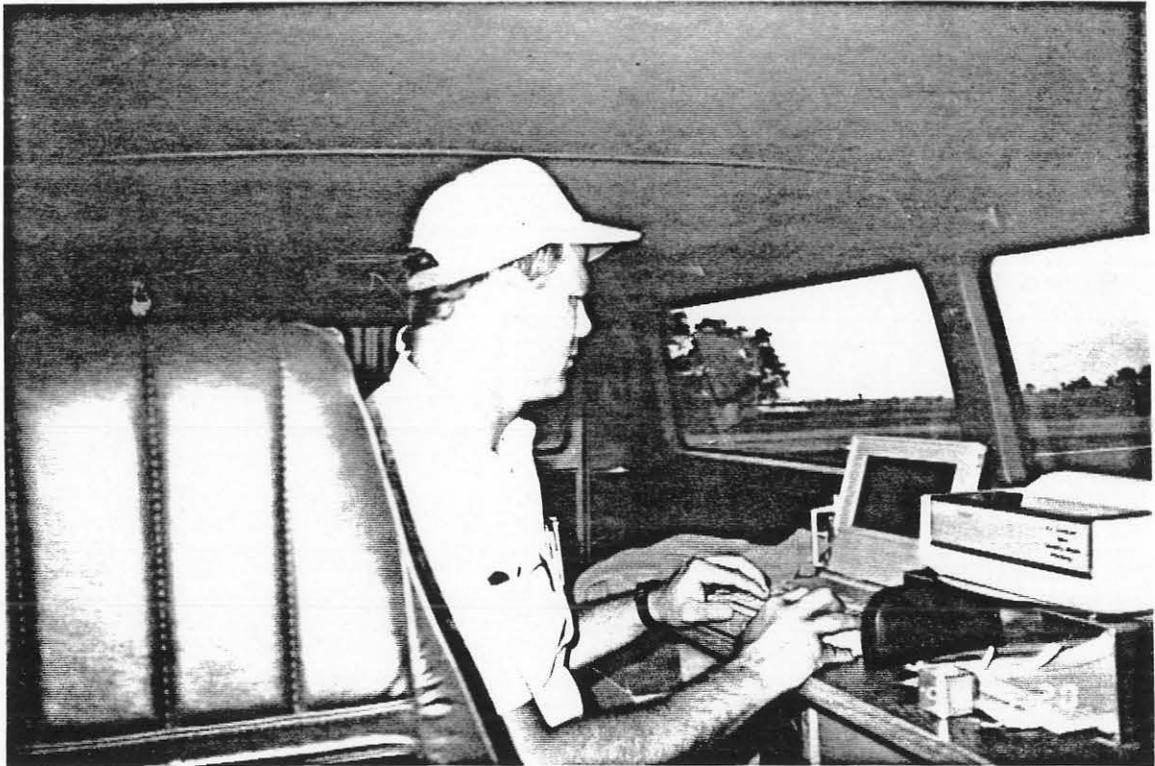


Figure 8. Member of Research Team Generating Random Sampling Plan in the Field



Figure 9. Member of Research Team Identifying Coordinates of a Sampling Point

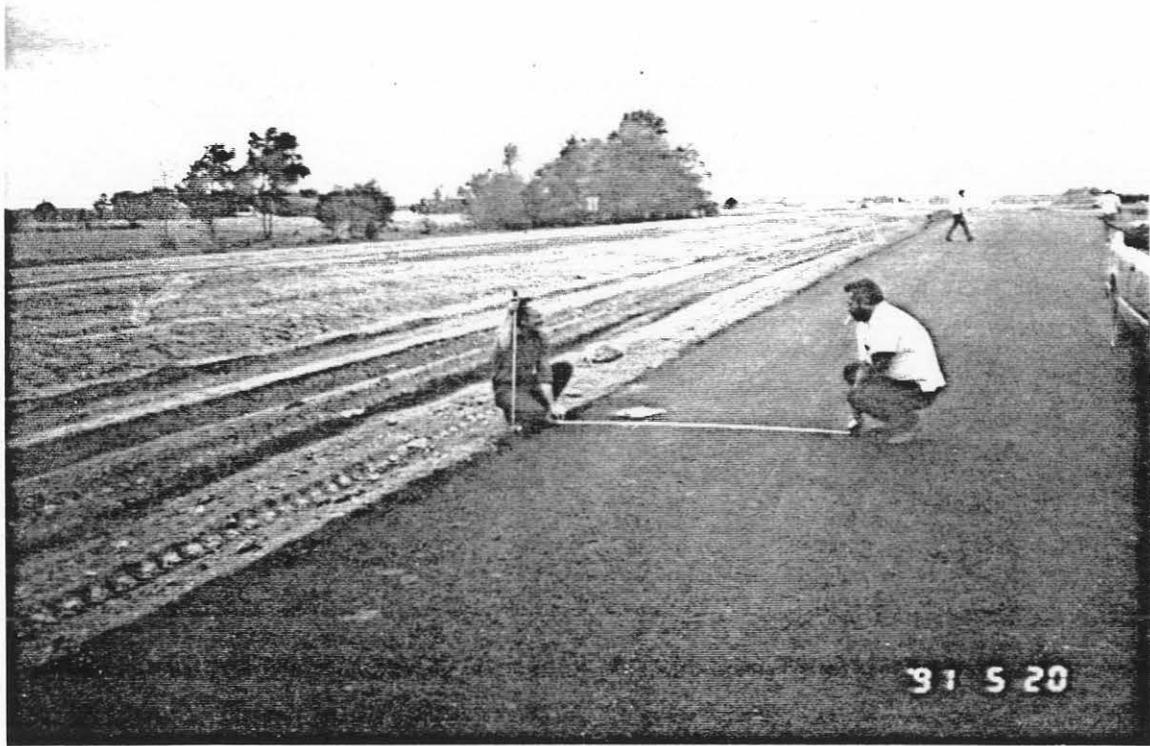


Figure 10. Another Photograph of Identifying Location of a Sampling Point

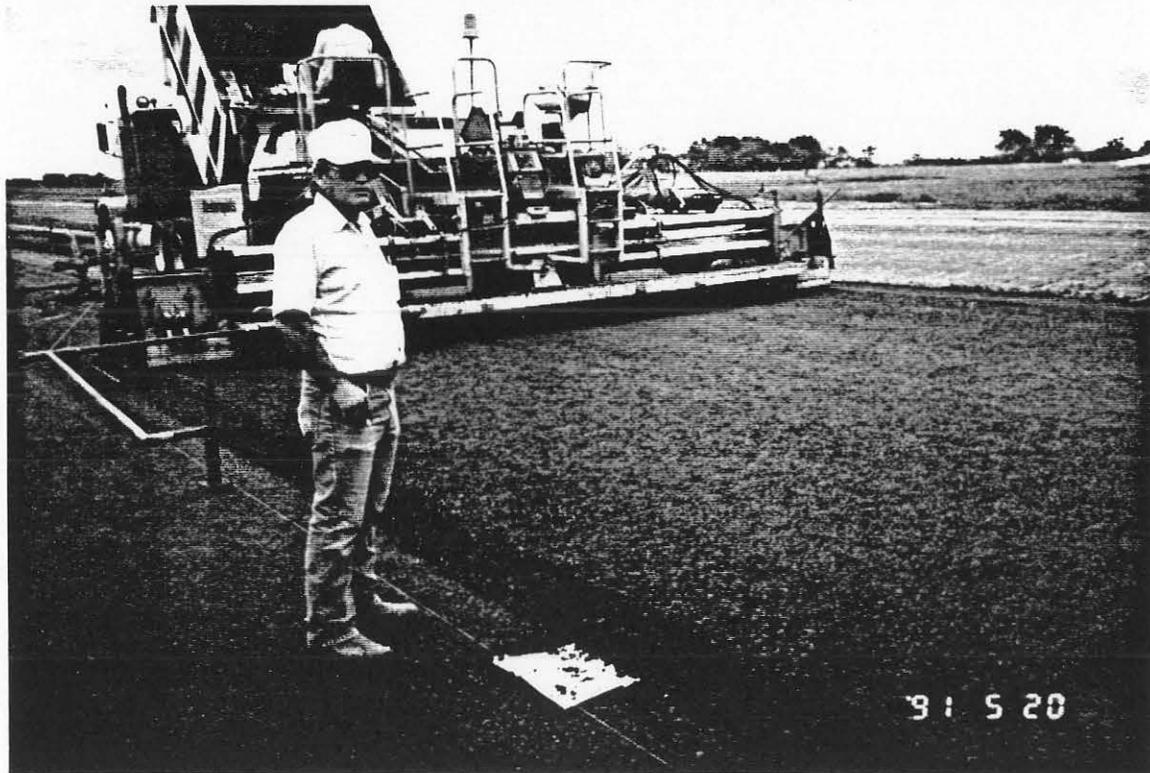


Figure 11. Separating Old and New Pavement Layers for Core Density Determination

CHAPTER 4

ANALYSIS AND INTERPRETATION OF RESULTS

This chapter summarizes results of the statistical analyses which were performed on measurements of material and construction variables to: 1) determine the components of variance due to materials, sampling, and testing, and 2) assess the level of compliance with the JMF tolerances and the QA/QC specification tolerances. Computations of the components of variance and other descriptive statistics were made using microcomputer program "NANOVA" which was developed for this purpose based on the principles discussed in Chapter 2. The program is written in Microsoft® QBasic® Version-6 [13].

DESCRIPTIVE STATISTICS OF TEST RESULTS

Tables 6 and 7 present summary statistics of the test results including the average, standard deviation, coefficient of variation, maximum and minimum values, and the 15th, 50th, and 85th percentiles. Figure 12 shows a comparison of the standard deviations of aggregate gradation determined from cold feed aggregate samples and bituminous mixture samples.

COMPONENTS OF VARIANCE

Tables 8 and 9 summarize the results of the nested analysis of variance and hypothesis testing. The detailed reports generated by program NANOVA are shown in Tables B-1 through B-28 of Appendix B. Figures C-1 through C-15 (Appendix C) illustrate the components of variance in the form of bar and pie charts. The following paragraphs summarize the major findings of the statistical analyses.

Mixture Analysis

1. Materials Variation

Sieves No. 4 and larger - Variability due to materials for sieves No. 4 and larger sieves ranged from 5.67% to 24.55% of the total variation. The percentage of overall variability due to materials for sieves 3/8", 1/2", 3/4", 1", and sieve No. 4 were 13.99%, 5.67%, 16.82%, 6.22%, and 24.55%, respectively. Sieve No. 4 had the highest percentage of total variability due to materials among sieves No. 4 and larger sieves.

Sieves No. 10 through No. 80 - For sieves No. 10 through No. 80, the percentage of total variability due to materials ranged from 41.34% to 53.82%. The corresponding percentages for sieves No. 10, No. 40, and No. 80 were 41.34%, 53.82%, and 45.30%, respectively.

TABLE 6. SUMMARY STATISTICS OF TEST RESULTS, COLD FEED AGGREGATE SAMPLES

Attribute	X_{max}	X_{min}	Mean	Range	Variance	Standard Deviation	CV %	Percentiles		
								15th	50th	85th
% Passing Sieve										
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	0.00	100.0	100.0	100.0
1"	100.00	94.80	97.81	5.20	1.39	1.18	1.21	96.6	97.7	99.1
3/4"	92.40	79.60	87.14	12.80	7.63	2.76	3.17	84.2	87.3	89.8
1/2"	76.40	57.30	67.72	19.10	18.85	4.34	6.41	62.4	67.8	73.0
3/8"	65.70	44.70	55.69	21.00	19.20	4.38	7.86	51.1	55.4	60.6
No. 4	42.60	24.30	33.98	18.30	12.13	3.48	10.24	30.6	33.4	37.9
No. 10	30.70	16.7	23.54	14.00	7.77	2.79	11.85	20.9	23.3	26.2
No. 40	19.00	9.40	14.71	9.60	3.31	1.82	12.37	13.0	14.4	16.6
No. 80	8.60	4.60	6.81	4.00	0.75	0.87	12.77	6.0	6.8	7.9
No. 200	4.67	0.79	2.99	3.88	0.57	0.75	25.08	2.1	3.1	3.7

TABLE 7. SUMMARY STATISTICS OF TEST RESULTS, BITUMINOUS MIXTURE & ROADWAY SAMPLES

Attribute	X_{max}	X_{min}	Mean	Range	Variance	Standard Deviation	CV %	Percentiles		
								15th	50th	85th
% Passing Sieve										
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	0.00	100.0	100.0	100.0
1"	100.00	93.90	98.45	6.10	2.85	1.69	1.72	96.8	98.6	100.0
3/4"	98.70	79.70	89.55	19.00	15.24	3.90	4.36	85.7	89.4	94.4
1/2"	81.30	60.50	71.36	20.80	20.16	4.49	6.29	66.3	71.1	77.0
3/8"	68.90	45.40	59.60	23.50	21.42	4.63	7.77	55.0	59.7	64.9
No. 4	44.50	27.00	37.70	17.50	10.86	3.30	8.75	34.0	37.9	41.0
No. 10	29.50	18.50	25.19	11.00	4.50	2.12	8.42	23.1	25.4	27.2
No. 40	18.40	12.00	15.24	6.40	1.76	1.33	8.73	13.6	15.4	16.5
No. 80	9.50	5.90	7.67	3.60	0.58	0.76	9.91	6.9	7.8	8.5
No. 200	5.47	2.23	3.75	3.24	0.35	0.59	15.73	3.2	3.7	4.3
% AC (Ext.)	4.41	3.01	3.75	1.40	0.09	0.30	8.00	3.4	3.8	4.1
% AC (Nuc.)	4.48	3.05	3.75	1.43	0.12	0.35	9.33	3.3	3.8	4.2
Avg. Rice's Gravity	2.56	2.46	2.50	0.10	0.00	0.02	0.01	2.5	2.5	2.5
Avg. LMSG	2.41	2.18	2.37	0.24	0.00	0.03	1.27	2.3	2.4	2.4
% Air Voids	14.39	2.48	5.29	11.91	2.82	1.68	31.76	4.2	5.0	6.0
Avg. Hveem Stability	63.30	34.00	50.89	29.30	28.93	5.38	10.57	45.6	50.4	56.7
Core Density	96.30	91.20	94.10	5.10	1.10	1.05	1.12	93.1	94.1	95.2
Nuclear Density	94.97	82.79	90.34	12.18	4.92	2.22	2.46	88.3	90.1	92.8

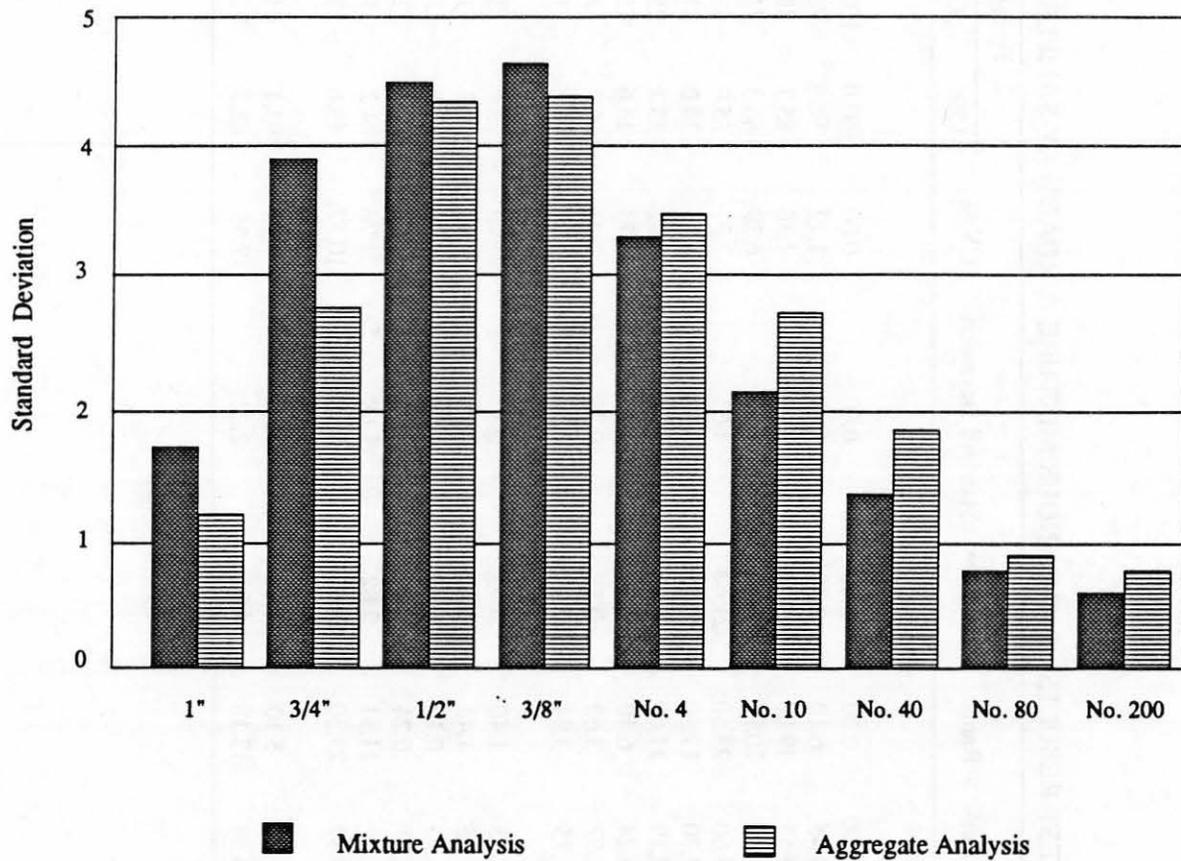


Figure 12. Standard Deviations of Gradation Analysis (Percent Passing)

TABLE 8. COMPONENTS OF VARIANCE, COLD FEED AGGREGATE SAMPLES

Attribute	Components of Variance						Hypothesis Testing			
	Material		Sampling		Testing		Hypothesis 1 ⁽¹⁾		Hypothesis 2 ⁽²⁾	
	Value	Percent	Value	Percent	Value	Percent	F-ratio	Conclusion ⁽³⁾	F-ratio	Conclusion ⁽³⁾
% Passing Sieve										
1 1/2"	0.0000	0.00	0.0000	0.00	0.0000	0.00	0.00	Accept H ₀	0.00	Accept H ₀
1"	0.3170	22.64	0.0005	0.03	1.0828	77.33	2.17	Reject H ₀	1.00	Accept H ₀
3/4"	1.6014	20.83	0.4317	5.62	5.6545	73.55	1.98	Accept H ₀	1.15	Accept H ₀
1/2"	5.4189	24.22	0.0000	0.00	16.9555	75.78	3.13	Reject H ₀	0.60	Accept H ₀
3/8"	4.6121	18.56	0.0000	0.00	20.2308	81.44	3.02	Reject H ₀	0.45	Accept H ₀ ⁽⁴⁾
No. 4	1.9480	12.14	0.0000	0.00	14.1044	87.86	2.24	Reject H ₀	0.45	Accept H ₀ ⁽⁴⁾
No. 10	0.8823	8.68	0.0000	0.00	9.2851	91.32	1.78	Accept H ₀	0.48	Accept H ₀
No. 40	0.4723	11.88	0.0000	0.00	3.5042	88.12	1.87	Accept H ₀	0.62	Accept H ₀
No. 80	0.2528	33.40	0.0000	0.00	0.5149	66.60	3.10	Reject H ₀	0.95	Accept H ₀
No. 200	0.3294	56.66	0.0000	18.44	0.1447	24.90	4.67	Reject H ₀	2.48	Reject H ₀

1 $H_0: \sigma_M^2 = 0, H_1: \sigma_M^2 > 0$

2 $H_0: \sigma_s^2 = 0, H_1: \sigma_s^2 > 0$

3 Level of Significance = 5%

4 F is significant

TABLE 9. COMPONENTS OF VARIANCE, BITUMINOUS MIXTURE & ROADWAY SAMPLES

Attribute	Components of Variance						Hypothesis Testing				
	Material		Sampling		Testing		Hypothesis 1 ⁽¹⁾		Hypothesis 2 ⁽²⁾		
	Value	Percent	Value	Percent	Value	Percent	F-ratio	Conclusion ⁽³⁾	F-ratio	Conclusion ⁽³⁾	
% Passing Sieve											
1 1/2"	0.0000	0.00	0.0000	0.00	0.0000	0.00	0.00	0.00	Accept H ₀	0.00	Accept H ₀
1"	0.1871	6.22	0.0000	0.00	2.8198	93.78	1.30	Accept H ₀	0.89	Accept H ₀	
3/4"	2.8692	16.82	0.0000	0.00	14.1874	83.18	2.07	Reject H ₀	0.75	Accept H ₀	
1/2"	1.1482	5.67	4.5915	22.68	14.5078	71.65	1.19	Accept H ₀	1.63	Accept H ₀	
3/8"	3.0184	13.99	4.8226	22.35	13.7324	63.65	1.52	Accept H ₀	1.70	Accept H ₀	
No. 4	2.6955	24.53	3.5309	32.13	4.7640	43.35	1.91	Accept H ₀	2.48	Reject H ₀	
No. 10	1.8909	41.34	0.9660	21.12	1.7168	37.54	3.07	Reject H ₀	2.13	Reject H ₀	
No. 40	0.9686	53.82	0.3058	16.99	0.5253	29.19	4.41	Reject H ₀	2.16	Reject H ₀	
No. 80	0.2667	45.30	0.1763	29.94	0.1458	24.76	3.14	Reject H ₀	3.42	Reject H ₀	
No. 200	0.1862	52.01	0.1118	31.23	0.0600	16.76	3.63	Reject H ₀	4.73	Reject H ₀	
% AC (Ext.)	0.0382	40.91	0.0175	18.80	0.0376	40.29	3.10	Reject H ₀	1.93	Reject H ₀	
% AC (Nuc.)	0.0852	68.22	0.0210	16.80	0.0187	14.98	6.62	Reject H ₀	3.24	Reject H ₀	
Avg. Rice's Gravity	0.0001	31.60	0.0002	49.88	0.0001	18.52	2.07	Reject H ₀	6.39	Reject H ₀	
Avg. LMSG	0.0006	51.92	0.0005	42.21	0.0001	5.87	3.30	Reject H ₀	15.39	Reject H ₀	
% Air Voids	1.5462	53.56	1.0491	36.34	0.2918	10.11	3.59	Reject H ₀	8.19	Reject H ₀	
Avg. Hveem Stab.	20.5205	68.58	5.0556	16.89	4.3475	14.53	6.68	Reject H ₀	3.33	Reject H ₀	
Core Density	0.2594	23.36	0.6333	57.03	0.2179	19.62	1.70	Accept H ₀	6.81	Reject H ₀	
Nuclear Density	2.1934	43.82	1.7513	34.99	1.0610	21.20	2.92	Accept H ₀	4.30	Reject H ₀	

1 H₀: σ²_M = 0, H₁: σ²_M > 0

2 H₀: σ²_S = 0, H₁: σ²_S > 0

3 Level of Significance = 5%

Sieve No. 200 - Variability due to materials for sieve No. 200 was 52.01% of the total variance.

Overall, sieve No. 40 had the largest percentage of variability due to materials among all sieves.

Asphalt Content - Asphalt content measurements obtained using the nuclear gauge showed higher percentage of total variability due to materials than the extraction method; the percentages were 68.22% for the nuclear gauge and 40.91% for the extraction method.

Roadway Density - Density measurements obtained using the nuclear gauge showed higher percentage of overall variability due to materials than core density measurements; the percentages were 43.82% and 23.36%, respectively.

% Air Voids, Hveem Stability, Average Rice's Gravity, and LMSG - The percentages of total variability due to materials for % air voids, average Hveem stability, average Rice's gravity, and average lab molded specific gravity (LMSG) were 53.56%, 68.58%, 31.60%, and 51.92%, respectively.

The highest percentage of overall variability due to materials in mixture analysis was associated with Hveem stability measurements.

F-Test Results - Results of the F-test indicated that the percent passing for each of sieves 3/8", 1/2", 1", 1 1/2", and sieve No. 4 was uniform throughout the lot, i.e., material variance was not significantly different from zero at the 95% confidence level. For each of sieves No. 10, No. 40, No. 80, No. 200, and 3/4", the F-test indicated that percent passing was not uniform throughout the lot, i.e., material variance was significantly greater than zero at the 95% confidence level.

In addition, the F-test indicated that material variance was not significantly different from zero for core density and nuclear density. For asphalt content measurements using both the nuclear gauge and the extraction method, average Rice's gravity measurements, average LMSG, % air voids, and average Hveem stability, the F-test showed that material variance was significantly greater than zero at the 95% confidence level.

2. Sampling Variation

Sieves No. 4 and larger - Variability due to sampling for sieves No. 4 and larger sieves ranged from 0.00% to 32.13% of the total variance. The percentages of overall variability due to sampling for sieves 3/8", 1/2", 3/4", 1", and sieve No. 4 were 22.35%, 22.68%, 0.00%, 0.00%, and 32.13%, respectively. Sieve No. 4 had the highest sampling variation in this group of sieves.

Sieves No. 10 through No. 80 - The percentage of total variability due to sampling ranged from 16.99% to 29.94%. For sieves No. 10, No. 40, and No. 80, the percentages were 21.12%, 16.99%, and 29.94%, respectively.

Sieve No. 200 - Variability due to sampling for sieve No. 200 was 31.23% of the total variance.

Overall, sieve No. 4 had the largest percentage of total variability due to sampling among all sieves.

Asphalt Content - Asphalt content measurements obtained using the extraction method showed higher percentage of total variability due to sampling than the nuclear gauge method; the percentages were 18.80% and 16.80%, respectively.

Roadway Density - Density measurements obtained using core samples exhibited higher percentage of total variance due to sampling than the nuclear gauge density measurements; the percentages were 57.03% and 34.99%, respectively.

% Air Voids, Hveem Stability, Average Rice's Gravity, and LMSG - The percentages of total variability due to sampling for % air voids, average Hveem stability, average Rice's gravity, and average LMSG, were 36.34%, 16.89%, 49.88%, and 42.21%, respectively.

In mixture analysis, the highest percentage of total variability due to sampling was associated with density measurements using core samples.

F-Test Results - Results of the F-test indicated that for sieves 3/8", 1/2", 3/4", 1", and 1 1/2" the contribution of sampling to the overall variability was not statistically significant at the 95% confidence level. For sieves No. 4, No. 10, No. 40, No. 80, and No. 200, the F-test indicated that sampling variance was significantly greater than zero at the 95% confidence level.

In addition, for asphalt content determinations using both the nuclear gauge and the extraction methods, density measurements using both the nuclear gauge and core methods, average Rice's gravity measurements, average LMSG, % air voids, and average Hveem stability, the F-tests showed that the sampling variance was significantly greater than zero at the 95% confidence level.

3. Testing Variation

Sieves No. 4 and larger - Variability due to testing for sieves No. 4 and larger sieves ranged from 43.35% to 93.78% of the total variance. The corresponding percentages for sieves 3/8", 1/2", 3/4", 1", and sieve No. 4 were 63.65%, 71.65%, 83.18%, 93.78%, and 43.35%, respectively. Sieve 1" had the highest testing variation in this group of sieves.

Sieves No. 10 through No. 80 - Testing variation ranged from 24.76% to 37.54% of the overall variation. The percentages of total variation due to testing for sieves No. 10, No. 40, and No. 80 were 37.54%, 29.19%, and 24.76%, respectively.

Sieve No. 200 - Variability due to testing was 16.76% of the total variance.

Overall, Sieve 1" had the largest percentage of total variability due to testing among all sieves analyzed.

Asphalt Content - Asphalt content measurements using the extraction method had higher percentage of total variability due to testing than asphalt content measurements using the nuclear gauge method; the percentages were 40.29% and 14.98%, respectively.

Roadway Density - Density measurements using the nuclear gauge showed higher percentage of total variability due to testing than density measurements obtained from core samples; the percentages were 21.20% and 19.62%, respectively.

% Air Voids, Hveem Stability, Rice's Gravity, and LMSG - The percent of total variability due to testing for % air voids, average Hveem stability, average Rice's gravity, and average LMSG, were 10.11%, 14.53%, 18.52%, and 5.87%, respectively.

The highest percentage of variability due to testing in mixture analysis was associated with average Hveem stability measurements.

Aggregate Analysis

1. Materials Variation

Sieves No. 4 and larger - Variability due to materials ranged from 12.14% to 24.22% of the total variation. The corresponding percentages for sieves 3/8", 1/2", 3/4", 1", and sieve No. 4 were 18.56%, 24.22%, 20.83%, 22.64%, and 12.14%, respectively. Sieve 1/2" had the highest percentage of overall variability due to materials in this group of sieves.

Sieves No. 10 through No. 80 - The percentage of total variation due to materials ranged from 8.68% to 33.40%. The corresponding percentages for sieves No. 10, No. 40, and No. 80 were 8.68%, 11.88%, and 33.40%, respectively. In this group of sieves, sieve No. 80 exhibited the highest percentage of total variability due to materials.

Sieve No. 200 - Variability due to materials for sieve No. 200 was 56.66% of the total variance.

Overall, sieve No. 200 had the largest percentage of total variability due to materials among all sieves.

F-Test Results - Results of the F-test indicated that the percent passing for each of sieves 1 1/2", 3/4", No. 10, and No. 40 was uniform throughout the lot, i.e., material variance was not significantly different from zero at the 95% confidence level. For each of sieves 1", 1/2", 3/8", No. 4, No. 80, and No. 200, the F-test indicated that material variance was significantly greater than zero at the 95% confidence level.

2. Sampling Variation

Sieves No. 4 and larger - Variability due to sampling ranged from 0.00% to 5.62% of the total variance. The corresponding percentages for sieves 3/8", 1/2", 3/4", 1", and sieve No. 4 were 0.00%, 0.00%, 5.62%, 0.03%, and 0.00%, respectively. Sieve 3/4" had the highest percentage of total variability due to sampling in this group of sieves.

Sieves No. 10 through No. 80 - There was no variability attributed to sampling.

Sieve No. 200 - Sampling variability was 18.44% of the total variance.

Overall, sieve No. 200 had the largest percentage of variability due to sampling among all sieves.

F-Test Results - Results of the F-test indicated that for each of sieves 1 1/2", 1", 3/4", 1/2", 3/8", No. 4, No. 10, No. 40, and No. 80, the contribution of sampling to the total variance was not significant at the 95% confidence level. For sieve No. 200, the F-test indicated that sampling variance was significantly greater than zero at the 95% confidence level.

3. Testing Variation

Sieves No. 4 and larger - Variability due to testing ranged from 73.55% to 87.86% of the total variance. The corresponding percentages for sieves 3/8", 1/2", 3/4", 1", and sieve No. 4 were 81.44%, 75.78%, 73.55%, 77.33%, and 87.86%, respectively. Sieve No. 4 had the highest percentage of total variability due to testing in this group of sieves.

Sieves No. 10 through No. 80 - The percentage of overall variability due to testing ranged from 66.60% to 91.32%. The corresponding percentages for sieves No. 10, No. 40, and No. 80 were 91.32%, 88.12%, and 66.60%, respectively. Sieve No. 10 exhibited the highest percentage of total variability due to testing in this group of sieves.

Sieve No. 200 - Testing variability accounted for 24.90% of the total variance.

Overall, sieve No. 10 had the largest percentage due to testing variability among all sieves.

Summary

Aggregate Analysis

- The largest source of variation for sieves No. 4 and larger, as well as sieves No. 10 through No. 80 was due to testing. For sieve No. 200, the largest source of variation was due to materials.
- The second largest source of variation for sieves No. 4 and larger, as well as sieves No. 10 through No. 80 was due to materials. For sieve No. 200, the second largest source of variation was due to testing.
- The smallest source of variation for all sieves included in aggregate analysis was due to sampling.

Mixture Analysis

- The largest source of variation for sieves No. 4 and larger was due to testing. For sieves No. 10 through No. 80, as well as sieve No. 200, the largest source of variation was due to materials.
- The second largest source of variation for all sieves was due to sampling, except for sieves 3/4", 1", and No. 80. For sieves 3/4" and 1", the second largest source of variation was due to materials, whereas for sieve No. 80 testing was the second largest source of variation.
- The smallest source of variation for sieves No. 4 and larger was due to materials except for sieves 3/4" and 1", where sampling was the smallest source of variation. For sieves No. 10 through No. 80, the smallest source of variation was due to sampling except for sieve No. 80, where testing was the smallest source of variation. For sieve No. 200, the smallest source of variation was due to testing.

Aggregate Analysis Versus Mixture Analysis

- Overall, sampling contributed a smaller percentage of total variability in aggregate analysis than in mixture analysis, except for sieve 3/4".
- The percentage of total variability due to testing was higher in aggregate analysis than in mixture analysis for sieves 1/2", 3/8", No. 4, No. 10, No. 40, No. 80, and No. 200.
- Aggregate analysis demonstrated higher percentage of total variation due to materials than mixture analysis for sieves 1", 3/4", 1/2", 3/8", and No. 200.

In general, the large variation attributed to sampling and testing suggests that the overall standard deviation, a measure of variability, is not in itself a true indication of construction material and process variability.

SPECIFICATION COMPLIANCE

JMF Tolerances

Table 10 lists the percentage of measurements included within the JMF tolerance limits and the conformal indices for each attribute. The conformal index (*C.I.*) is defined as the root mean square of the deviations of a group of measurements from a target or specified value, that is,

$$C.I. = \sqrt{\frac{\sum_{i=1}^n |X_i - T|^2}{n}} \quad (25)$$

where T is the target value and n is the number of measurements.

Like the standard deviation, the conformal index is a measure of dispersion in a group of measurements. Nevertheless, the standard deviation is a measure of the average deviation from the central value, whereas the conformal index is a measure of the target miss or degree of accordance with a standard value [9]. The relationship between the standard deviation and the conformal index is given by the following equation:

$$C.I. = \sqrt{\frac{(n-1)\sigma^2 + n d^2}{n}} \quad (26)$$

where d is the deviation of the average of a group of n measurements from the target value.

In general, the conformal indices are appreciably greater than the corresponding standard deviations shown in Tables 6 and 7; which would typically be interpreted as a shift in the process average. Nevertheless, the large variation due to sampling and testing prevents a true evaluation of material and process variation.

QA/QC Specification Tolerances

Table 11 presents the percentage of measurements which fall within the ODOT QA/QC specification tolerances for each attribute. Details of the QA/QC specification are included in Appendix F. The tolerances used in the analysis correspond to *one test and 100% pay factor*. Figures D-1 through D-14 (Appendix D) depict histograms of the quality attributes and the corresponding QA/QC specification tolerances.

In general, the QA/QC specification tolerances seem to be practical and defensible. The only exception is the nuclear density tolerances where only 12% of the measurements were included within the prescribed tolerances. Chapter 5 presents an evaluation of the nuclear gauge for in-place density determination.

The 2-sigma and the 3-sigma limits are summarized in Tables 12 and 13 along with the percentage of measurements which fall within these limits. Table 14 lists the tolerances required to include approximately 85% of the measurements.

Table 10. US-412 Project, Percent within JMF Tolerances and Conformal Indices

Attribute	JMF	JMF Tolerances	% within JMF Tolerances		Conformal Index (C.I.)	
			Aggregate Analysis	Mixture Analysis	Aggregate Analysis	Mixture Analysis
% Passing Sieve						
1 1/2"	100	0	100.0	100.0	0.00	0.00
1"	98	± 7	100.0	100.0	1.19	1.74
3/4"	87	± 7	98.9	82.6	2.75	4.64
1/2"	70	± 7	82.6	84.8	4.88	4.67
No. 4	34	± 7	96.7	85.9	3.46	4.95
No. 10	25	± 4	79.3	94.6	3.14	2.12
No. 40	16	± 4	97.8	100.0	2.22	1.53
No. 80	8	± 4	100.0	100.0	1.47	0.82
No. 200	4	± 2	89.1	100.0	1.26	0.64
% AC (Extraction)	4.1	± 0.4		60.9		0.46
% AC (Nuclear)	4.1	± 0.4		51.1		0.49
% Air Voids	4 - 6			76.1		1.69
% Hveem Stability	40 Min.			97.1		
% Density (Core)	92 - 96			84.0		1.05
% Density (Nuclear)	92 - 96			22.0		4.27

Table 11. US-412 Project, Percent within QA/AC Specification Tolerances

Attribute	JMF Target	QA/QC Specifications		Percent Within Tolerances	
		Allowable Deviation ⁽¹⁾	Specified Tolerances ⁽¹⁾	Aggregate Analysis	Mixture analysis
% Passing Sieve					
1 1/2"	100	± 8.0	92.0 - 100.0	100.0	100.0
1"	98	± 8.0	90.0 - 100.0	100.0	100.0
3/4"	87	± 8.0	79.0 - 95.0	100.0	94.6
1/2"	70	± 8.0	62.0 - 78.0	89.1	88.0
No. 4	34	± 8.0	26.0 - 42.0	96.7	95.7
No. 10	25	± 6.5	18.5 - 31.5	96.8	100.0
No. 40	16	± 6.5	9.5 - 22.5	98.9	100.0
No. 80	8	± 6.5	1.5 - 14.5	100.0	100.0
No. 200	4	± 3.0	1.0 - 7.0	98.9	100.0
% AC (Extraction)	4.1	± 0.7	3.4 - 4.8		89.1
% AC (Nuclear)	4.1	± 0.7	3.4 - 4.8		81.8
% Air Voids	5.0	± 2.5	2.5 - 7.5		93.2
% Hveem Stability	40 Min.	- 2.0	38 - 100		98.5
% Density (Core)	94	(-2) - (+4)	92 - 98		86.0
% Density (Nuclear)	94	(-2) - (+4)	92 - 98		22.0

1 One test and 100% Pay Factor

Table 12. US-412 Project, Aggregate Analysis, Percent within $\bar{X} \pm 2S$ and $\bar{X} \pm 3S$ Limits

Attribute	\bar{X}	S	$\bar{X} \pm 2S$		$\bar{X} \pm 3S$	
			Limits	PWL ⁽¹⁾	Limits	PWL ⁽¹⁾
% Passing Sieve						
1 1/2"	100.00	0.00	100.0 - 100.0	100.0	100.0 - 100.0	100.0
1"	97.81	1.18	95.5 - 100.0	95.7	94.3 - 100.0	100.0
3/4"	87.14	2.76	92.7 - 81.6	96.7	78.9 - 95.4	100.0
1/2"	67.72	4.34	59.0 - 76.4	97.8	54.7 - 80.8	100.0
No. 4	33.98	3.48	27.0 - 40.9	96.7	23.5 - 44.4	100.0
No. 10	23.54	2.79	18.0 - 29.1	92.4	15.2 - 31.9	100.0
No. 40	14.71	1.82	11.1 - 18.4	93.5	9.3 - 20.2	100.0
No. 80	6.81	0.87	5.1 - 8.6	96.7	4.2 - 9.4	100.0
No. 200	2.99	0.75	1.5 - 4.5	95.7	0.7 - 5.3	100.0

1 PWL = percent within limits

Table 13. US-412 Project, Mixture Analysis, Percent within $\bar{X} \pm 2S$ and $\bar{X} \pm 3S$ Limits

Attribute	\bar{X}	S	$\bar{X} \pm 2S$		$\bar{X} \pm 3S$	
			Limits	PWL ⁽¹⁾	Limits	PWL ⁽¹⁾
% Passing Sieve						
1 1/2"	100.00	0.00	100.0 - 100.0	100.0	100.0 - 100.0	100.0
1"	98.45	1.69	95.1 - 100.0	94.6	93.4 - 100.0	100.0
3/4"	89.55	3.90	81.7 - 97.4	96.7	77.8 - 100.0	100.0
1/2"	71.36	4.49	62.4 - 80.3	96.7	57.9 - 84.8	100.0
No. 4	37.70	3.30	31.1 - 44.3	95.7	27.8 - 47.6	98.9
No. 10	25.19	2.12	21.0 - 29.4	94.6	18.8 - 31.6	98.9
No. 40	15.24	1.33	12.6 - 17.9	93.5	11.3 - 19.2	100.0
No. 80	7.67	0.76	6.2 - 9.2	96.7	5.4 - 10.0	100.0
No. 200	3.75	0.59	2.6 - 4.9	93.5	2.0 - 5.5	100.0
% AC (Extraction)	3.75	0.30	3.15 - 4.36	94.6	2.84 - 4.66	100.0
% AC (Nuclear)	3.75	0.35	3.05 - 4.45	98.7	2.70 - 4.80	100.0
% Air Voids	5.29	1.68	1.93 - 8.65	95.5	0.25 - 10.33	97.7
% Hveem Stability	50.89	5.38	40.1 - 61.7	94.1	34.8 - 67.0	98.5
% Density (Core)	94.10	1.05	92.0 - 96.2	85.0	91.0 - 97.2	92.0
% Density (Nuclear)	90.34	2.22	85.9 - 94.8	89.0	83.7 - 97.0	91.0

1 PWL = percent within limits

Table 14. US-412 Project, Tolerances That Include Approximately 85% of Measurements

Attribute	JMF Target	Aggregate Analysis			Mixture Analysis		
		Deviation ⁽¹⁾	Tolerances ⁽¹⁾	PWT ⁽²⁾	Deviation ⁽¹⁾	Tolerances ⁽¹⁾	PWT ⁽²⁾
% Passing Sieve							
1 1/2"	100	± 0.0	100.0 - 100.0	100.0	± 0.0	100.0 - 100.0	100.0
1"	98	± 2.0	96.0 - 100.0	92.4	± 2.0	96.0 - 100.0	90.2
3/4"	87	± 4.0	83.0 - 91.0	84.8	± 7.0	80.0 - 94.0	82.6
1/2"	70	± 8.0	62.0 - 78.0	89.1	± 8.0	62.0 - 78.0	88.0
No. 4	34	± 5.0	29.0 - 39.0	82.6	± 7.0	27.0 - 41.0	85.9
No. 10	25	± 5.0	20.0 - 30.0	89.1	± 3.0	22.0 - 28.0	87.0
No. 40	16	± 3.0	13.0 - 19.0	88.0	± 2.0	14.0 - 18.0	81.5
No. 80	8	± 2.0	6.0 - 10.0	87.0	± 1.5	6.5 - 9.5	94.6
No. 200	4	± 2.0	2.0 - 6.0	89.1	± 1.0	3.0 - 5.0	87.0
% AC (Extraction)	4.1				± 0.7	3.4 - 4.8	89.1
% AC (Nuclear)	4.1				± 0.8	3.3 - 4.9	88.6
% Air Voids	5.0				± 2.0	3.0 - 7.0	89.8
% Hveem Stability	40 Min.				± 0	40 - 100	97.1
% Density (Core)	94				(-2) - (+4)	92 - 98	86.0
% Density (Nuclear)	94				(-7) - (+4)	87 - 98	86.0

1 One test

2 Percent within computed tolerances

CHAPTER 5

EVALUATION OF NUCLEAR DENSITY GAUGES

This chapter is concerned with comparing the in-place density measurements obtained using core samples with those obtained using the nuclear gauge. Statistical analyses were used to model the relationship between the two methods and to test hypotheses regarding the equality of the means of both methods.

SIGNIFICANCE OF DENSITY

The total volume of air between the coated aggregate particles in a compacted bituminous mixture expressed as a percent of the bulk volume of the compacted mixture is referred to as *voids in total mix (VTM)* or simply *air voids*. Air voids is probably the single most important factor that affects the pavement performance. For a given aggregate gradation, the air voids are primarily controlled by asphalt content, compactive effort during construction, and additional compaction under traffic. Reducing air voids to an acceptable level during construction improves the strength, durability, resistance to deformation, resistance to moisture damage, and impermeability of the mix.

In-place density of the compacted bituminous mixture is directly related to air voids. Therefore, density must be closely controlled to insure that air voids in the freshly compacted mixture are within an acceptable range. The method used by ODOT for specifying in-place density requires that the contractor achieve a prescribed minimum percentage of the *theoretical maximum density (TMD)*.

MEASUREMENT OF DENSITY

The two primary methods of measuring in-place density are: 1) removing cores from the compacted pavement, and 2) using nuclear gauges. Density determination from core samples provides fairly accurate results. Nevertheless, this method suffers from being expensive, slow, and destructive. It requires drilling a 6-inch (150 mm) diameter hole into the pavement which must then be repaired. After cutting the core, the freshly placed material must be separated from the underlying material attached to the core. A sheet of paper or other bond breaking material is usually placed on the existing surface prior to placing the fresh mixture. Typically, density results using the core method are obtained the day after construction is completed. The time lag between drilling the cores and receipt of test results limits the use of this method to acceptance sampling and testing.

Nuclear density gauges have the advantage of being rapid and nondestructive. The short test time allows sampling frequencies to be increased and provides the contractors with density measurements while the bituminous mix is hot enough to compact further when necessary. Use of nuclear gauges for measuring in-place density grew rapidly during the 1970s. A TRB survey conducted in 1983 showed that

of the 45 states which participated in the survey, 28 states used nuclear gauges and nine used core samples exclusively for measuring density, while eight other states used a combination of both methods [17].

Most nuclear gauges operate in the backscatter mode. A radiation source emits gamma ray photons which are directed downward into the pavement. Detectors placed near the radiation source measure the gamma photons scattered back in the direction of the detector. The number of photons detected is a function of the number of photons scattered in the direction of the detector and the number of photons absorbed by the material. To determine the density of a thin lift of bituminous concrete placed over an old pavement, the thickness of the top layer and the density of the underlying material are keyed into a microprocessor which computes the density of the top lift. Some newer gauges employ two detectors which are placed at different distances from the radiation source and require only inputting the thickness of the top layer.

The chemical composition of the bituminous mix is a significant source of error in nuclear density readings. In general, the higher the atomic number of the material being tested, the greater the Compton scattering and absorption effect. The accuracy of the nuclear gauge readings is also influenced by the thickness of the top lift and the surface texture. To mitigate these effects, bias correction factors are determined for the particular mix being tested by correlating nuclear and core density measurements. Recent studies concerning field evaluation of nuclear density gauges have concluded that with experienced gauge operators, proper bias corrections, and statistically adequate number of gauge readings, the nuclear gauges are capable of measuring density of thin lifts with an acceptable degree of accuracy [11, 20].

TEST RESULTS

As discussed in Chapter 3, core samples were drilled immediately after recording the nuclear density gauge readings at each randomly selected location. The cores were labeled and transferred to the laboratories where they were cut to the appropriate thickness and tested according to OHD L-14. Four nuclear density gauges were used: Troxler Model 3440 (Muskogee Residency), Troxler Model 4640 (Materials Division), Seamon Model C-200 (Cummins Construction), and Troxler Model 3440 (Cummins Construction). Summary of the test results is given in Tables A-27 and A-28 (Appendix A).

STATISTICAL ANALYSES

Regression Analysis

Figures 13a through 16a present scatter plots of the density measurements. Linear regression analysis was used to determine the equations of the straight lines which best fit the data based on the principle of least squares. The general form of these equations is given by:

$$Y = a + bX \quad (27)$$

where Y is the expected value of core density, X is the density measurement obtained from nuclear gauge, and a & b are coefficients.

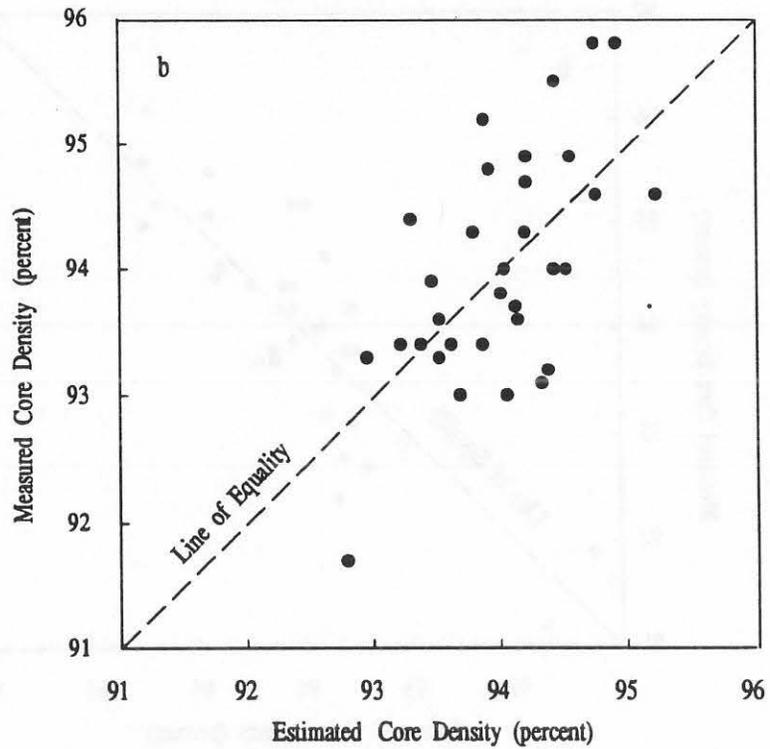
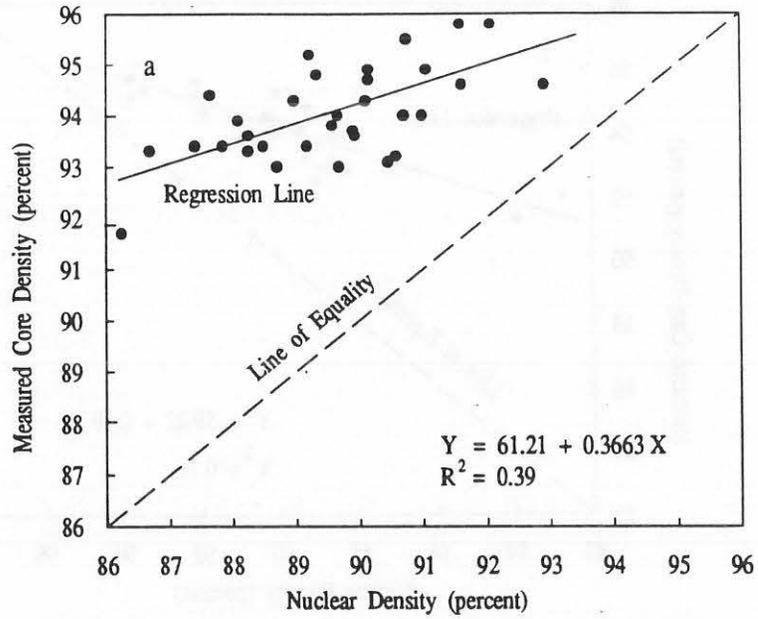


Figure 13. Scatter Plot of (a) Measured Core Density versus Nuclear Density, and (b) Measured versus Estimated Core Densities - Troxler 3440 (Muskogee Residency)

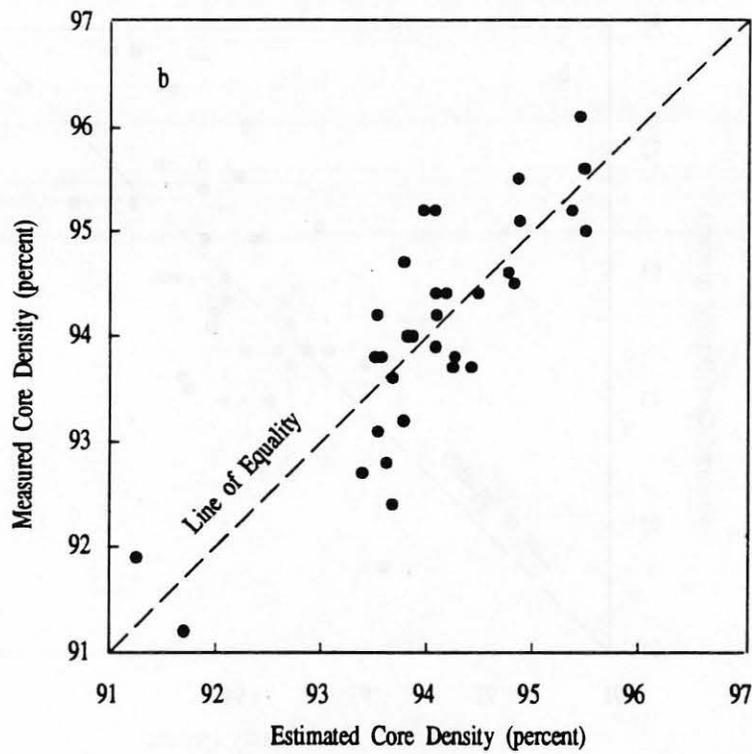
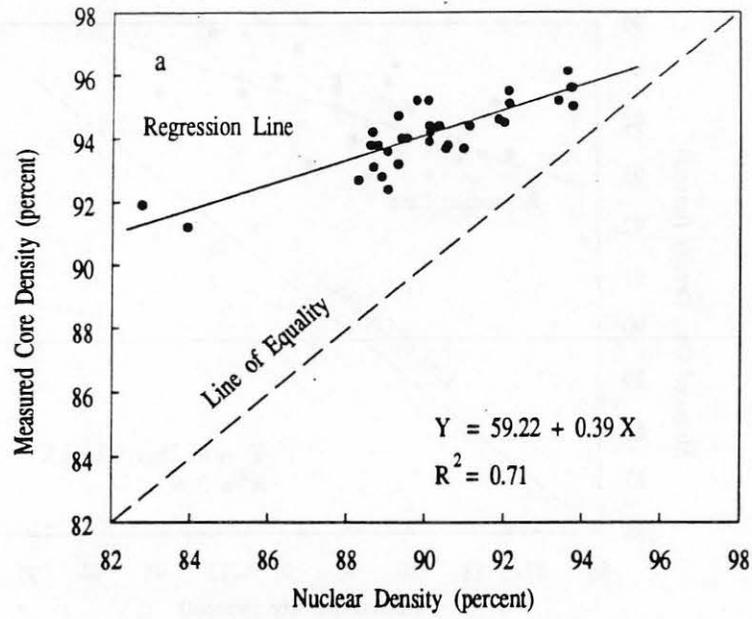


Figure 14. Scatter Plot of (a) Measured Core Density versus Nuclear Density, and (b) Measured versus Estimated Core Densities - Troxler 4640 (Materials Division)

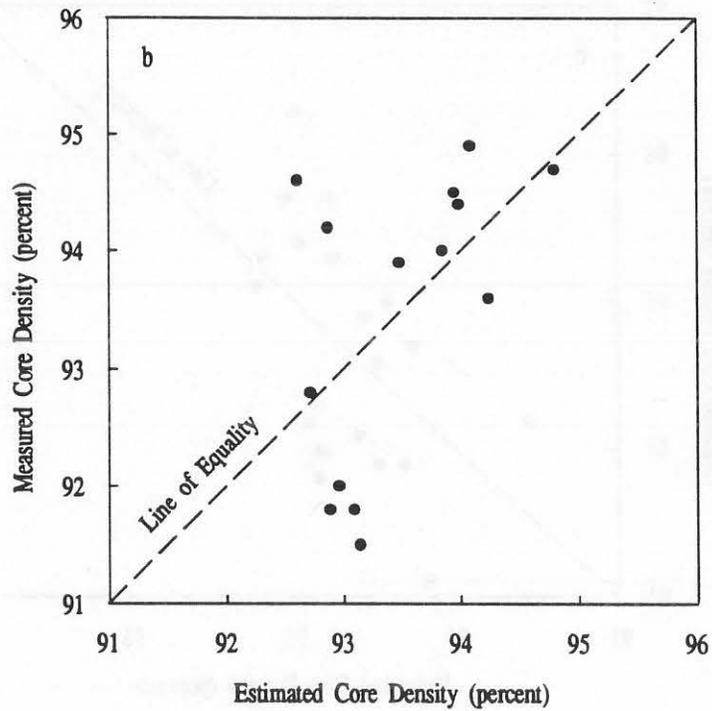
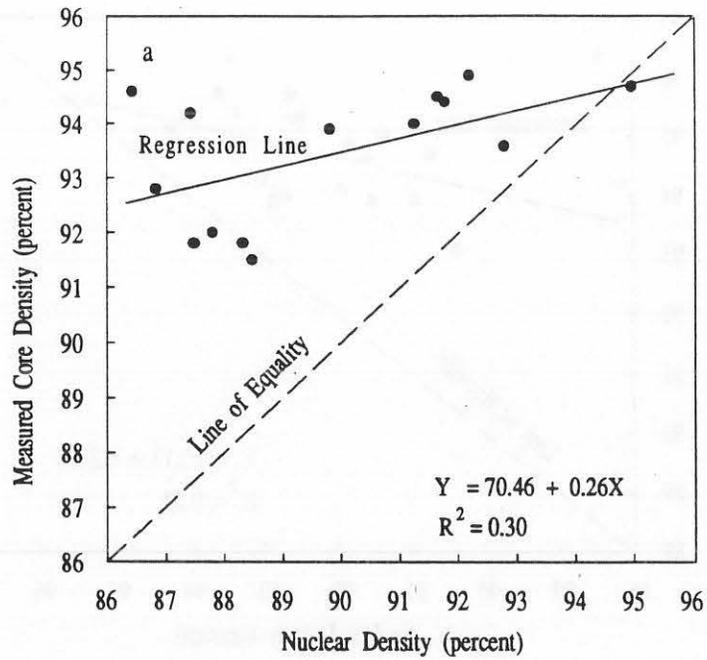


Figure 15. Scatter Plot of (a) Measured Core Density versus Nuclear Density, and (b) Measured versus Estimated Core Densities - Seamon C200 (Cummins Construction)

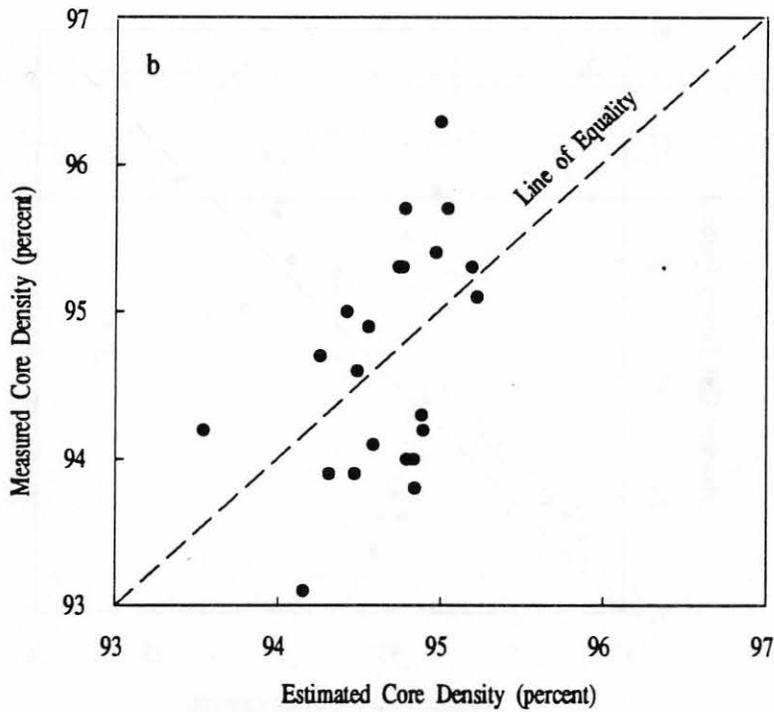
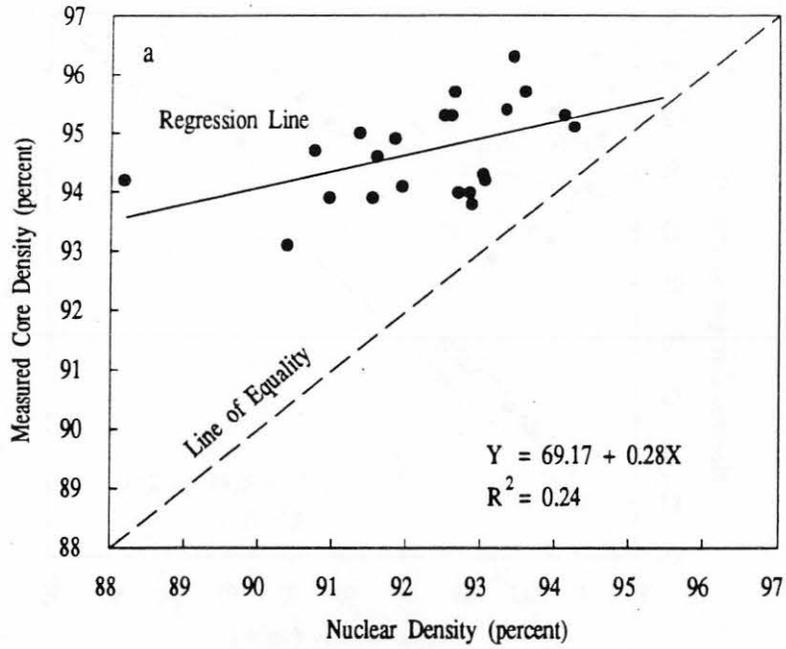


Figure 16. Scatter Plot of (a) Measured Core Density versus Nuclear Density, and (b) Measured versus Estimated Core Densities - Troxler 3440 (Cummins Construction)

Table 15 summarizes the results of regression analysis. The correlation coefficient varies from 0.49 to 0.84 (R^2 between 0.24 and 0.71). Hypothesis testing concerning the significance of the regression coefficients ($H_0: \beta = 0$ versus $H_a: \beta \neq 0$) indicated that these coefficients are significantly different from zero at the 95% confidence level. In other words, there is evidence to indicate that core densities are linearly related to nuclear densities. The calibrated relationships are shown on the scatter plots of Figures 13a through 16a. In addition, Figures 13b through 16b show scatter plots of measured core densities versus estimated core densities from the calibrated relationships.

TABLE 15. CALIBRATED RELATIONSHIPS BETWEEN CORE AND NUCLEAR DENSITIES

Nuclear Gauge	N	Equation	R^2	Std. Error of Y Estimate	Std. Error of Regression Coeff.
Troxler 3440 (Muskogee Residency)	32	$Y = 61.21 + 0.366 X$	0.392	0.720	0.083
Troxler 4640 (Materials Division)	32	$Y = 59.22 + 0.387 X$	0.708	0.601	0.387
Seamon C200 (Cummins Const.)	14	$Y = 70.46 + 0.256 X$	0.297	1.078	0.114
Troxler 3440 (Cummins Const.)	22	$Y = 69.17 + 0.276 X$	0.237	0.706	0.111

Paired-Difference Test

Figure 17 depicts the relationship between measured core density and the difference between density measurements. To test the hypothesis that the average difference between density measurements is equal to zero, that is,

$$H_0: \mu_1 = \mu_2 \quad \text{against} \quad H_a: \mu_1 \neq \mu_2$$

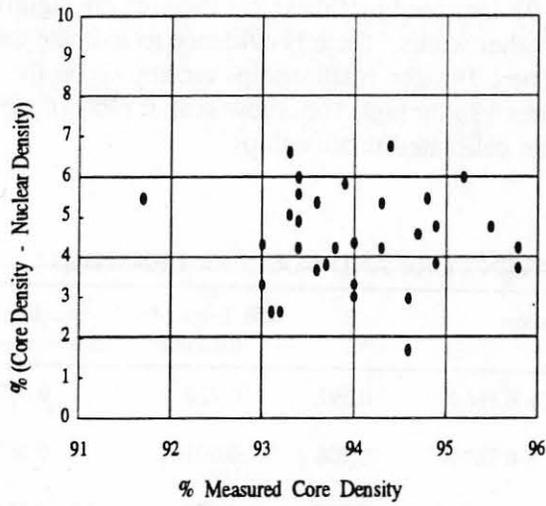
the test-statistic is given by:

$$t = \frac{\bar{D}}{s_D / \sqrt{n}} \quad (28)$$

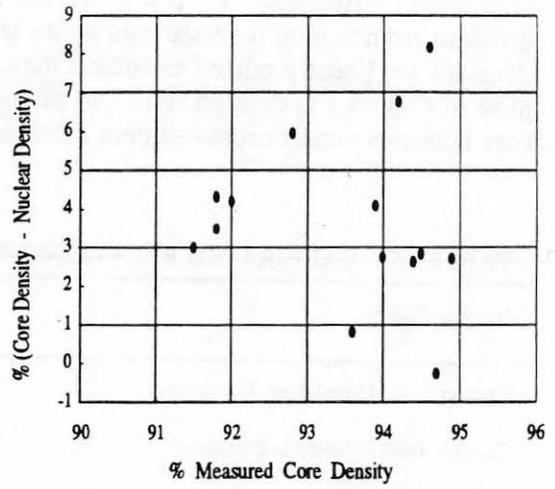
where:

- μ_1 = population mean of core density measurements;
- μ_2 = population mean of nuclear density measurements;
- n = sample size (number of paired observations);
- s_D = sample standard deviation of the differences between core and nuclear density measurements; and
- D = sample mean of the differences between core and nuclear density measurements.

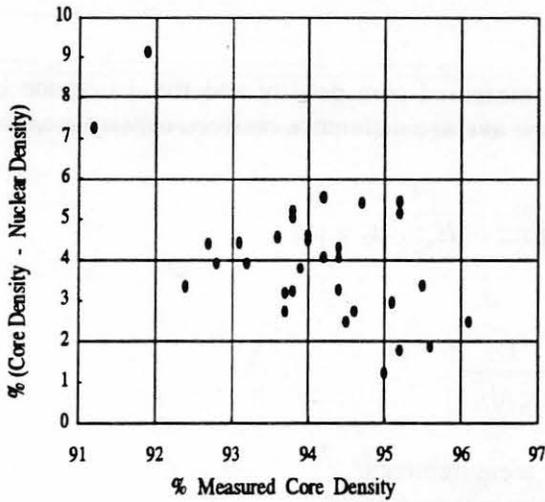
For a desired confidence level ($1 - \alpha$), the computed t-value given by equation 28 is compared with a critical t-value corresponding to $n - 1$ degrees of freedom ($t_{\alpha/2, df}$). If the absolute value of the



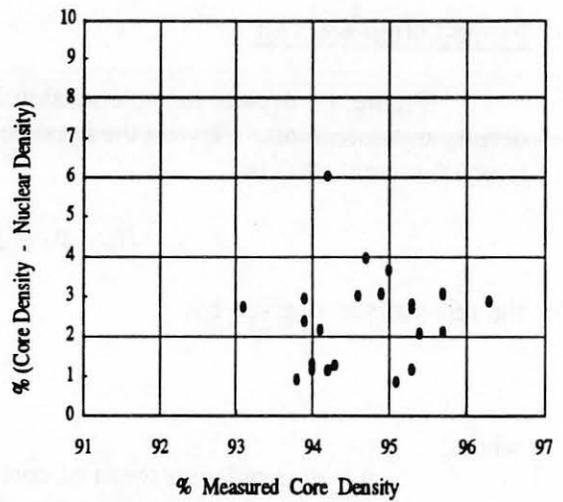
Troxler 3440 - Muskogee Residency



Troxler 4640 - Materials Division



Seamon C200 - Cummins Construction



Troxler 3440 - Cummins Construction

Figure 17. Core Density versus Difference between Core and Nuclear Densities

computed t-statistic is less than $t_{\alpha/2, df}$, H_o is not rejected. Otherwise, H_a is accepted and H_o is rejected. Table 16 summarizes the results of hypothesis testing.

TABLE 16. HYPOTHESIS TESTING RESULTS, PAIRED COMPARISONS

Nuclear Gauge	N ⁽¹⁾	D %	S _D %	t-value	Conclusion ⁽²⁾
Troxler 3440 (Muskogee Residency)	32	4.446	1.213	20.74	Accept H_a
Troxler 4640 (Materials Division)	32	4.031	1.575	14.48	Accept H_a
Seamon C200 (Cummins Const.)	14	3.664	2.212	6.20	Accept H_a
Troxler 3440 (Cummins Const.)	22	2.419	1.218	9.31	Accept H_a

- 1 N = number of observations
 2 $H_o: \mu_1 = \mu_2$
 $H_a: \mu_1 \neq \mu_2$
 Level of Confidence = 95%

CHAPTER 6

EVALUATION OF NUCLEAR ASPHALT CONTENT GAUGE

This chapter presents a comparison between measurements of asphalt content obtained using the centrifuge extraction method and the nuclear gauge method. Statistical analyses were performed to model the relationship between the two methods and to draw inferences concerning the differences between them.

SIGNIFICANCE OF ASPHALT CONTENT

The physical properties and relative proportions of asphalt cement and aggregate influence the pavement performance throughout its design life, provided that pavement has been properly compacted. Asphalt content affects the voids, stability, and thickness of the asphalt film coating the aggregate in a bituminous paving mixture. A mixture with low asphalt content is not durable, and one with high asphalt content is not stable. Improper asphalt content of a mixture can result from a number of factors related to the production process (inaccurate scales and measuring devices, poor maintenance at the production plant, segregation) as well as sampling and testing errors.

MEASUREMENT OF ASPHALT CONTENT

Asphalt content determination methods may be grouped into three categories: 1) solvent extraction, 2) nuclear gauges, and 3) automatic recordation. A survey conducted by the National Asphalt Paving Association in 1988 indicated that 28 states used solvent extraction method, 3 states used the nuclear gauge method, and seven states used the automatic recordation method exclusively for measuring asphalt content. Twelve other states used different combinations of the three methods [16].

Solvent extraction methods (centrifuge, reflux, and vacuum) utilize chemical solvents to dissolve the asphalt cement from the aggregate in a sample of the bituminous mixture. The mass of the asphalt cement removed by the solvent is determined from the total mass of the sample minus the mass of moisture, aggregate, and mineral matter. One advantage of the extraction methods is that they allow determination of the aggregate gradation following the extraction of asphalt cement. Nevertheless, the traditional chemical solvents used in the extraction test include chlorinated hydrocarbons which are toxic and difficult to dispose. Biodegradable solvents are being used by some states but they require modifications of the extraction procedures to maintain the accuracy levels provided by the traditional solvents [19].

The nuclear gauge method measures asphalt content by noting the presence of hydrogen in a sample of bituminous mixture. A radioactive source emits neutrons that pass through the sample to a detector which collects those neutrons that have been thermalized by collision with hydrogen atoms in the asphalt cement. The count of thermalized neutrons is directly proportional to the amount of hydrogen

present in the bituminous mixture sample. Asphalt content is determined by means of calibration curves that permit comparing the count recorded by the gauge with counts obtained from reference samples with known asphalt content. Since hydrogen is present in both water and asphalt cement, the moisture content of the sample is subtracted directly from the percent of asphalt in the sample. Use of the nuclear gauge method allows for increasing the frequency of asphalt content determinations for both quality control and acceptance purposes. Nevertheless, aggregate gradation can not be determined from the sample of bituminous mixture as in the case of solvent extraction methods. Cold feed gradation tests can be performed on the aggregate separately to supplement the nuclear gauge results and obtain a complete picture of the composition of the mixture.

A recent state-of-practice report published by the FHWA noted that the accuracy and variability of both the solvent extraction and the nuclear gauge methods are similar [19]. The report concluded that replacing the solvent extraction procedures by the nuclear gauge improves the reliability of asphalt content determination.

Asphalt content measurement by automatic recordation employs computer equipment at the production plant to obtain direct readings of the weights of asphalt being metered to the mixture. This method provides a good overall check on the average asphalt content, but it does not provide direct indication of the amount of asphalt cement added to a particular batch of the material being produced by a drum mix plant. In addition, aggregate gradation cannot be performed on samples of the mixture without an extraction procedure.

TEST RESULTS

As discussed in Chapter 3, sample units of the freshly mixed bituminous concrete were obtained from the hauling trucks containing the preselected random tonnage according to *AASHTO T168-90* [1]. Two sample-units, each having a minimum mass of 90 lb (40 kg), were selected from each subplot. The sample units were labeled and transferred to the different laboratories where they were tested for asphalt content using: 1) the centrifuge extraction method (OHD L-26), and 2) the Troxler 3241-C nuclear gauge method. Summary of the test results is given in Tables A-21 and A-22 (Appendix A).

STATISTICAL ANALYSES

Regression Analysis

Figure 18 presents scatter plot of the asphalt content measurements. Linear regression analysis was used to determine the equations of the straight lines which best fit the data based on the principle of least squares. The calibrated relationship is given by:

$$Y = 1.664 + 0.559 X \quad (29)$$

where Y is the expected value of the extracted asphalt content and X is the nuclear gauge asphalt content. This relationship is shown on the scatter plot of Figure 18. The coefficient of correlation

is 0.63 ($R^2 = 0.40$) and the standard error of the estimate is 0.24.

Hypothesis testing concerning the regression coefficient ($H_o: \beta = 0$ versus $H_a: \beta \neq 0$) indicated that the slope of the regression line is significantly different from zero at the 95% confidence level. In other words, there is evidence to indicate that asphalt content measurements using the extraction test and the nuclear gauge are linearly related.

Paired-Difference Test

Figure 19 depicts the relationship between extracted asphalt content and the difference between asphalt content by extraction and the nuclear gauge. To test the hypothesis that the average difference between density measurements is equal to zero, that is,

$$H_o: \mu_1 = \mu_2 \quad \text{against} \quad H_a: \mu_1 \neq \mu_2$$

the computed t-value given by equation 28 is 0.41 ($\bar{D} = 0.0123$, $S_D = 0.283$, and $df = 87$). Therefore, the null hypothesis H_o is not rejected, i.e., there is no significant difference between the average asphalt contents obtained from the extraction test and the nuclear gauge at the 95% confidence level.



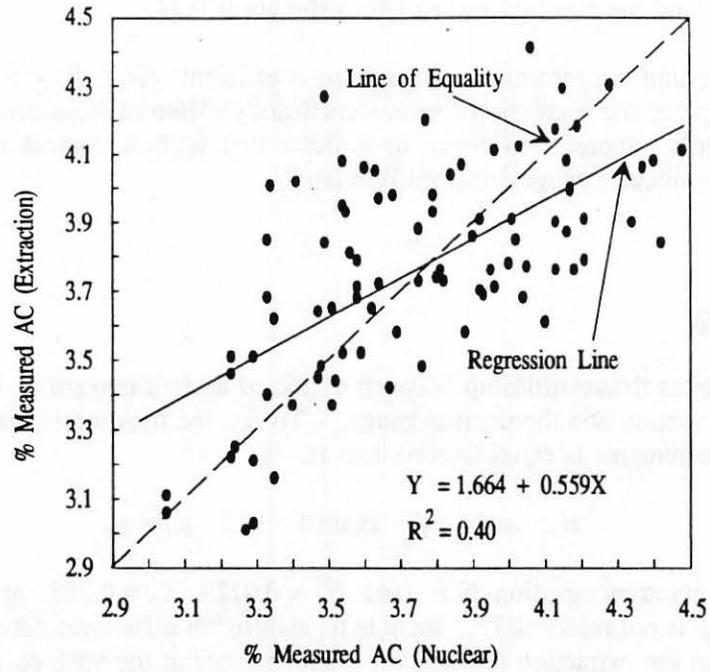


Figure 18. Extracted AC versus Nuclear AC

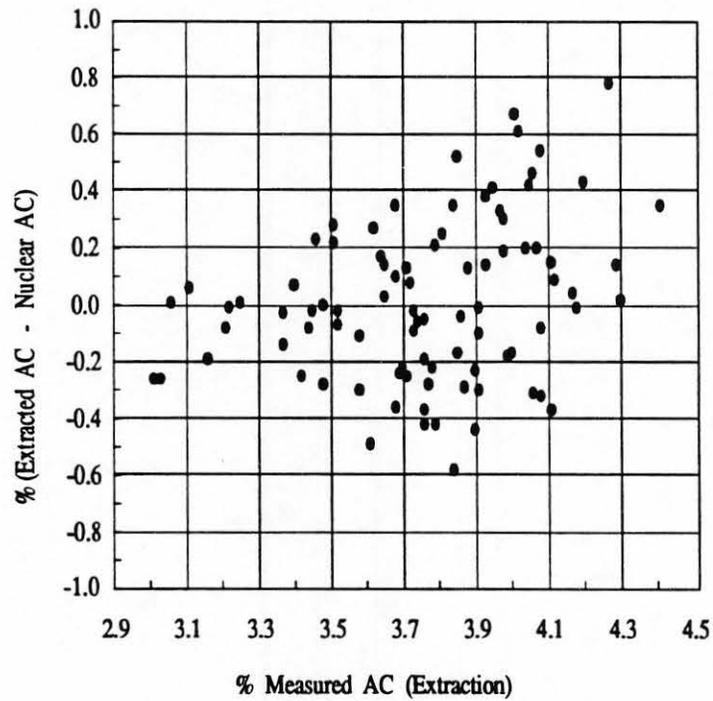


Figure 19. Extracted AC versus Difference between Extracted AC and Nuclear AC

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Components of Variance

Sampling and testing variances represent a significant portion of the total observed variance in the measured quality attributes of bituminous concrete pavement construction. Analysis of variance results indicated that the combined contributions of testing and sampling to the total observed variation were in the following ranges:

- Aggregate gradation from cold feed samples: 76% to 88% for sieves No. 4 and larger, 67 to 91% for sieves No. 10 through No. 80, and 43% for sieve No. 200.
- Aggregate gradation from bituminous mixture samples: 75% to 94% for sieves No. 4 and larger, 46 to 59% for sieves No. 10 through No. 80, and 48% for sieve No. 200.
- Asphalt Content: 59% for the solvent extraction method and 32% for the nuclear gauge method.
- Air Voids and Stability: 46% and 31%, respectively.
- In-Place Density: 77% for the core method and 56% for the nuclear gauge method.

Variation due to sampling and testing can be reduced by taking the average of several test results, improving sampling and testing methods, and proper training of personnel performing control and acceptance tests.

Specification Compliance

Percent within JMF Tolerances

The computed percentages within JMF tolerances indicated lower percentages than expected for asphalt content, air voids, and in-place density. In addition, there was good as well as poor agreements between the computed percentages within tolerances for aggregate gradation using the cold feed samples and bituminous mixture samples. Cold feed aggregate samples showed that 79.3% and 89.1% of aggregates passing sieves No. 10 and No. 200 were within limits, whereas the percentages determined from bituminous mixture samples were 94.6% and 100%, respectively. Similarly, the percent within tolerances for the aggregate passing sieves 1/2" and No. 4 were 72.8% and 85.9%, respectively, for

bituminous mixture samples, compared to 90.2% and 96.7%, respectively, for cold feed aggregate samples.

Values of the conformance indices were higher than expected, particularly for aggregate passing sieves 3/4", 1/2", and No. 4. This would normally be interpreted as a shift of the process average from the target value. Nevertheless, the large variances due to sampling and testing prevent a true evaluation of material and process variation.

Percent within QA/QC Specification Tolerances

The computed percentages within QA/QC specification tolerances indicated that the present tolerances are practical and defensible. The only exception is tolerances for in-place density measured using the nuclear gauge. Good as well as poor agreements exist between the computed percentages within QA/QC tolerances for aggregate gradation using the cold feed samples and bituminous mixture samples.

A clear delineation of responsibility should result in a more uniform product. Quality control should be assigned to the contractor who has actual control of construction materials and processes. Acceptance should be based on samples obtained at random to have a representative picture of the entire lot.

Nuclear Density Gauge

Correlations between individual density measurements obtained from the nuclear gauge and core samples ranged from 0.49 to 0.84. A larger percentage of total variability due to sampling and testing was exhibited by the core method than the nuclear gauge method. Although the averages of density measurements using both methods were significantly different, the use of calibrated relationships through regression analysis improved the estimation of core densities from nuclear measurements. Findings of the literature review indicated that with proper field calibration, gauge seating, and multiple readings, the nuclear gauges are capable of measuring the density of thin lifts with acceptable degree of accuracy.

Nuclear Asphalt Content Gauge

Variability due to testing was less with the nuclear gauge method than the solvent extraction method. The correlation coefficient between individual asphalt content measurements using the extraction method and the nuclear gauge method was 0.63. No significant difference was found between the average asphalt content obtained from the extraction method and the average asphalt content obtained using the nuclear gauge method. Use of the nuclear gauge method allows for increasing the frequency of asphalt content determinations and eliminates the toxic solvents required by the extraction method. Aggregate gradation from cold feed samples can be used to supplement the results of the nuclear gauge and obtain a complete picture of the composition of the bituminous mixture.

RECOMMENDATIONS

- The conclusions presented in this chapter are based on measurements of quality attributes obtained from one construction project. As called for in the sampling and testing program, data should be obtained from three additional projects to have a good representation of the variability in acceptable bituminous concrete pavement materials and construction in Oklahoma.
- More data should be collected to permit a thorough evaluation of the nuclear density gauge and the nuclear asphalt content gauge.
- Although the allowable deviations used in the current QA/QC specifications are practical and defensible, this method of determining pay factors is somewhat empirical and has no statistical basis. The percent within limits method outlined in the *AASHTO R9-90* [1] is recommended for use by ODOT.
- The large variances due to sampling and testing can be reduced by improving the skills of both ODOT and contractor's personnel through training.

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APPENDIX A

**TEST RESULTS
US-412 PROJECT**

TABLE A-1. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 1 1/2 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	100.00	100.00	100.00	100.00
2	100.00	100.00	100.00	100.00
3	100.00	100.00	100.00	100.00
4	100.00	100.00	100.00	100.00
5	100.00	100.00	100.00	100.00
6	100.00	100.00	100.00	100.00
7	100.00	100.00	100.00	100.00
8	100.00	100.00	100.00	100.00
9	100.00	100.00	100.00	100.00
10	100.00	100.00	100.00	100.00
11	100.00	100.00	100.00	100.00
12	100.00	100.00	100.00	100.00
13	100.00	100.00	100.00	100.00
14	100.00	100.00	100.00	100.00
15	100.00	100.00	100.00	100.00
16	100.00	100.00	100.00	100.00
17	100.00	100.00	100.00	100.00
18	100.00	100.00	100.00	100.00
19	100.00	100.00	100.00	100.00
20	100.00	100.00	100.00	100.00
21	100.00	100.00	100.00	100.00
22	100.00	100.00	100.00	100.00
23	100.00	100.00	100.00	100.00

TABLE A-2. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 1 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	98.70	98.80	100.00	96.60
2	97.60	96.60	96.60	97.60
3	98.40	95.10	97.50	95.60
4	97.40	97.20	96.80	97.90
5	94.80	96.70	97.10	95.30
6	97.00	98.40	98.10	97.40
7	98.30	99.20	97.20	98.00
8	97.80	97.50	99.00	97.70
9	99.00	99.40	96.90	97.00
10	99.30	98.60	99.10	97.40
11	98.80	97.40	97.50	99.20
12	98.60	96.60	97.60	95.80
13	100.00	100.00	100.00	98.60
14	97.40	99.10	96.80	96.10
15	97.60	96.40	97.10	98.40
16	96.40	98.80	98.30	98.70
17	99.40	96.50	98.60	98.40
18	99.10	99.10	98.70	98.90
19	98.20	95.60	98.60	97.70
20	98.00	97.60	97.30	97.70
21	97.50	98.00	98.60	97.70
22	96.60	98.10	98.30	98.50
23	97.20	95.20	100.00	98.00

Table A-3. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 3/4 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	86.40	92.40	85.40	86.40
2	83.10	81.10	84.50	88.30
3	89.40	84.90	88.30	89.00
4	85.80	85.20	87.90	87.60
5	81.70	83.10	84.30	83.20
6	79.60	90.90	84.20	83.30
7	88.50	90.10	86.40	90.80
8	89.20	89.20	86.70	88.40
9	90.40	92.00	85.40	86.00
10	92.40	89.60	84.80	86.40
11	88.30	85.90	84.20	89.80
12	83.00	82.90	84.60	88.20
13	88.40	92.00	91.80	88.00
14	88.70	86.10	85.80	82.60
15	87.40	85.40	86.00	88.20
16	86.10	89.20	86.60	88.50
17	91.50	85.70	91.80	85.60
18	87.90	86.50	84.30	85.10
19	86.00	87.50	86.50	88.50
20	88.70	87.20	87.00	89.20
21	86.00	88.40	87.30	88.20
22	90.70	89.30	91.30	89.20
23	81.20	88.70	88.90	88.80

TABLE A-4. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 1/2 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	68.20	76.40	70.70	70.10
2	60.80	61.00	63.40	66.30
3	73.20	59.20	70.50	66.60
4	65.60	65.50	65.90	67.00
5	61.80	61.20	62.10	62.40
6	57.30	73.00	63.80	62.50
7	72.00	73.90	65.50	75.50
8	69.80	73.80	71.20	71.70
9	71.30	75.30	66.30	62.20
10	73.40	73.10	62.50	68.70
11	67.30	66.80	60.90	71.30
12	67.70	68.10	64.50	62.90
13	67.30	69.60	73.70	67.70
14	67.80	69.30	68.10	63.00
15	70.80	65.80	66.50	68.10
16	68.30	73.50	68.80	71.90
17	76.10	64.70	74.70	65.10
18	68.10	69.80	61.90	67.60
19	63.00	66.80	59.50	68.90
20	68.10	66.90	65.30	72.70
21	65.90	72.60	68.10	73.60
22	71.00	69.90	69.90	69.90
23	59.90	69.50	65.90	64.60

TABLE A-5. US-412 PROJECT, COLD FEED AGGREGATE SAMLES - SIEVE: 3/8 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	56.80	65.70	59.90	59.60
2	49.90	51.10	51.30	53.50
3	62.10	49.20	58.40	55.50
4	53.60	53.40	54.10	55.90
5	52.60	52.40	50.90	51.80
6	44.70	62.20	51.20	49.90
7	60.80	61.90	52.30	63.70
8	56.40	62.60	59.80	58.60
9	57.80	62.70	53.40	48.50
10	60.60	60.60	49.90	57.80
11	54.20	53.30	47.40	57.40
12	55.60	53.80	52.10	51.60
13	53.70	60.40	60.00	54.90
14	55.40	57.10	56.90	53.60
15	60.60	54.00	54.70	56.50
16	54.50	61.30	54.10	58.30
17	63.00	51.70	63.70	52.00
18	56.70	57.50	49.40	55.10
19	49.80	53.30	46.30	57.40
20	57.50	56.00	54.60	59.70
21	52.20	59.20	54.20	61.10
22	60.30	56.20	57.50	58.00
23	49.10	60.50	54.10	52.50

TABLE A-6. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 4

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	36.30	40.50	37.00	34.90
2	31.30	33.60	30.70	32.80
3	38.30	30.70	35.20	32.00
4	31.70	31.60	32.00	33.90
5	33.30	33.50	31.90	33.40
6	24.30	39.10	30.70	30.60
7	37.90	38.00	30.40	40.60
8	35.50	42.60	40.70	36.80
9	34.50	39.70	32.00	25.50
10	35.00	35.60	29.10	35.80
11	32.50	31.80	27.60	35.00
12	34.70	33.40	33.20	32.00
13	33.50	37.00	34.70	32.00
14	32.80	34.70	34.10	32.70
15	39.40	33.10	32.50	35.50
16	32.60	40.20	30.10	35.10
17	36.70	28.50	38.70	28.80
18	35.10	33.40	29.30	33.20
19	30.30	32.00	28.00	36.00
20	36.60	34.80	32.90	37.80
21	30.70	36.50	31.50	39.90
22	37.40	34.60	33.10	35.10
23	30.60	39.50	33.30	32.30

TABLE A-7. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 10

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	25.90	27.50	26.30	24.00
2	21.60	23.60	20.50	22.40
3	26.70	20.40	25.10	21.10
4	20.90	21.60	22.70	23.80
5	22.60	22.90	21.60	22.80
6	17.50	30.70	21.40	20.90
7	26.20	25.80	21.50	29.50
8	24.70	30.50	29.20	25.10
9	23.80	29.20	22.10	16.70
10	23.70	24.30	18.80	25.60
11	22.20	21.60	18.60	24.00
12	22.80	22.60	23.30	21.50
13	22.80	25.70	25.10	23.70
14	22.00	24.30	23.10	22.60
15	27.40	22.10	22.10	24.70
16	22.90	29.00	20.60	24.70
17	25.50	19.20	27.30	19.70
18	24.40	23.80	21.20	23.50
19	20.80	21.70	19.80	24.10
20	26.10	24.20	22.80	25.50
21	19.90	24.40	21.50	27.90
22	26.10	24.20	21.80	24.20
23	21.20	27.80	23.50	22.60

TABLE A-8. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 40

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	16.40	17.10	16.60	15.10
2	13.80	15.00	13.10	14.50
3	16.40	12.90	16.10	13.20
4	13.40	13.90	14.10	15.20
5	13.00	13.30	12.60	13.20
6	9.40	18.60	13.20	12.10
7	15.00	14.50	13.80	18.40
8	16.00	18.80	17.80	15.00
9	15.90	19.00	13.60	10.40
10	14.10	13.50	12.20	14.80
11	14.30	13.70	12.20	15.60
12	14.00	14.30	15.20	13.70
13	14.90	16.80	17.20	16.50
14	13.00	15.10	13.90	13.80
15	16.90	14.10	14.80	16.40
16	14.10	18.10	13.40	15.90
17	15.90	12.00	16.60	12.30
18	15.50	15.50	14.00	15.30
19	13.60	14.00	13.50	15.40
20	16.70	14.40	13.50	15.30
21	12.60	15.20	13.70	17.80
22	17.30	16.00	13.90	15.60
23	12.30	15.80	13.60	13.10

TABLE A-9. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 80

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	7.90	7.90	7.00	6.80
2	6.30	6.60	6.00	6.60
3	7.70	6.70	7.20	6.50
4	7.20	7.20	7.20	8.00
5	5.20	5.20	5.10	5.50
6	4.80	7.90	6.20	5.10
7	6.50	6.20	6.10	7.40
8	8.00	7.00	6.60	6.00
9	7.40	8.10	7.40	4.60
10	6.30	5.60	5.70	6.50
11	6.80	6.30	6.20	7.10
12	6.10	6.50	6.90	6.60
13	7.20	7.90	7.50	7.00
14	5.80	6.90	6.00	6.10
15	7.60	6.50	7.80	8.40
16	6.40	8.10	6.70	7.70
17	8.00	6.00	6.80	6.40
18	7.20	7.30	6.80	7.00
19	6.10	5.50	6.40	7.60
20	7.70	7.90	6.80	6.80
21	6.00	6.90	5.90	7.40
22	8.60	8.00	7.10	8.10
23	6.70	8.10	7.10	7.20

TABLE A-10. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 200

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	3.38	3.83	3.40	3.10
2	2.88	3.18	2.80	3.06
3	3.10	2.89	2.86	2.76
4	2.98	2.75	2.75	3.19
5	2.24	2.11	2.08	2.27
6	1.60	2.39	2.02	1.80
7	2.80	2.95	2.73	3.54
8	4.22	1.60	2.06	1.42
9	3.55	3.66	1.52	1.85
10	1.36	0.79	1.69	1.87
11	3.65	3.25	3.33	3.68
12	2.65	2.86	3.36	3.11
13	3.20	3.43	2.72	2.36
14	2.47	2.78	2.43	2.23
15	2.55	2.13	3.02	2.91
16	2.75	3.42	3.22	3.49
17	3.43	2.86	2.89	2.62
18	3.48	3.64	3.47	3.36
19	3.67	3.95	4.32	4.67
20	4.01	4.38	3.75	3.58
21	3.09	3.42	3.30	3.88
22	4.01	3.86	3.44	4.10
23	3.20	3.70	3.30	3.49

TABLE A-11. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 1 1/2 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	100.00	100.00	100.00	100.00
2	100.00	100.00	100.00	100.00
3	100.00	100.00	100.00	100.00
4	100.00	100.00	100.00	100.00
5	100.00	100.00	100.00	100.00
6	100.00	100.00	100.00	100.00
7	100.00	100.00	100.00	100.00
8	100.00	100.00	100.00	100.00
9	100.00	100.00	100.00	100.00
10	100.00	100.00	100.00	100.00
11	100.00	100.00	100.00	100.00
12	100.00	100.00	100.00	100.00
13	100.00	100.00	100.00	100.00
14	100.00	100.00	100.00	100.00
15	100.00	100.00	100.00	100.00
16	100.00	100.00	100.00	100.00
17	100.00	100.00	100.00	100.00
18	100.00	100.00	100.00	100.00
19	100.00	100.00	100.00	100.00
20	100.00	100.00	100.00	100.00
21	100.00	100.00	100.00	100.00
22	100.00	100.00	100.00	100.00
23	100.00	100.00	100.00	100.00

TABLE A-12. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 1 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	96.90	100.00	97.00	98.60
2	97.70	97.60	95.70	99.00
3	98.20	97.00	97.20	96.20
4	100.00	100.00	97.60	100.00
5	100.00	98.70	97.90	93.90
6	96.20	98.60	98.20	98.30
7	97.50	98.90	100.00	97.20
8	100.00	95.30	98.60	97.10
9	100.00	97.40	99.00	97.80
10	98.40	98.20	100.00	93.90
11	100.00	98.60	100.00	95.30
12	98.30	100.00	100.00	100.00
13	100.00	100.00	100.00	100.00
14	100.00	100.00	98.40	98.30
15	99.00	100.00	100.00	100.00
16	97.10	97.80	100.00	100.00
17	100.00	98.30	98.60	98.30
18	100.00	94.20	100.00	100.00
19	98.90	93.90	98.70	95.80
20	97.90	100.00	94.50	98.70
21	96.20	96.80	98.50	100.00
22	100.00	100.00	100.00	100.00
23	98.50	97.10	100.00	100.00

TABLE A-13. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 3/4 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	81.40	90.40	89.90	91.00
2	89.00	88.00	84.30	90.30
3	88.20	89.90	88.30	89.00
4	87.90	92.10	88.20	93.40
5	89.80	90.10	85.30	87.00
6	82.10	86.40	89.70	88.20
7	89.90	84.50	90.80	83.20
8	89.50	83.40	87.60	88.80
9	94.90	82.00	87.40	89.20
10	93.80	82.80	90.00	88.60
11	93.80	94.90	91.90	86.20
12	93.40	86.80	86.50	88.80
13	87.50	90.40	91.40	94.90
14	87.00	94.70	91.70	90.80
15	92.30	94.90	96.60	94.40
16	88.40	86.90	91.30	94.00
17	90.90	86.80	85.70	89.40
18	94.50	79.70	90.10	94.80
19	96.00	85.80	94.20	85.70
20	92.40	88.90	86.10	84.80
21	85.90	86.40	88.80	84.20
22	94.40	92.70	95.40	98.70
23	91.10	88.40	94.00	96.70

TABLE A-14. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 1/2 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	64.10	65.20	67.50	70.40
2	72.60	72.80	68.70	70.80
3	71.40	71.60	69.90	69.60
4	70.80	79.50	68.40	72.70
5	71.10	70.30	67.50	69.20
6	64.10	67.30	71.20	69.50
7	69.00	69.00	73.70	66.70
8	69.40	68.70	70.80	69.20
9	79.60	64.20	68.30	73.80
10	74.50	64.20	71.60	69.30
11	73.70	77.00	78.80	65.30
12	77.40	68.20	74.00	69.60
13	63.70	64.40	74.50	74.10
14	71.60	78.50	76.00	72.30
15	78.20	81.30	80.40	73.90
16	72.10	71.80	75.70	74.40
17	72.40	69.50	67.80	71.70
18	70.40	66.50	72.20	78.20
19	78.60	71.10	74.10	60.50
20	75.00	72.20	65.30	63.90
21	66.30	68.10	74.10	69.00
22	75.00	72.60	78.60	77.70
23	68.00	66.20	76.80	77.90

TABLE A-15. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 3/8 inch

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	47.90	50.30	54.20	56.70
2	59.70	61.10	59.00	59.40
3	59.80	59.80	58.10	58.90
4	57.70	67.10	57.00	60.50
5	58.90	57.00	55.40	55.00
6	53.40	56.50	60.40	55.50
7	59.30	59.40	61.30	55.70
8	56.90	55.80	57.00	55.50
9	67.70	53.30	56.50	60.40
10	63.40	55.70	60.20	61.30
11	61.80	62.30	65.60	54.60
12	64.20	56.90	59.90	54.60
13	51.80	54.00	63.00	64.30
14	61.40	66.50	64.00	62.20
15	65.80	68.90	65.40	61.40
16	62.20	63.20	65.00	64.90
17	61.10	56.60	58.70	60.50
18	61.10	55.30	62.60	63.10
19	66.60	57.90	62.10	45.40
20	64.90	58.70	53.60	50.80
21	55.90	59.60	64.50	57.20
22	63.60	63.20	65.80	65.50
23	55.90	56.90	67.20	66.10

TABLE A-16. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 4

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	29.00	28.10	31.70	33.40
2	39.30	40.10	39.60	38.10
3	37.90	37.70	38.20	38.20
4	36.00	41.60	36.50	37.60
5	36.70	35.20	34.00	33.10
6	33.60	35.10	37.10	36.00
7	38.30	38.70	40.20	35.40
8	36.70	34.60	37.60	35.90
9	44.50	35.70	37.10	37.90
10	39.40	37.00	37.90	39.40
11	39.40	40.30	41.80	34.70
12	40.40	36.70	36.80	35.00
13	32.40	33.70	38.30	39.50
14	39.90	41.80	40.10	39.30
15	41.50	42.80	38.90	37.10
16	40.60	41.00	41.50	43.30
17	37.30	36.50	37.00	37.70
18	37.30	34.00	40.00	40.70
19	41.40	37.80	37.90	27.00
20	42.30	37.30	32.90	31.70
21	38.50	40.50	40.70	37.10
22	41.30	41.80	40.60	40.90
23	34.00	35.70	41.50	40.40

TABLE A-17. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 10

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	19.40	19.30	20.40	21.30
2	26.40	26.90	26.80	25.90
3	24.80	25.00	25.70	25.80
4	24.00	27.60	24.80	25.60
5	24.90	24.50	22.80	22.70
6	22.40	23.70	24.70	24.10
7	25.10	25.30	26.90	24.00
8	24.90	23.40	25.50	24.60
9	28.10	23.50	24.40	24.80
10	26.40	25.10	25.80	26.30
11	26.80	27.10	27.90	23.50
12	26.40	24.30	24.40	23.30
13	21.80	22.40	25.50	26.20
14	26.70	27.90	26.90	26.60
15	28.40	29.50	27.20	26.00
16	27.00	27.00	27.40	28.50
17	24.70	24.20	24.60	25.00
18	25.40	23.40	26.10	27.30
19	27.20	25.10	24.80	18.50
20	26.60	24.30	21.90	21.00
21	25.80	26.60	26.40	24.30
22	27.60	27.70	26.80	27.20
23	23.10	26.20	27.80	26.00

TABLE A-18. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 40

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	12.10	12.20	12.40	13.10
2	16.00	16.00	15.90	15.70
3	14.90	15.10	15.40	15.50
4	16.40	18.40	16.50	17.50
5	16.00	15.60	13.70	14.00
6	12.70	13.50	13.50	13.10
7	14.30	14.40	15.40	14.10
8	15.30	14.20	15.50	14.90
9	17.00	14.50	15.10	15.40
10	16.20	15.10	15.50	15.90
11	16.40	16.60	16.70	14.40
12	16.30	15.10	15.10	14.70
13	13.60	13.90	15.70	16.20
14	15.60	16.40	15.90	15.60
15	17.50	17.90	17.10	16.30
16	15.60	15.50	16.30	16.90
17	15.40	15.10	14.10	14.50
18	15.50	14.50	15.40	16.20
19	16.40	15.10	15.50	12.00
20	15.90	14.90	13.60	13.00
21	15.40	16.60	16.10	14.80
22	16.80	16.50	16.40	16.60
23	13.20	13.50	15.30	14.30

TABLE A-19. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 80

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	6.40	6.40	6.50	6.90
2	8.00	8.10	7.90	8.00
3	7.90	8.00	8.10	8.10
4	8.70	9.50	8.50	9.40
5	8.90	8.00	6.20	6.60
6	6.40	6.90	7.00	6.60
7	7.00	7.00	6.90	6.50
8	7.20	6.60	7.40	7.00
9	7.80	6.90	7.00	7.20
10	8.70	8.10	8.20	8.30
11	8.00	8.00	7.70	6.90
12	8.20	7.70	7.80	7.60
13	7.10	7.40	8.20	8.50
14	7.60	8.00	7.90	7.70
15	9.00	9.00	8.90	8.40
16	7.30	7.10	7.90	8.40
17	8.00	7.80	6.60	7.00
18	7.30	7.00	7.30	7.80
19	8.20	7.60	7.80	5.90
20	8.20	7.70	6.90	6.60
21	7.70	7.80	8.10	7.30
22	8.60	8.40	8.50	8.60
23	7.70	8.00	8.70	7.70

TABLE A-20. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 200

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	3.40	3.38	3.39	3.56
2	3.14	3.61	3.37	3.83
3	3.47	3.42	3.48	3.64
4	4.25	4.54	3.95	4.57
5	4.65	4.93	2.92	3.38
6	2.23	2.49	2.67	2.42
7	3.24	3.21	2.88	2.83
8	3.56	3.27	3.89	3.57
9	3.92	3.35	3.44	3.52
10	3.84	3.59	3.53	3.57
11	4.05	3.98	3.82	3.44
12	4.34	3.97	4.08	3.88
13	3.50	3.79	4.18	4.36
14	3.39	3.59	3.67	3.02
15	4.37	4.17	4.12	3.89
16	2.94	2.82	3.39	3.80
17	4.02	3.94	3.05	3.17
18	3.69	3.69	3.75	3.96
19	5.23	5.47	5.19	4.07
20	4.63	3.98	3.77	3.50
21	3.93	3.58	4.23	3.92
22	4.41	4.14	4.30	4.52
23	3.90	3.60	4.23	4.50

TABLE A-21. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - % AC (EXTRACTION)

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	3.21	3.11	3.40	3.51
2	3.90	3.91	3.68	3.70
3	4.00	3.86	4.12	3.76
4	3.52	4.02	3.68	3.62
5	3.16	3.22	3.03	3.01
6	3.51	3.52	3.61	3.65
7	3.64	3.65	3.84	3.48
8	3.73	3.42	3.52	3.58
9	4.27	3.48	3.65	3.72
10	4.07	3.74	4.04	4.20
11	3.76	3.99	4.17	3.71
12	4.01	3.85	3.46	3.51
13	3.25	3.37	3.98	4.05
14	3.85	4.11	3.76	3.61
15	3.90	4.41	3.95	3.93
16	3.81	4.08	4.06	3.88
17	3.93	3.73	3.79	3.84
18	3.71	3.45	3.68	3.79
19	4.18	3.76	3.91	3.06
20	3.97	3.58	3.37	3.44
21	3.77	3.78	3.98	3.69
22	4.08	4.11	4.08	4.06
23	3.91	3.87	4.29	4.30

TABLE A-22. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - % AC (NUCLEAR)

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	3.29	3.05	3.33	3.29
2	4.13	4.01	4.04	3.92
3	4.17	3.90	4.03	4.13
4	3.54	3.41	3.33	3.35
5	3.35	3.23	3.29	3.27
6	3.47	3.51	3.49	3.48
7	3.82	3.67	3.59	3.69
8	3.49	3.76	3.62	3.64
9	3.87	3.80	3.84	3.77
10	3.95	4.17	4.13	3.96
11	3.34	3.33	3.23	3.23
12	3.24	3.40	3.68	3.63
13	4.02	3.96	4.18	4.10
14	4.34	4.06	3.54	3.55
15	3.56	3.54	3.60	3.75
16	3.79	3.75	4.21	4.42
17	3.58	3.47	3.58	3.58
18	4.19	3.81	3.92	3.05
19	3.64	3.88	3.51	3.52
20	4.05	4.00	3.79	3.93
21	4.40	4.48	4.16	4.37
22	4.21	4.16	4.15	4.28

TABLE A-23. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - AVERAGE RICES

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	2.51	2.53	2.49	2.46
2	2.47	2.47	2.48	2.49
3	2.48	2.48	2.47	2.48
4	2.50	2.50	2.49	2.49
5	2.54	2.56	2.54	2.54
6	2.51	2.51	2.50	2.50
7	2.51	2.50	2.53	2.53
8	2.51	2.50	2.50	2.50
9	2.50	2.50	2.51	2.50
10	2.48	2.49	2.47	2.47
11	2.51	2.51	2.49	2.51
12	2.51	2.52	2.51	2.52
13	2.52	2.52	2.49	2.49
14	2.50	2.49	2.49	2.50
15	2.48	2.48	2.50	2.50
16	2.49	2.50	2.49	2.49
17	2.50	2.50	2.49	2.48
18	2.54	2.52	2.50	2.53
19	2.54	2.51	2.48	2.46
20	2.50	2.49	2.51	2.50
21	2.48	2.48	2.53	2.53
22	2.49	2.49	2.50	2.49
23	2.50	2.49	2.49	2.50

TABLE A-24. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SPECIFIC GRAVITY

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	2.37 2
1	2.37	2.38	2.35	2.37
2	2.37	2.36	2.36	2.37
3	2.37	2.37	2.39	2.36
4	2.39	2.39	2.39	2.40
5	2.39	2.37	2.32	2.33
6	2.38	2.38	2.37	2.37
7	2.36	2.36	2.36	2.36
8	2.36	2.37	2.36	2.37
9	2.38	2.38	2.37	2.38
10	2.37	2.35	2.36	2.35
11	2.38	2.38	2.38	2.35
12	2.40	2.39	2.39	2.38
13	2.38	2.39	2.38	2.39
14	2.37	2.37	2.37	2.37
15	2.36	2.37	2.37	2.36
16	2.39	2.39	2.36	2.37
17	2.18	2.20	2.32	2.31
18	2.38	2.40	2.40	2.40
19	2.39	2.40	2.41	2.40
20	2.38	2.38	2.37	2.37
21	2.37	2.37	2.37	2.37
22	2.39	2.38	2.37	2.37

TABLE A-25. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - % AIR VOIDS

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	5.45	5.58	5.83	4.04
2	4.32	4.49	4.96	4.99
3	4.37	4.62	3.24	4.78
4	4.46	4.53	4.33	3.93
5	6.02	7.37	8.97	8.16
6	5.17	5.35	5.49	5.31
7	5.95	5.86	6.70	6.63
8	5.98	5.44	5.70	5.18
9	4.79	4.71	5.34	5.01
10	4.49	5.53	4.33	4.72
11	5.28	5.52	5.10	6.87
12	4.96	5.12	4.02	4.47
13	4.78	4.26	4.24	4.44
14	4.39	4.48	5.01	5.24
15	5.15	5.14	5.05	5.07
16	4.32	4.48	5.02	4.63
17	14.39	12.88	7.26	8.66
18	6.54	4.09	2.92	2.48
19	4.46	3.83	3.98	4.22
20	4.13	3.98	6.24	6.45
21	4.79	5.12	5.06	5.50
22	4.37	4.28	5.10	5.45

TABLE A-26. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - AVERAGE STABILITY

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	55.20	58.10	48.40	51.10
2	50.40	47.60	48.10	52.60
3	38.00	34.00	43.80	45.90
4	48.60	48.70	52.90	53.50
5	60.60	57.70	61.70	58.80
6	50.50	44.30	49.10	45.60
7	49.90	55.30	53.00	54.80
8	45.40	46.20	46.00	44.60
9	50.60	46.50	49.60	50.40
10	55.20	56.70	55.50	57.80
11	45.00	46.10	48.30	46.10
12	44.40	45.10	52.00	53.80
13	54.30	53.80	55.10	52.80
14	63.30	57.60	58.40	57.50
15	49.60	49.00	45.80	48.70
16	49.90	49.30	53.40	47.90
17	50.00	52.00	52.60	56.00

TABLE A-27. US-412 PROJECT, ROADWAY SAMPLES - CORE DENSITY

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	95.80	95.80	94.30	94.30
2	95.20	95.20	93.60	93.80
3	93.90	94.20	95.20	94.40
4	94.90	93.40	93.70	94.80
5	94.00	94.00	94.90	95.50
6	95.00	94.20	94.10	93.90
7	93.80	94.60	94.40	94.50
8	92.80	92.70	93.10	92.40
9	94.70	93.20	91.90	91.20
10	93.30	93.00	93.00	93.40
11	94.40	92.80	92.00	91.50
12	91.80	91.80	94.60	94.20
13	93.40	93.80	93.10	93.30
14	94.70	94.90	94.00	94.20
15	93.80	94.40	94.20	93.70
16	94.30	94.00	93.90	93.10
17	94.60	94.60	93.60	91.70
18	95.20	95.00	94.60	93.70
19	94.70	94.00	93.20	93.60
20	95.10	95.40	95.30	95.30
21	96.30	95.70	95.50	95.10
22	93.80	94.00	96.10	95.60
23	94.50	94.70	94.90	93.90
24	93.60	94.00	95.70	95.30
25	93.90	93.40	94.00	94.40

TABLE A-28. US-412 PROJECT, ROADWAY SAMPLES - NUCLEAR DENSITY

Sublot No.	Sample Unit 1		Sample Unit 2	
	Test 1	Test 2	Test 1	Test 2
1	92.08	91.59	88.98	90.10
2	90.07	89.79	89.05	88.61
3	90.11	88.66	89.23	87.65
4	90.14	88.50	89.90	89.34
5	90.71	90.99	91.07	90.75
6	91.36	88.18	91.94	91.54
7	92.88	91.59	91.15	92.03
8	88.90	88.30	88.69	89.06
9	89.31	89.31	82.79	83.95
10	88.25	89.70	88.70	89.18
11	91.79	86.85	87.81	88.50
12	88.33	87.50	86.44	87.45
13	87.85	89.58	90.47	86.69
14	90.75	91.84	92.85	93.06
15	88.78	90.11	90.13	90.53
16	93.03	92.70	90.96	90.39
17	92.92	91.63	88.25	86.24
18	93.42	93.77	91.88	90.98
19	90.14	89.66	90.59	89.94
20	94.26	93.34	94.13	92.50
21	93.44	93.60	92.13	92.15
22	90.58	89.41	93.63	93.73
23	91.67	94.97	92.20	89.82
24	92.80	91.27	92.64	92.60
25	88.09	87.41	89.54	90.35

APPENDIX B

NESTED ANALYSIS OF VARIANCE RESULTS

TABLE B-1. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 1 1/2 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	0.000	22	0.000	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	0.000	23	0.000	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	0.000	46	0.000	σ_T^2
Total	0.000	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.0000	0.0000	0.00	0.00
Sampling	0.0000	0.0000	0.00	0.00
Testing	0.0000	0.0000	0.00	0.00
Total	0.0000	0.0000	0.00	0.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	0.00	$H_0: \sigma_S^2 = 0$	0.00
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

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TABLE B-2. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 1 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	51.738	22	2.352	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	24.926	23	1.084	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	49.808	46	1.083	σ_T^2
Total	126.472	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.3170	0.3170	22.64	22.64
Sampling	0.0005	0.0005	0.03	0.03
Testing	1.0828	1.0828	77.33	77.33
Total	1.4003	1.4003	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	2.17	$H_0: \sigma_S^2 = 0$	1.00
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-3. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 3/4 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	284.322	22	12.924	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	149.913	23	6.518	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	260.108	46	5.655	σ_T^2
Total	694.343	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	1.6014	1.6014	20.83	20.83
Sampling	0.4317	0.4317	5.62	5.62
Testing	5.6545	5.6545	73.55	73.55
Total	7.6877	7.6877	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.98	$H_0: \sigma_S^2 = 0$	1.15
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-4. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 1/2 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	701.040	22	31.865	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	234.363	23	10.190	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	779.953	46	16.955	σ_T^2
Total	1715.356	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	5.4189	5.4189	28.53	24.22
Sampling	-3.3829	0.0000	-17.81	0.00
Testing	16.9555	16.9555	89.28	75.78
Total	18.9915	22.3744	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.13	$H_0: \sigma_S^2 = 0$	0.60
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-5. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: 3/8 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	606.830	22	27.583	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	210.105	23	9.135	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	930.616	46	20.231	σ_T^2
Total	1747.551	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	4.6121	4.6121	23.90	18.56
Sampling	-5.5479	0.0000	-28.75	0.00
Testing	20.2308	20.2308	104.85	81.44
Total	19.2949	24.8421	100.00	100.00

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Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.02	$H_0: \sigma_S^2 = 0$	0.45
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-6. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 4

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	310.023	22	14.092	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	144.903	23	6.300	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	648.801	46	14.104	σ_T^2
Total	1103.727	91		

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Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	1.9480	1.9480	16.03	12.14
Sampling	-3.9021	0.0000	-32.12	0.00
Testing	14.1044	14.1044	116.08	87.86
Total	12.1502	16.0524	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	2.24	$H_0: \sigma_S^2 = 0$	0.45
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-7. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 10

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	176.564	22	8.026	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	103.414	23	4.496	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	427.114	46	9.285	σ_T^2
Total	707.092	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.8823	0.8823	11.35	8.68
Sampling	-2.3944	0.0000	-30.80	0.00
Testing	9.2851	9.2851	119.45	91.32
Total	7.7730	10.1674	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.78	$H_0: \sigma_S^2 = 0$	0.48
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-8. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 40

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	89.544	22	4.070	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	50.162	23	2.181	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	161.195	46	3.504	σ_T^2
Total	300.901	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.4723	0.4723	14.25	11.88
Sampling	-0.6616	0.0000	-19.96	0.00
Testing	3.5042	3.5042	105.71	88.12
Total	3.3149	3.9765	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.87	$H_0: \sigma_S^2 = 0$	0.62
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-9. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 80

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	33.529	22	1.524	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	11.303	23	0.491	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	23.685	46	0.515	σ_T^2
Total	68.517	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.2582	0.2582	33.91	33.40
Sampling	-0.0117	0.0000	-1.54	0.00
Testing	0.5149	0.5149	67.63	66.60
Total	0.7613	0.7731	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.10	$H_0: \sigma_S^2 = 0$	0.95
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-10. US-412 PROJECT, COLD FEED AGGREGATE SAMPLES - SIEVE: No. 200

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	36.884	22	1.677	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	8.259	23	0.359	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	6.658	46	0.145	σ_T^2
Total	51.801	91		

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Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.3294	0.3294	56.66	56.66
Sampling	0.1072	0.1072	18.44	18.44
Testing	0.1447	0.1447	24.90	24.90
Total	0.5813	0.5813	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	4.67	$H_0: \sigma_S^2 = 0$	2.48
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-11. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 1 1/2 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	0.000	22	0.000	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	0.000	23	0.000	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	0.000	46	0.000	σ_T^2
Total	0.000	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.00	0.00	0.00	0.00
Sampling	0.00	0.00	0.00	0.00
Testing	0.00	0.00	0.00	0.00
Total	0.00	0.00	0.00	0.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	0.00	$H_0: \sigma_S^2 = 0$	0.00
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-12. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 1 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	71.913	22	3.269	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	57.967	23	2.520	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	129.709	46	2.820	σ_T^2
Total	259.590	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.1871	0.1871	6.55	6.22
Sampling	-0.1497	0.0000	-5.24	0.00
Testing	2.8198	2.8198	98.69	93.78
Total	2.8572	3.0069	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.30	$H_0: \sigma_S^2 = 0$	0.89
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-13. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 3/4 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	487.869	22	22.176	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	246.080	23	10.669	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	652.621	46	14.187	σ_T^2
Total	1386.569	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	2.8692	2.8692	18.74	16.82
Sampling	-1.7441	0.0000	-11.39	0.00
Testing	14.1874	14.1874	92.65	83.18
Total	15.3124	17.0566	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	2.07	$H_0: \sigma_S^2 = 0$	0.75
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-14. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 1/2 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	622.239	22	28.284	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	544.888	23	23.691	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	667.359	46	14.508	σ_T^2
Total	1834.486	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	1.1482	1.1482	5.67	5.67
Sampling	4.5915	4.5915	22.68	22.68
Testing	14.5078	14.5078	71.65	71.65
Total	20.2475	20.2475	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.19	$H_0: \sigma_S^2 = 0$	1.63
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-15. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: 3/8 inch

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	779.925	22	35.451	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	537.683	23	23.378	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	631.691	46	13.732	σ_T^2
Total	1949.299	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	3.0184	3.0184	13.99	13.99
Sampling	4.8226	4.8226	22.35	22.35
Testing	13.7324	13.7324	63.65	63.65
Total	21.5734	21.5734	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.52	$H_0: \sigma_S^2 = 0$	1.70
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-16. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 4

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	497.372	22	22.608	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	271.994	23	11.826	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	219.144	46	4.764	σ_T^2
Total	988.509	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	2.6955	2.6955	24.53	24.53
Sampling	3.5309	3.5309	32.13	32.13
Testing	4.7640	4.7640	43.35	43.35
Total	10.9904	10.9904	100.00	100.100

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.91	$H_0: \sigma_S^2 = 0$	2.48
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-17. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 10

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	246.671	22	11.212	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	83.921	23	3.649	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	78.975	46	1.717	σ_T^2
Total	409.567	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	1.8909	1.8909	41.34	41.34
Sampling	0.9660	0.9660	21.12	21.12
Testing	1.7168	1.7168	37.54	37.54
Total	4.5737	4.5737	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.07	$H_0: \sigma_S^2 = 0$	2.13
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-18. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 40

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	110.245	22	5.011	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	26.147	23	1.137	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	24.165	46	0.525	σ_T^2
Total	160.557	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.9686	0.9686	53.82	53.82
Sampling	0.3058	0.3058	16.99	16.99
Testing	0.5253	0.5253	29.19	29.19
Total	1.7997	1.7997	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	4.41	$H_0: \sigma_S^2 = 0$	2.16
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-19. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 80

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	34.434	22	1.565	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	11.463	23	0.498	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	6.705	46	0.146	σ_T^2
Total	52.602	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.2667	0.2667	45.30	45.30
Sampling	0.1763	0.1763	29.94	29.94
Testing	0.1458	0.1458	24.76	24.76
Total	0.5888	0.5888	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.14	$H_0: \sigma_S^2 = 0$	3.42
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-20. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SIEVE: No. 200

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	22.626	22	1.028	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	6.523	23	0.284	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	2.760	46	0.060	σ_T^2
Total	31.909	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.1862	0.1862	52.01	52.01
Sampling	0.1118	0.1118	31.23	31.23
Testing	0.0600	0.0600	16.76	16.76
Total	0.3580	0.3580	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.63	$H_0: \sigma_S^2 = 0$	4.73
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-21. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - % AC (EXTRACTION)

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	4.956	22	0.225	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	1.671	23	0.073	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	1.729	46	0.038	σ_T^2
Total	8.356	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.0382	0.0382	40.91	40.91
Sampling	0.0175	0.0175	18.80	18.80
Testing	0.0376	0.0376	40.29	40.29
Total	0.0933	0.0933	100.00	100.00

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Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.10	$H_0: \sigma_S^2 = 0$	1.93
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-22. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - % AC (NUCLEAR)

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	8.431	21	0.401	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	1.335	22	0.061	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	0.823	44	0.019	σ_T^2
Total	10.589	87		

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Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.0852	0.0852	68.22	68.22
Sampling	0.0210	0.0210	16.80	16.80
Testing	0.0187	0.0187	14.98	14.98
Total	0.1249	0.1249	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	6.62	$H_0: \sigma_S^2 = 0$	3.24
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-23. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - AVERAGE RICES

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	0.020	22	0.001	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	0.010	23	0.000	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	0.003	46	0.000	σ_T^2
Total	0.033	91		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.0001	0.0001	31.60	31.60
Sampling	0.0002	0.0002	49.88	49.88
Testing	0.0001	0.0001	18.52	18.52
Total	0.0004	0.0004	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	2.07	$H_0: \sigma_S^2 = 0$	6.39
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-24. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - SPECIFIC GRAVITY

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	0.070	21	0.003	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	0.022	22	0.001	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	0.003	44	0.000	σ_T^2
Total	0.096	87		

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Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.0006	0.0006	51.92	51.92
Sampling	0.0005	0.0005	42.21	42.21
Testing	0.0001	0.0001	5.87	5.87
Total	0.0012	0.0012	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.30	$H_0: \sigma_S^2 = 0$	15.39
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-25. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - % AIR VOIDS

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	180.073	21	8.575	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	52.581	22	2.390	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	12.838	44	0.292	σ_T^2
Total	245.492	87		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	1.5462	1.5462	53.56	53.56
Sampling	1.0491	1.0491	36.34	36.34
Testing	0.2918	0.2918	10.11	10.11
Total	2.8871	2.8871	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	3.59	$H_0: \sigma_S^2 = 0$	8.19
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-26. US-412 PROJECT, BITUMINOUS MIXTURE SAMPLES - AVERAGE STABILITY

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	1544.653	16	96.541	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	245.796	17	14.459	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	147.814	34	4.347	σ_T^2
Total	1938.263	67		

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Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	20.5205	20.5205	68.58	68.58
Sampling	5.0556	5.0556	16.89	16.89
Testing	4.3475	4.3475	14.53	14.53
Total	29.9236	29.9236	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	6.68	$H_0: \sigma_S^2 = 0$	3.33
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-27. US-412 PROJECT, ROADWAY SAMPLES - CORE DENSITY

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	60.534	24	2.522	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	37.113	25	1.485	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	10.893	50	0.218	σ_T^2
Total	108.540	99		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	0.2594	0.2594	23.36	23.36
Sampling	0.6333	0.6333	57.03	57.03
Testing	0.2179	0.2179	19.62	19.62
Total	1.1106	1.1106	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	1.70	$H_0: \sigma_S^2 = 0$	6.81
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

TABLE B-28. US-412 PROJECT, ROADWAY SAMPLES - NUCLEAR DENSITY

Source of Variation	Sum of Squares	d.f.	Mean Square, M.S.	Expected M.S.
Between Sublots	320.091	24	13.337	$\sigma_T^2 + 2 \sigma_S^2 + 4 \sigma_M^2$
Between Sample Units	114.087	25	4.563	$\sigma_T^2 + 2 \sigma_S^2$
Between Tests	53.048	50	1.061	σ_T^2
Total	487.226	99		

Component	Variance		Percent of Total Variance	
	Computed	Rounded	Computed	Rounded
Material	2.1934	2.1934	43.82	43.82
Sampling	1.7513	1.7513	34.99	34.99
Testing	1.0610	1.0610	21.20	21.20
Total	5.0056	5.0056	100.00	100.00

Hypothesis 1	Computed F-Ratio	Hypothesis 2	Computed F-Ratio
$H_0: \sigma_M^2 = 0$	2.92	$H_0: \sigma_S^2 = 0$	4.30
$H_1: \sigma_M^2 > 0$		$H_1: \sigma_S^2 > 0$	

APPENDIX C

COMPONENTS OF VARIANCE

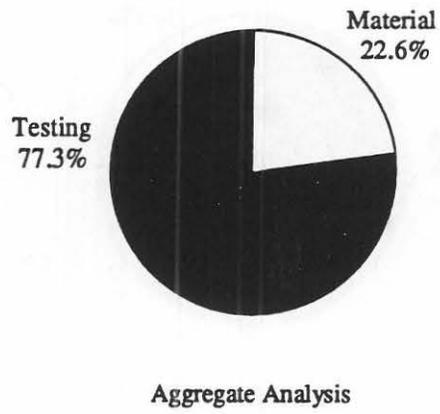
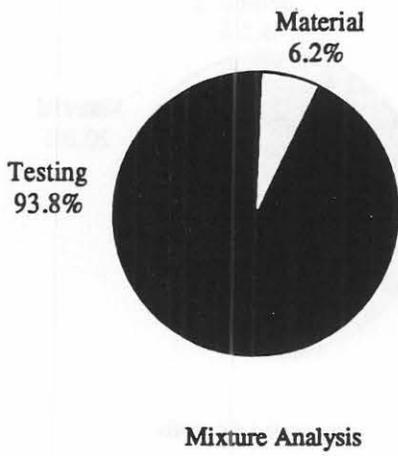
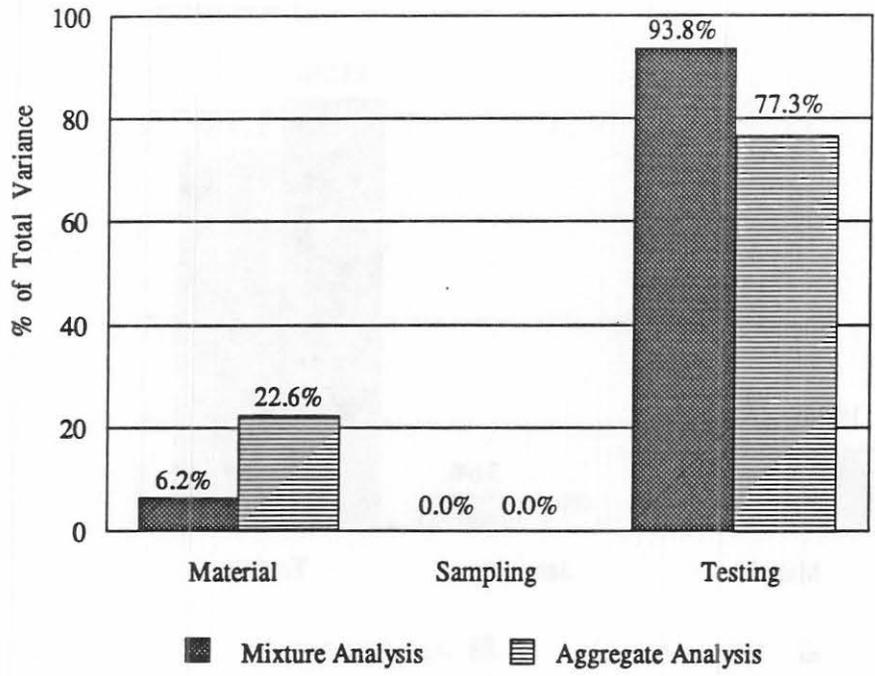


Figure C-1. Components of Variance, Sieve 1"

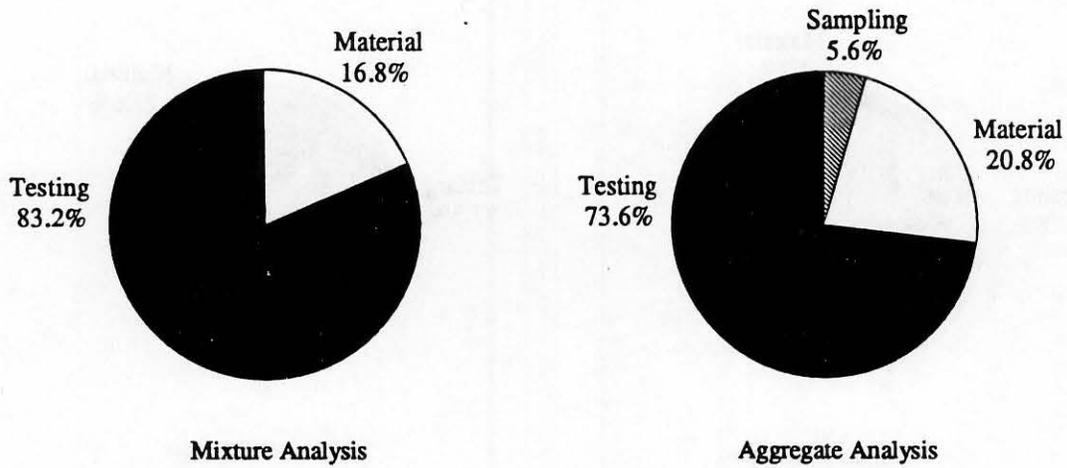
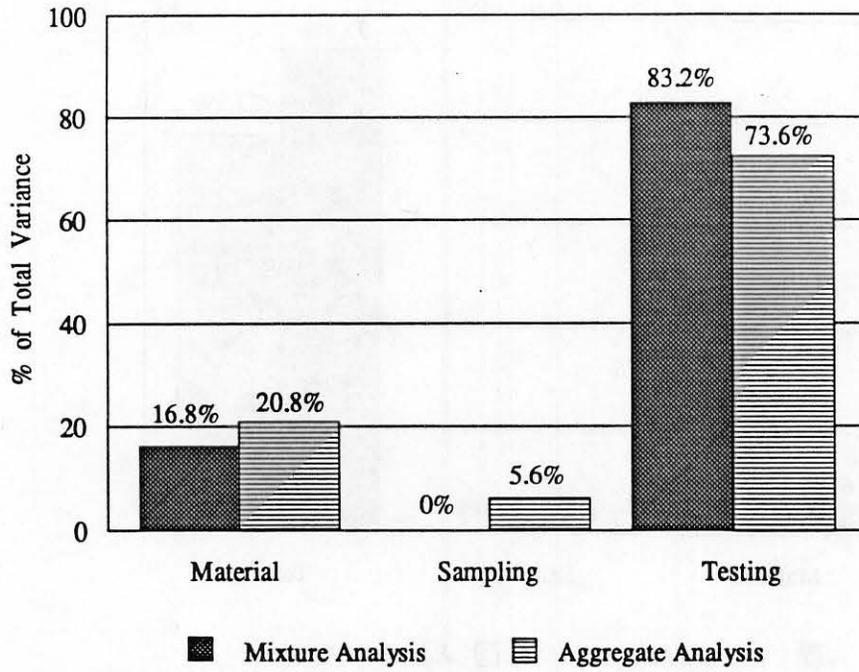
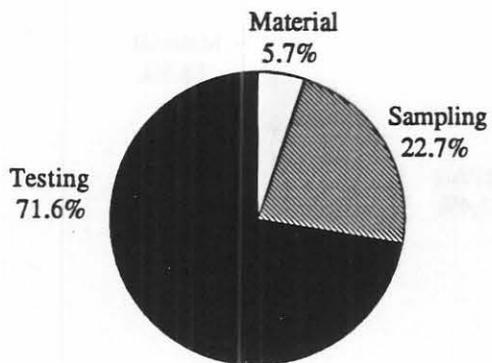
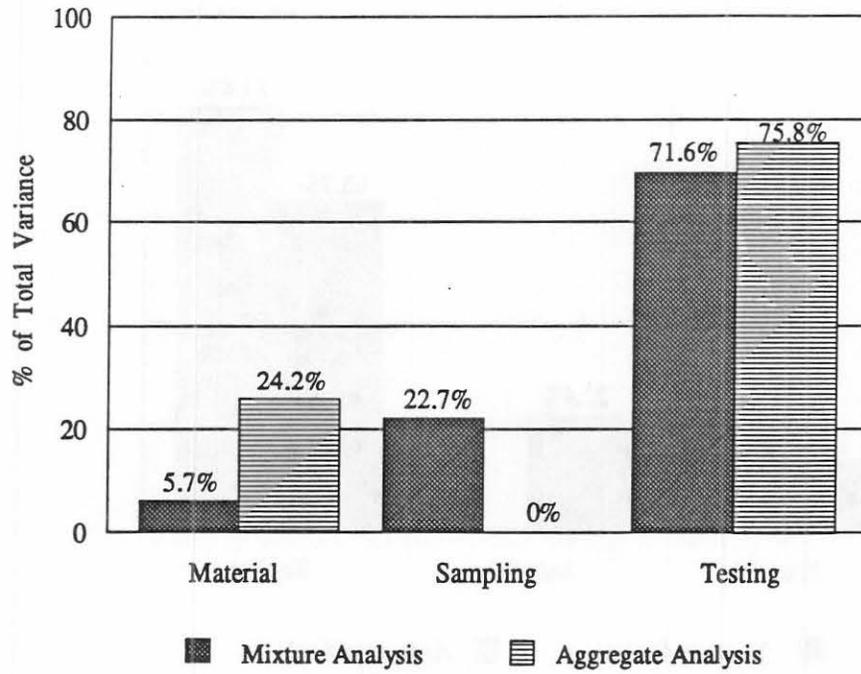
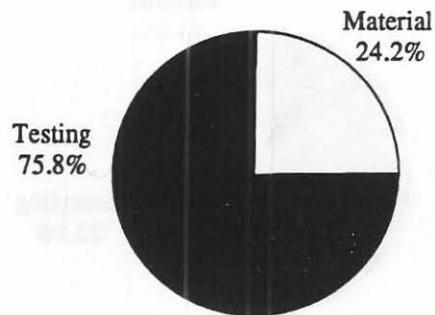


Figure C-2. Components of Variance, Sieve 3/4"



Mixture Analysis



Aggregate Analysis

Figure C-3. Components of Variance, Sieve 1/2"

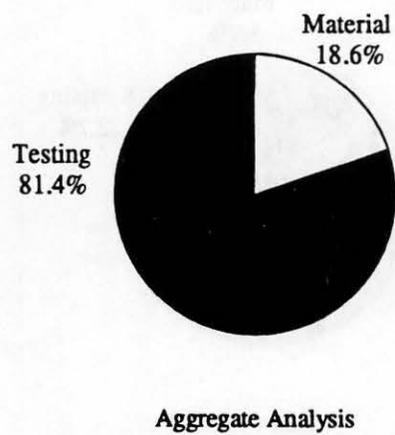
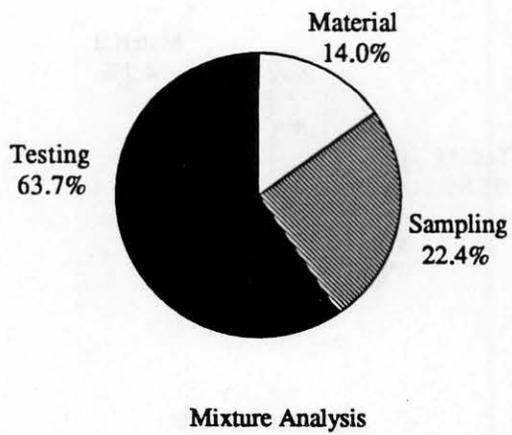
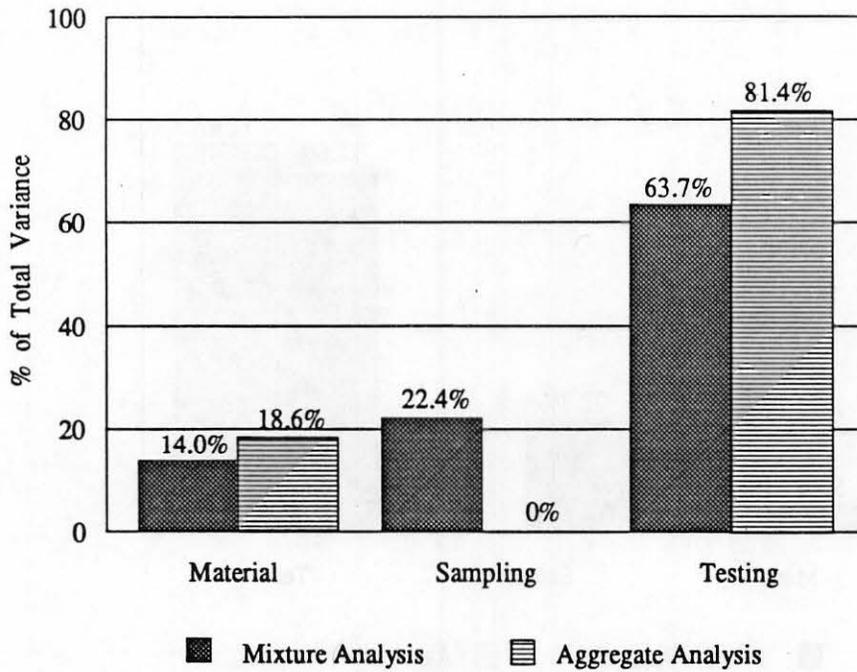


Figure C-4. Components of Variance, Sieve 3/8"

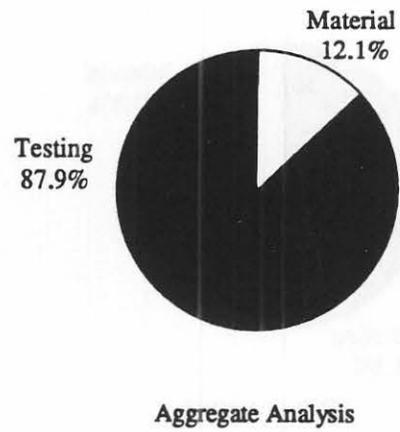
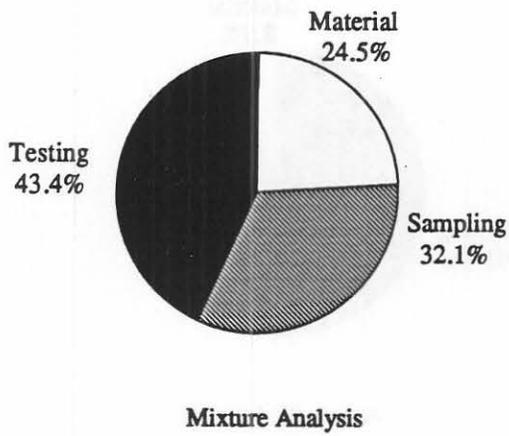
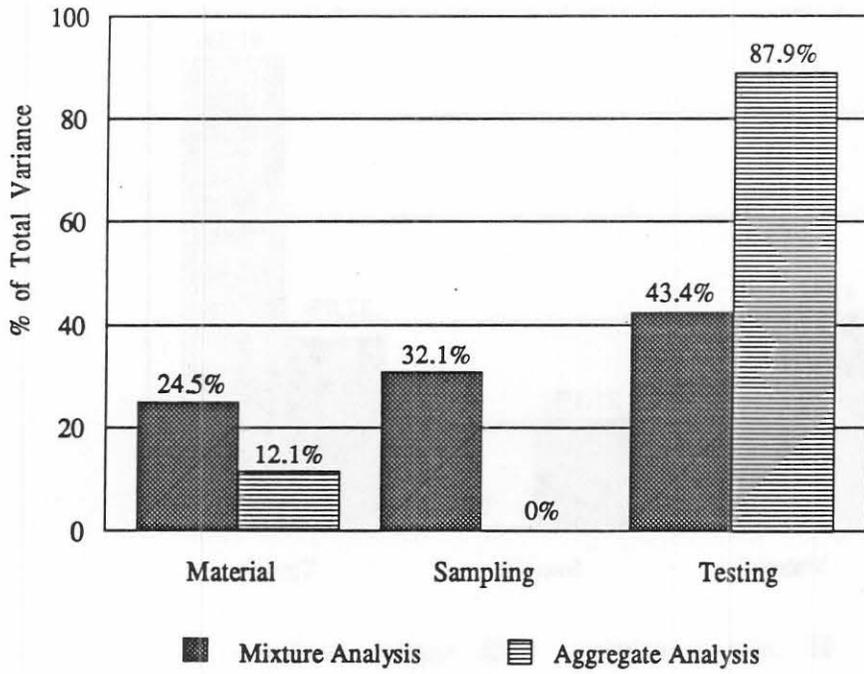


Figure C-5. Components of Variance, Sieve No. 4

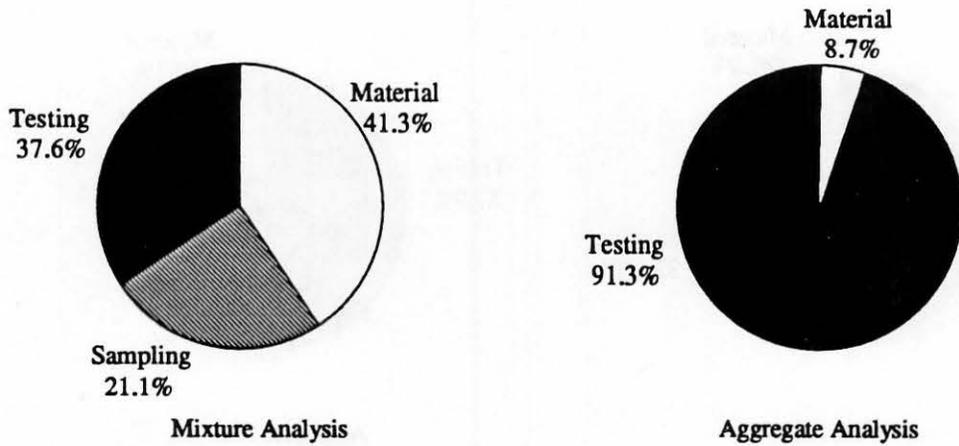
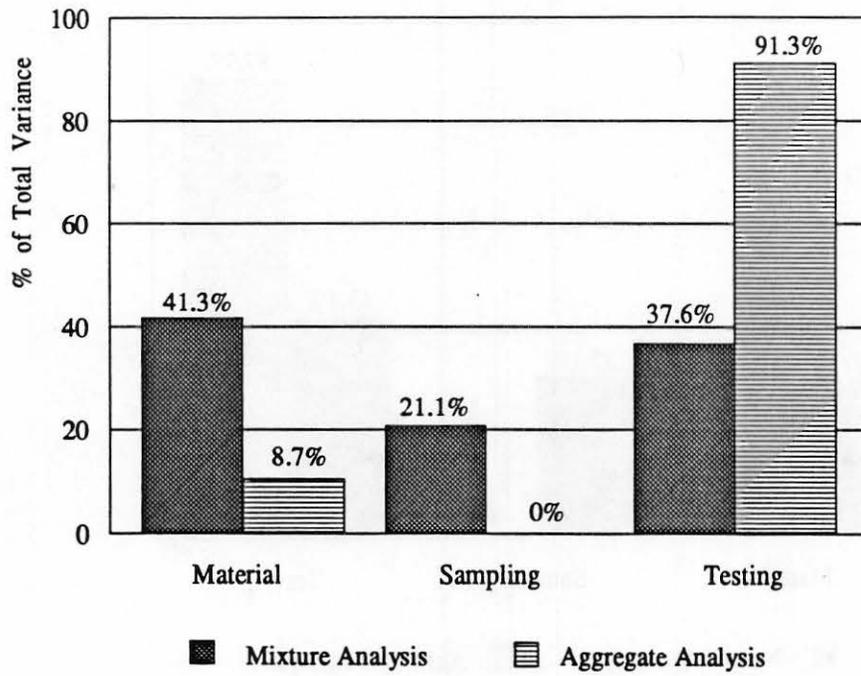


Figure C-6. Components of Variance, Sieve No. 10

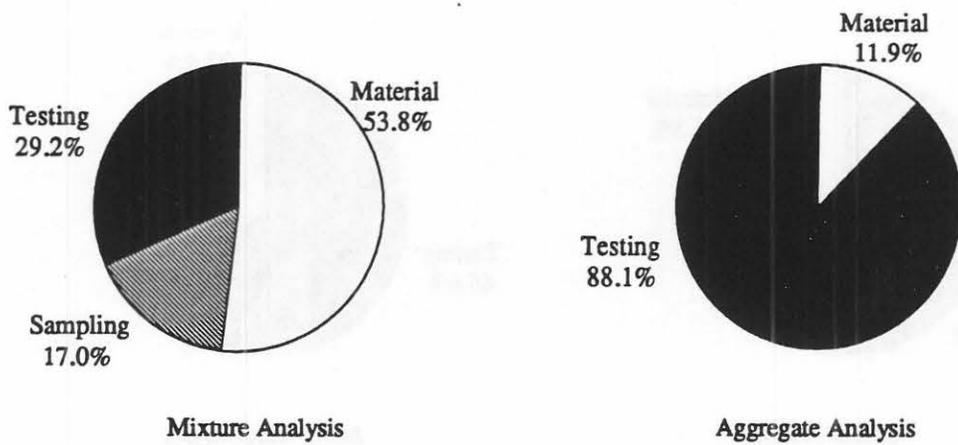
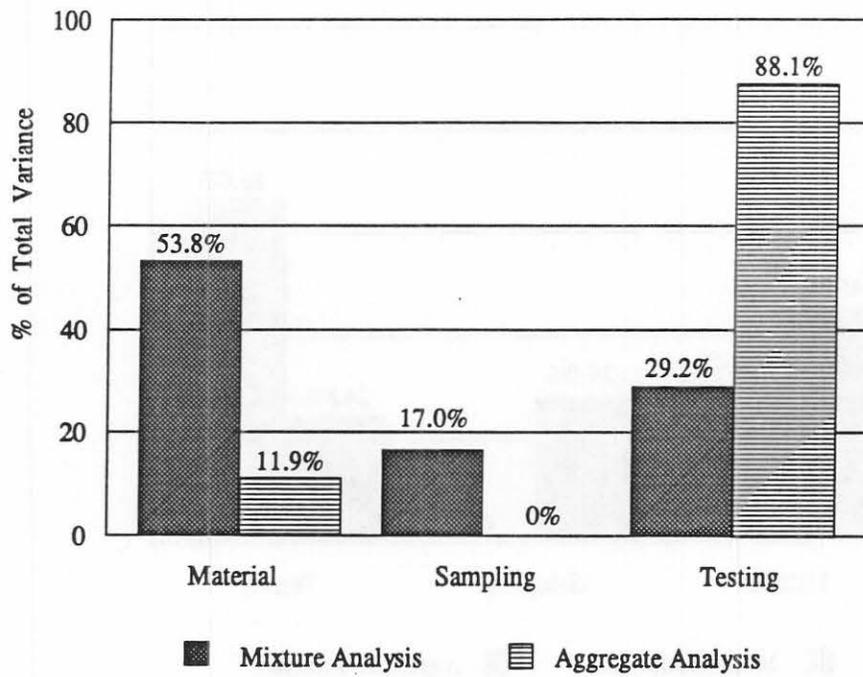


Figure C-7. Components of Variance, Sieve No. 40

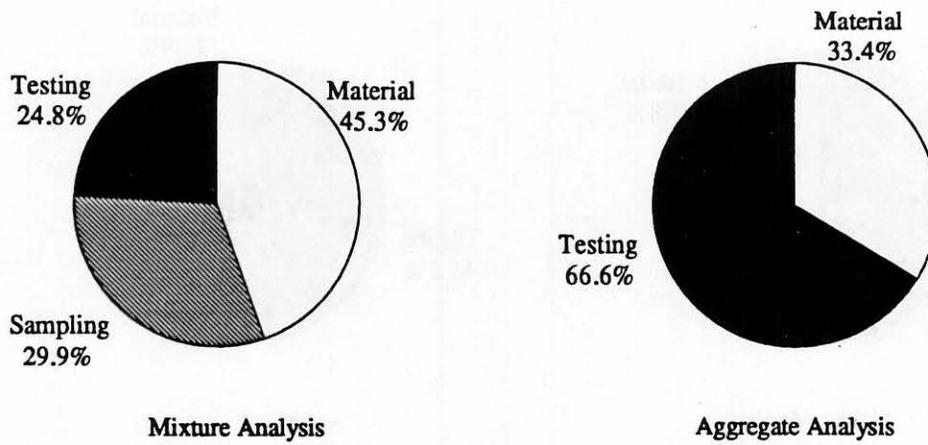
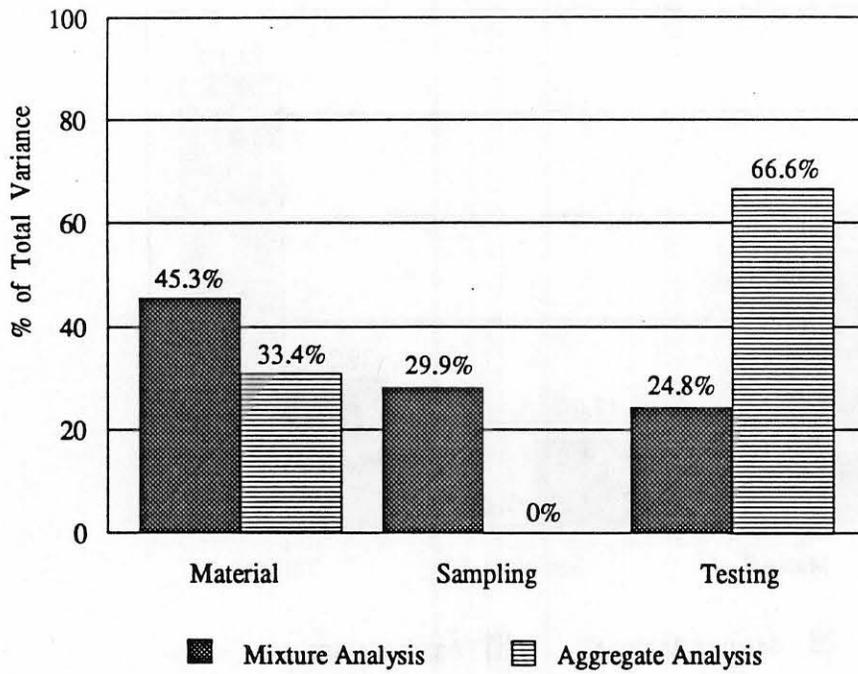
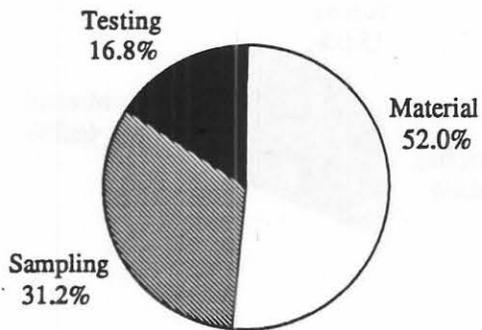
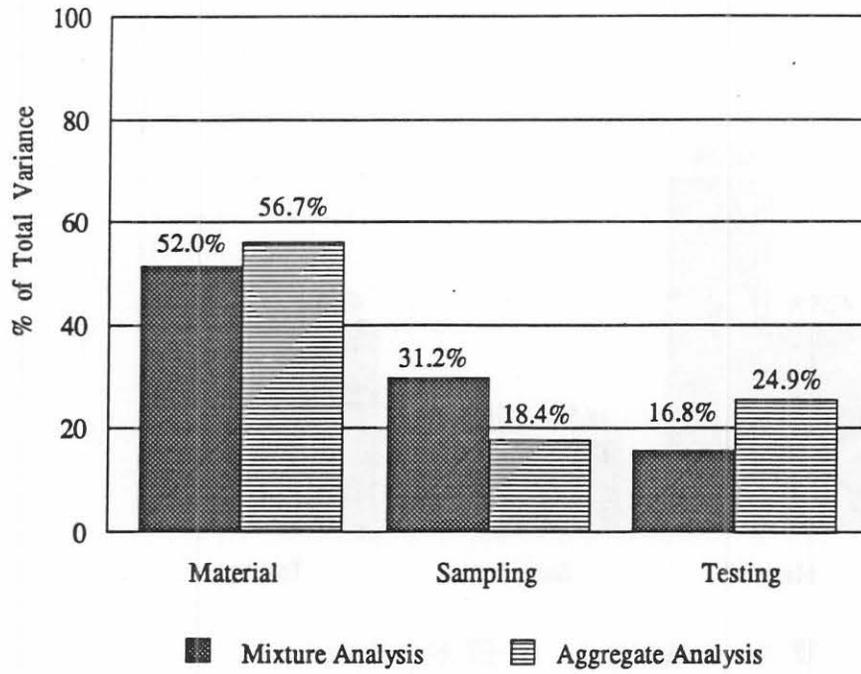
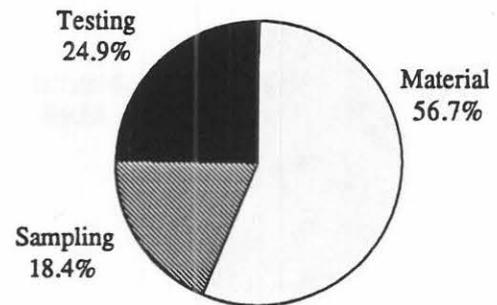


Figure C-8. Components of Variance, Sieve No. 80



Mixture Analysis



Aggregate Analysis

Figure C-9. Components of Variance, Sieve No. 200

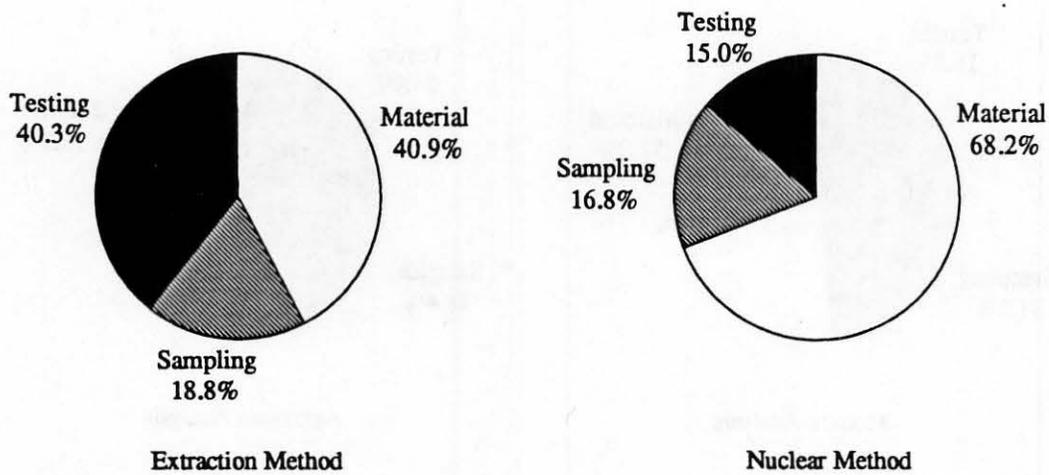
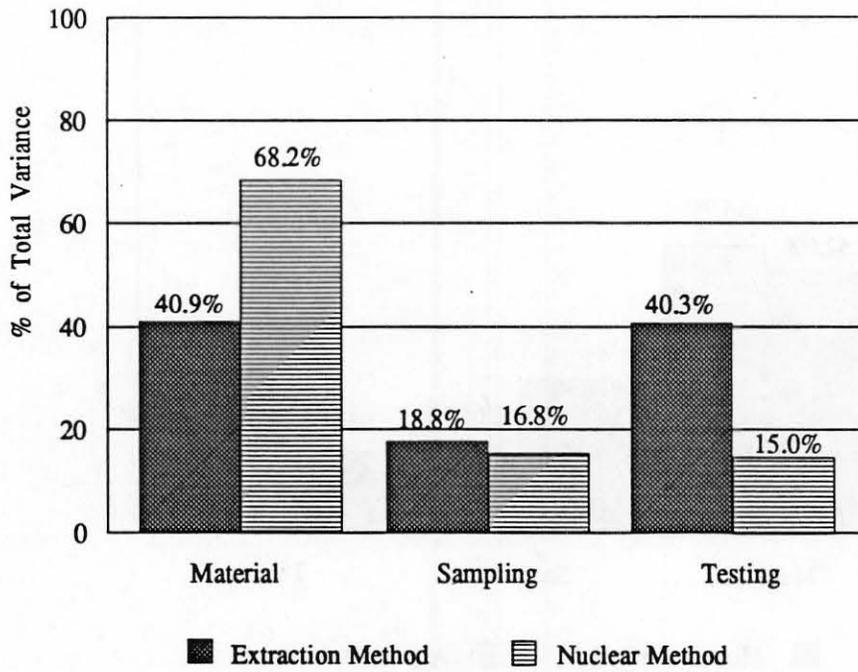


Figure C-10. Components of Variance, % Asphalt Content

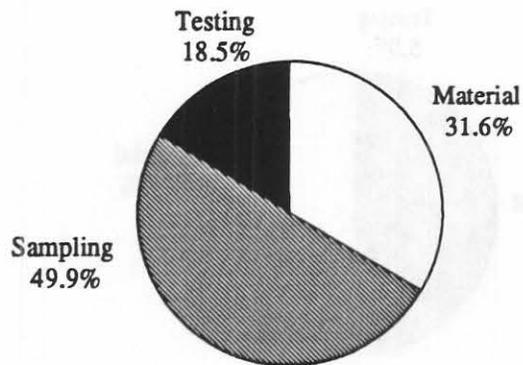
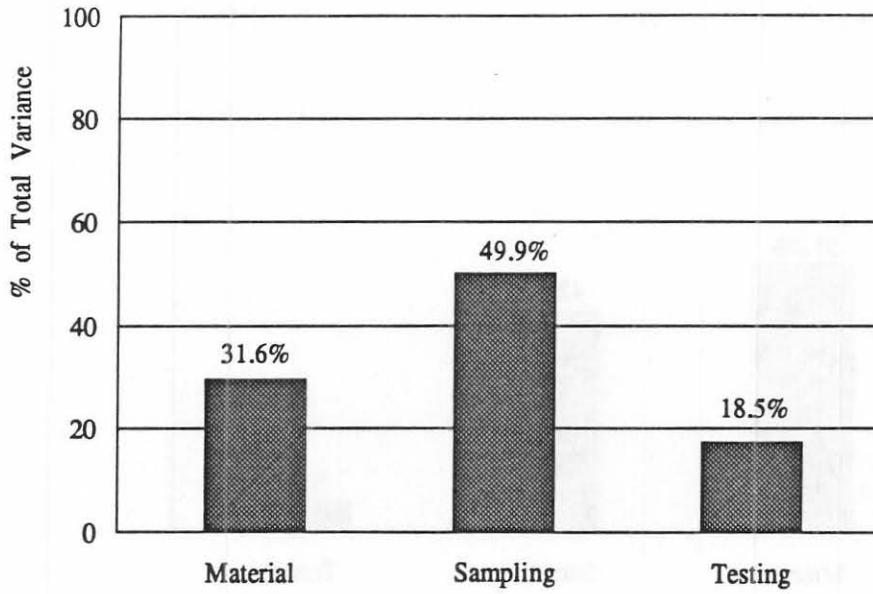


Figure C-11. Components of Variance, Average Rice's Gravity

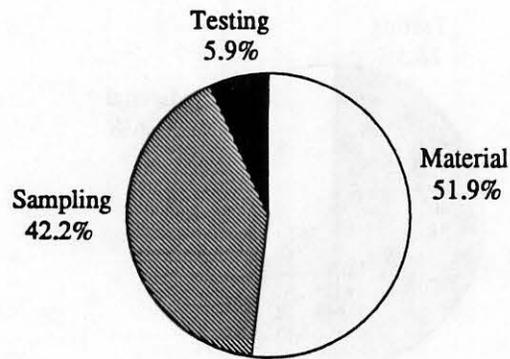
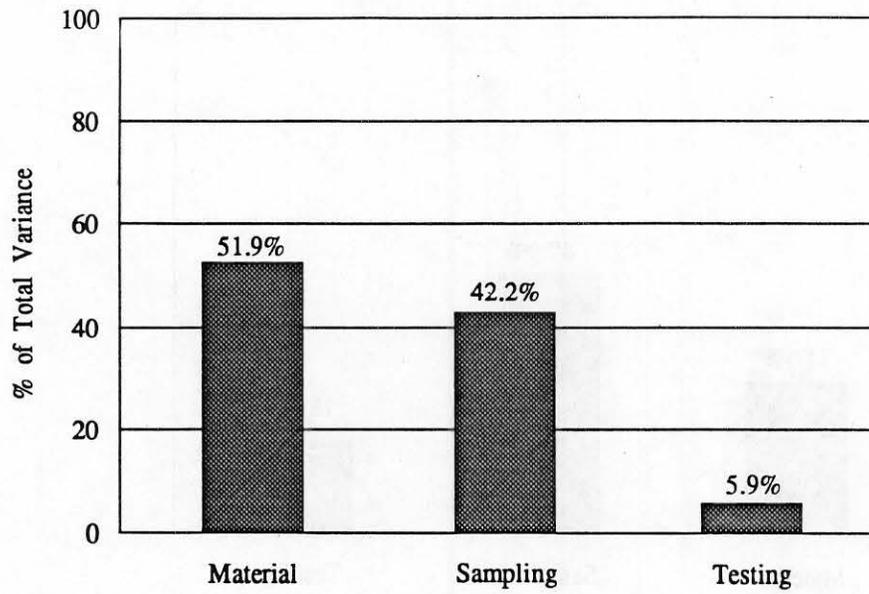


Figure C-12. Components of Variance, Average Lab Molded Specific Gravity (LMSG)

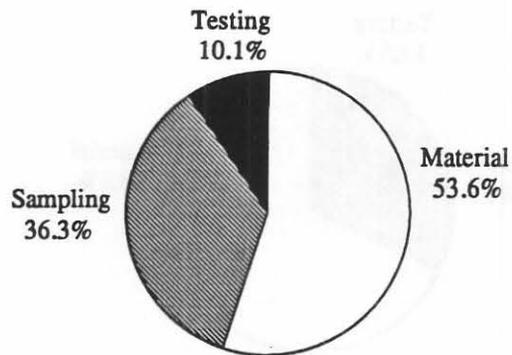
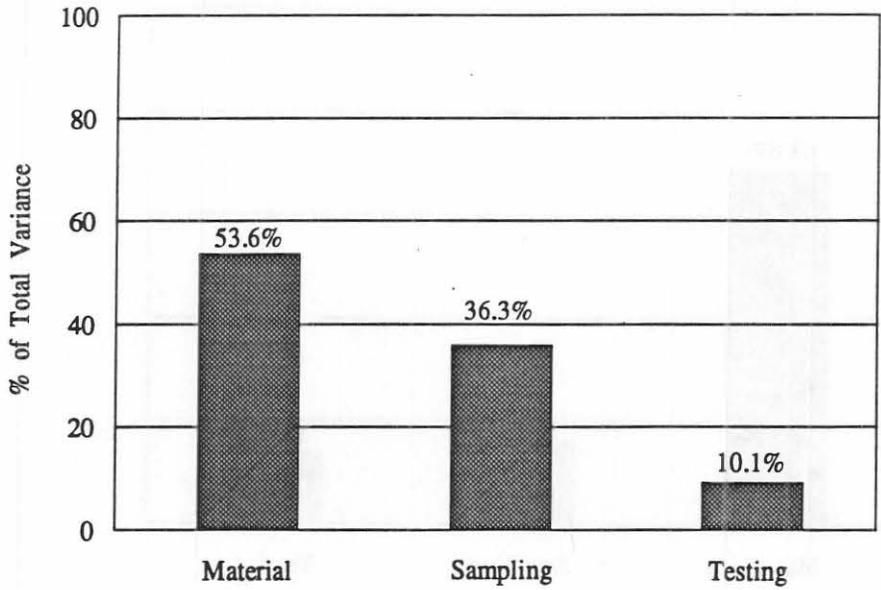


Figure C-13. Components of Variance, % Air Voids

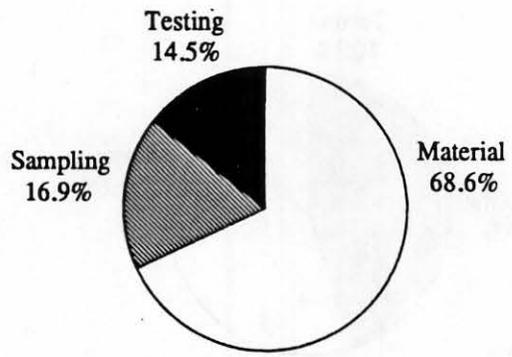
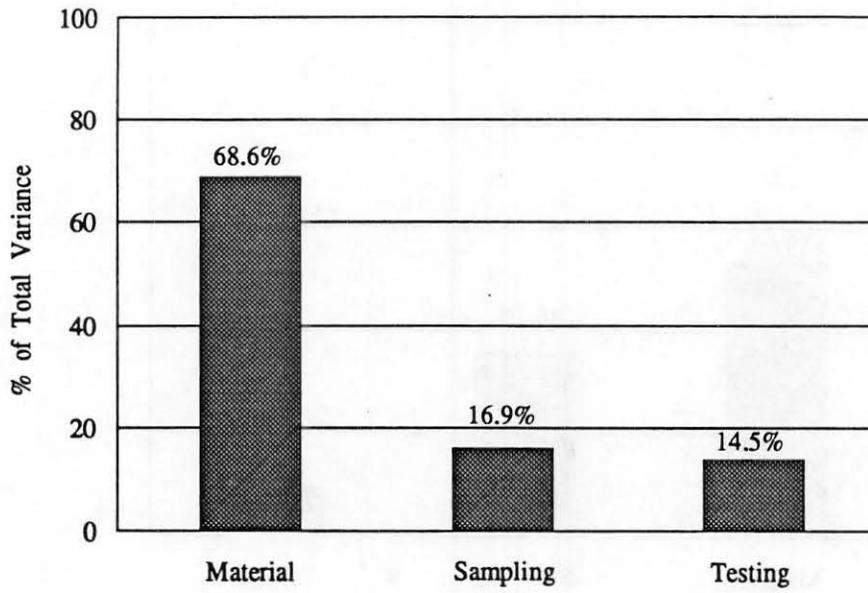


Figure C-14. Components of Variance, Hveem Stability

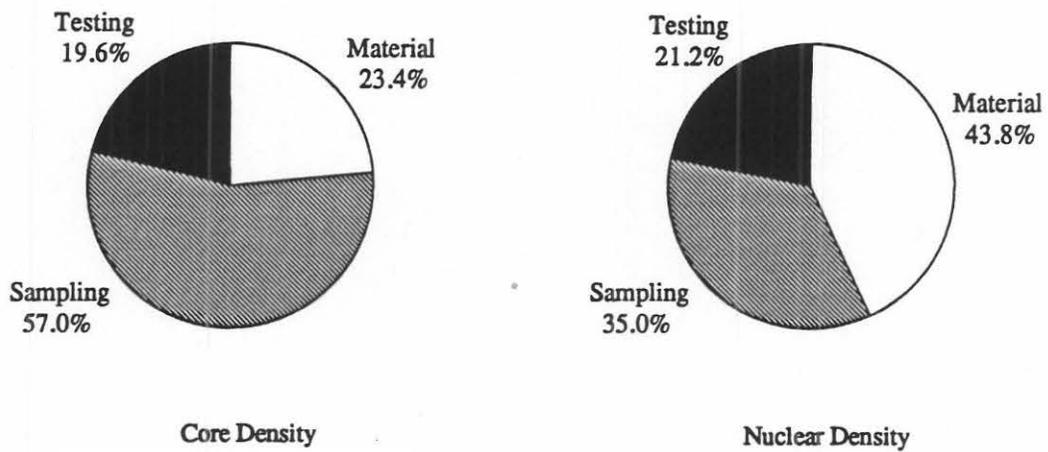
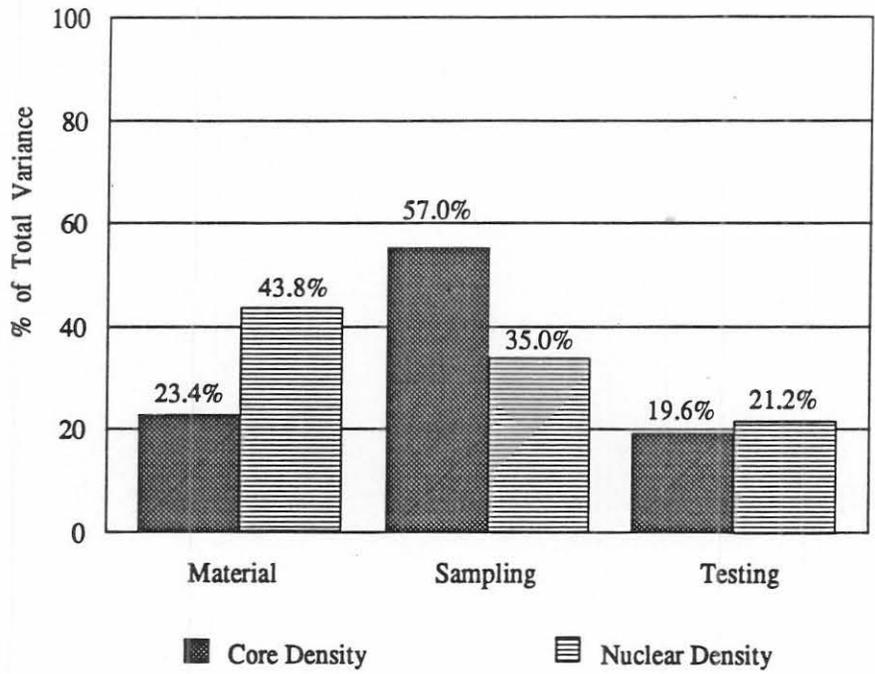


Figure C-15. Components of Variance, In-place Density

APPENDIX D

QA/QC SPECIFICATION TOLERANCES
AND
2-SIGMA LIMITS & 3-SIGMA LIMITS

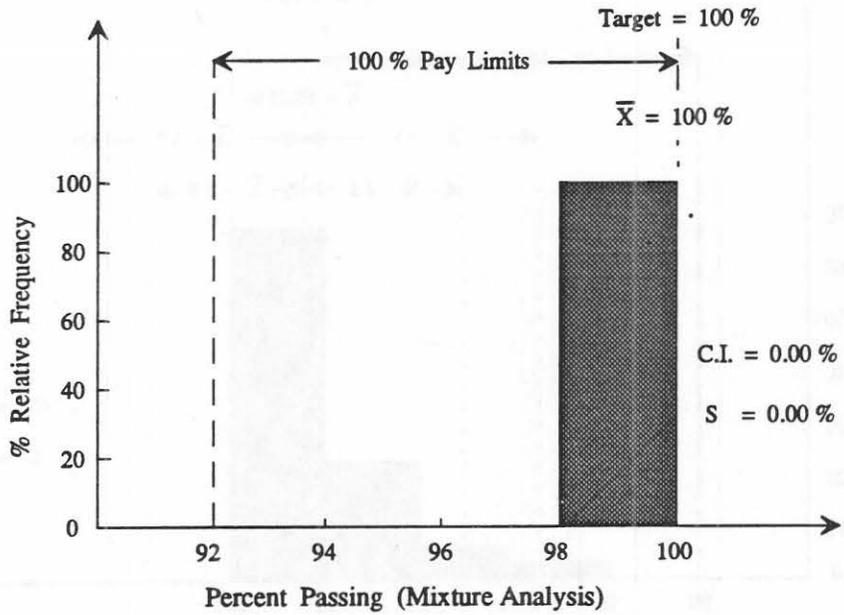
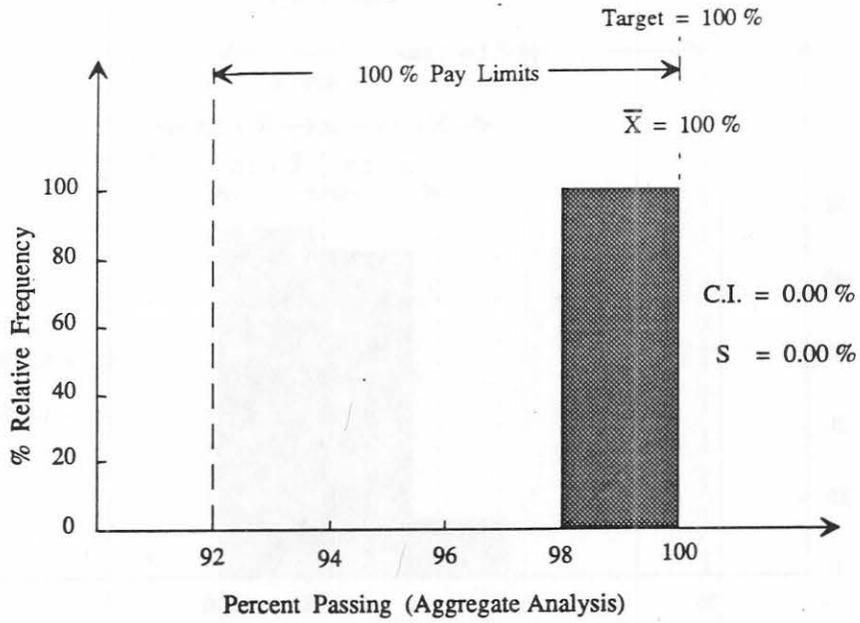


Figure D-1. Percent Passing Sieve 1-1/2"

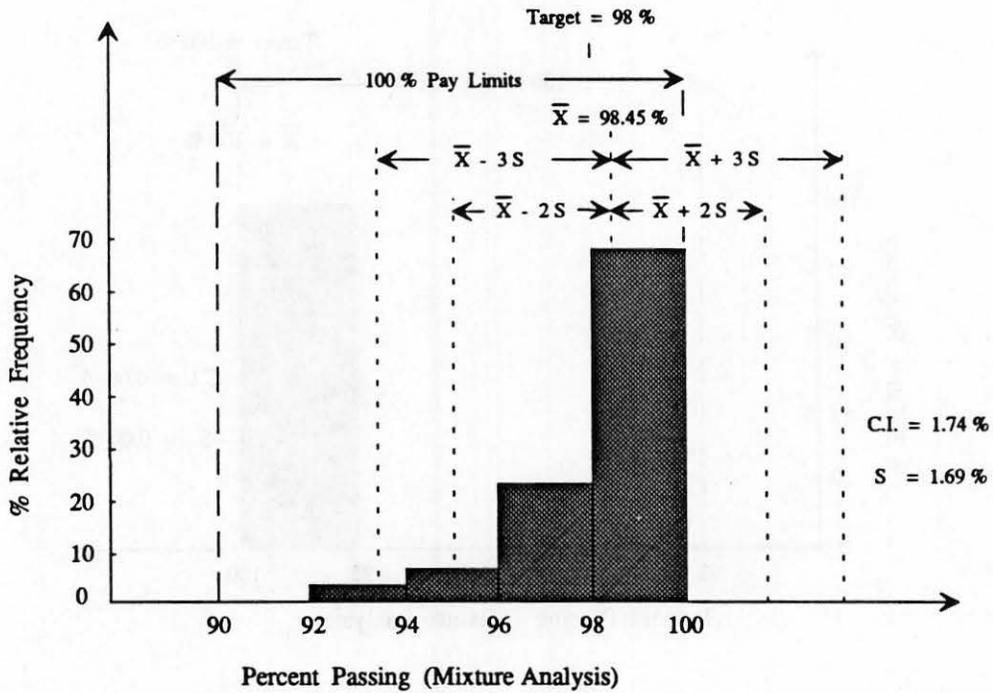
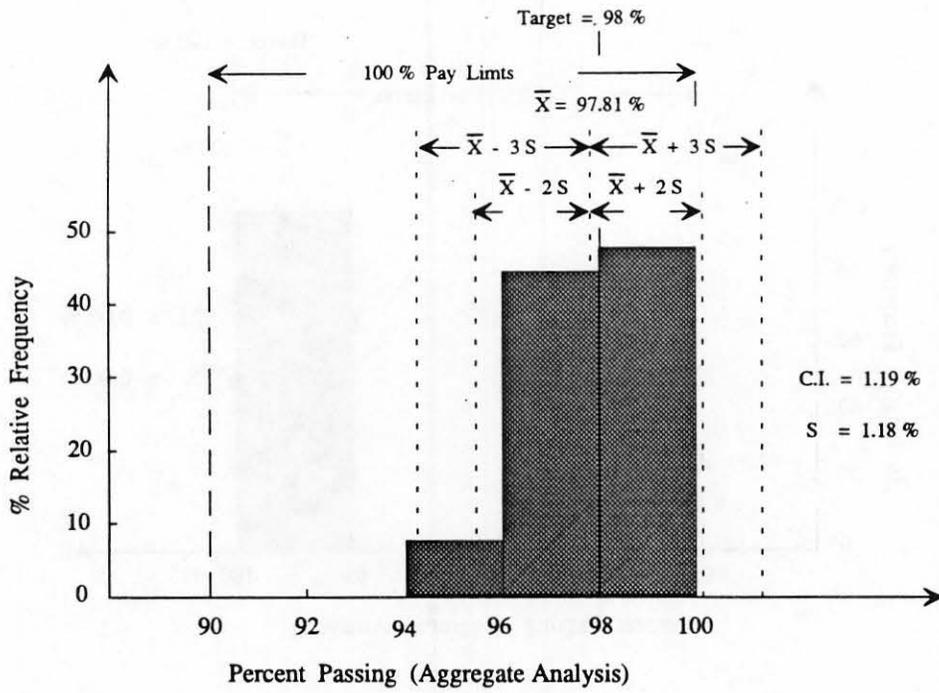


Figure D-2. Percent Passing Sieve 1"

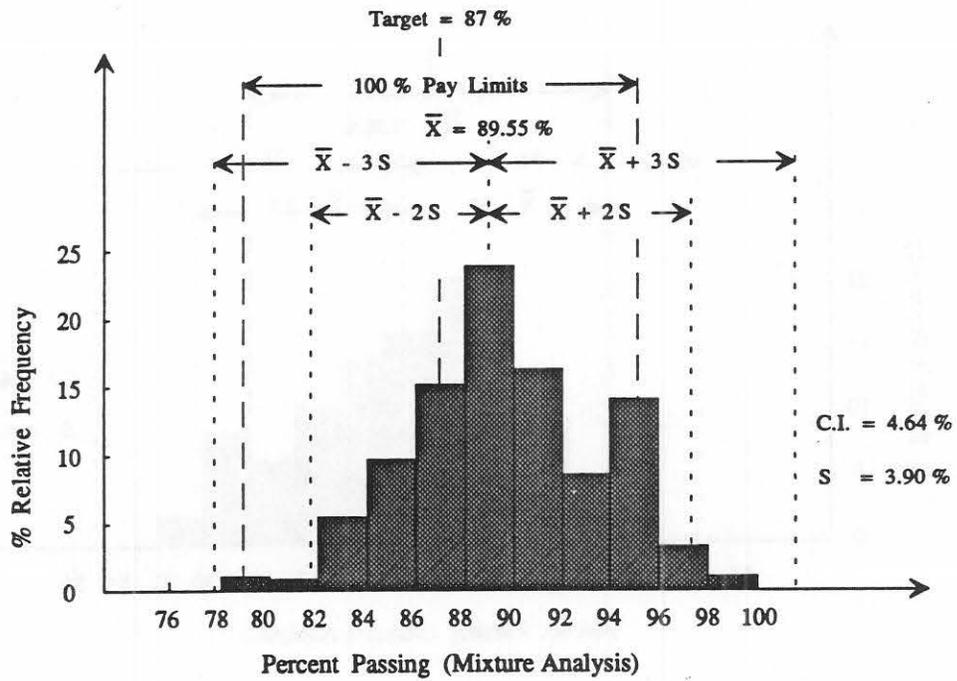
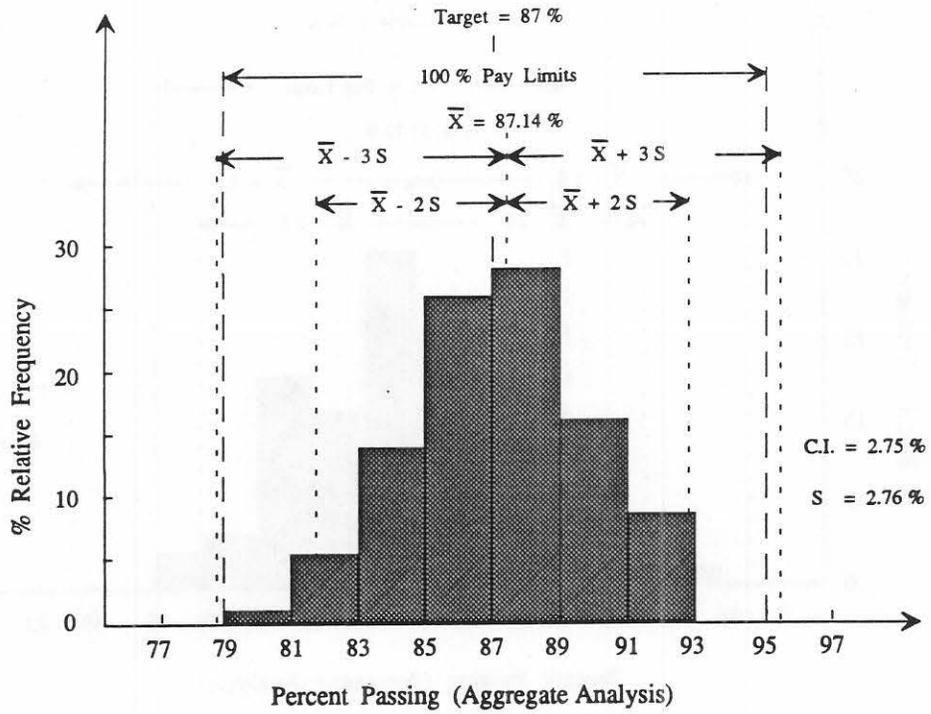


Figure D-3. Percent Passing Sieve 3/4"

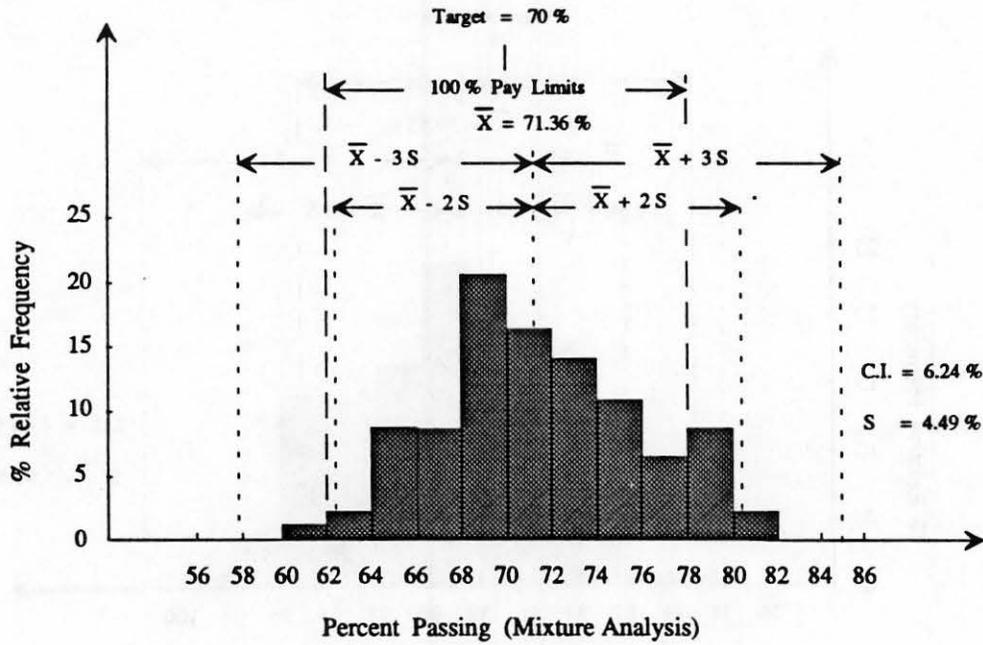
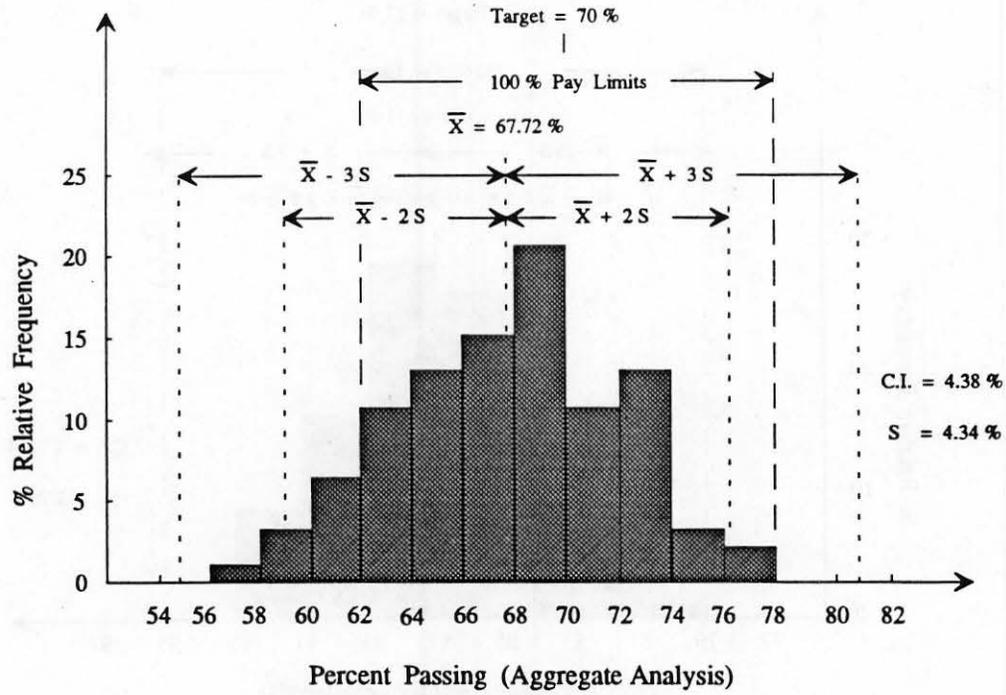


Figure D-4. Percent Passing Sieve 1/2"

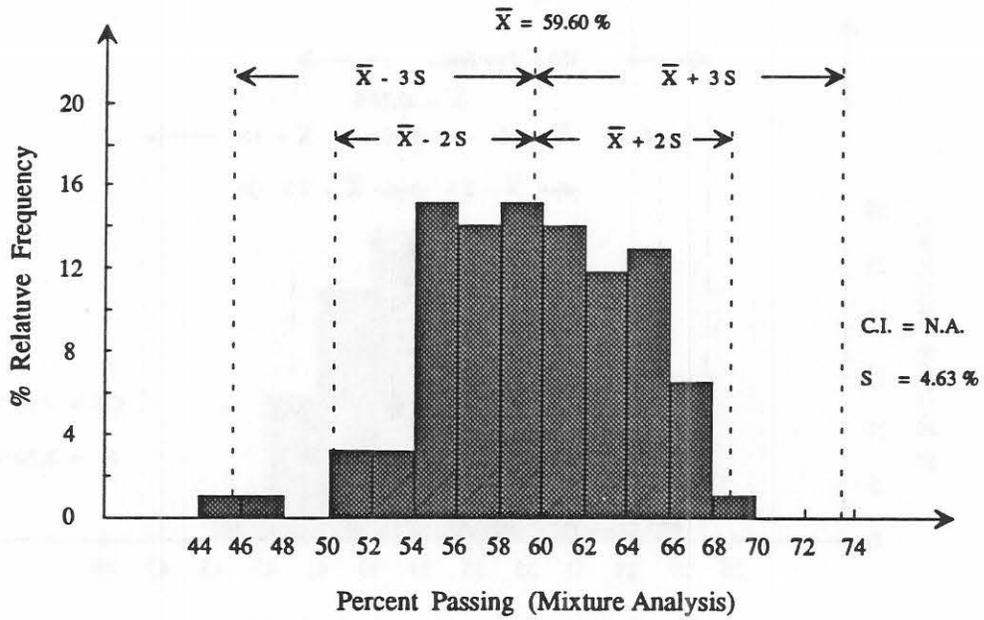
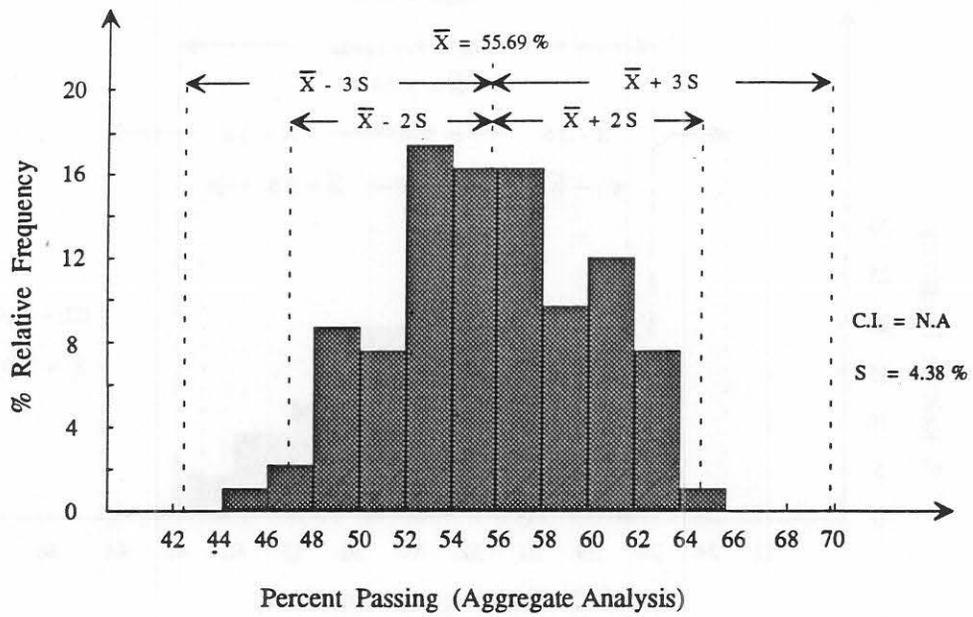


Figure D-5. Percent Passing Sieve 3/8"

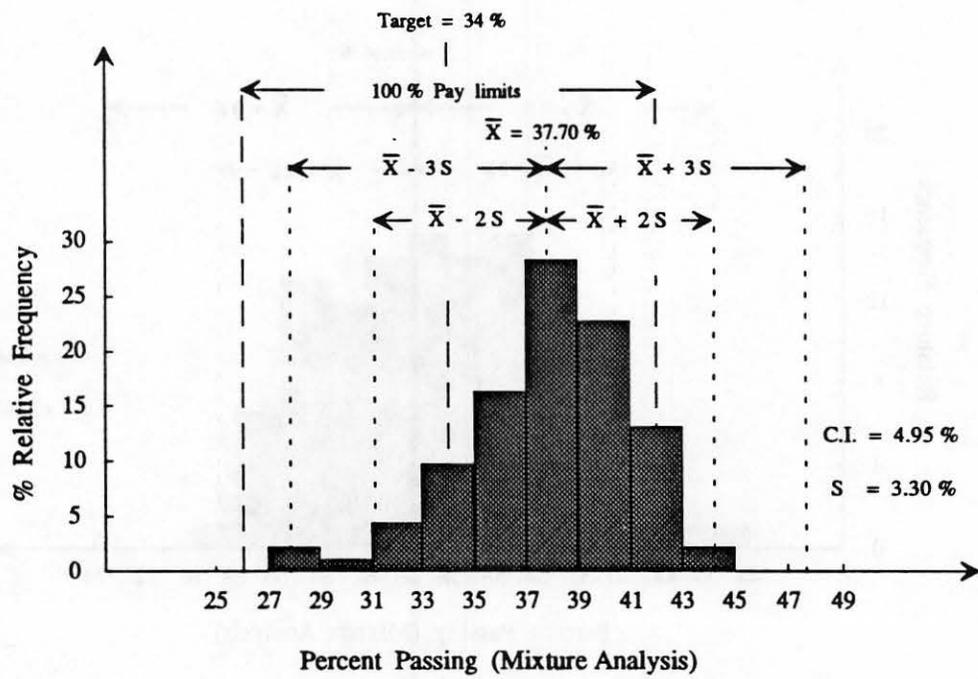
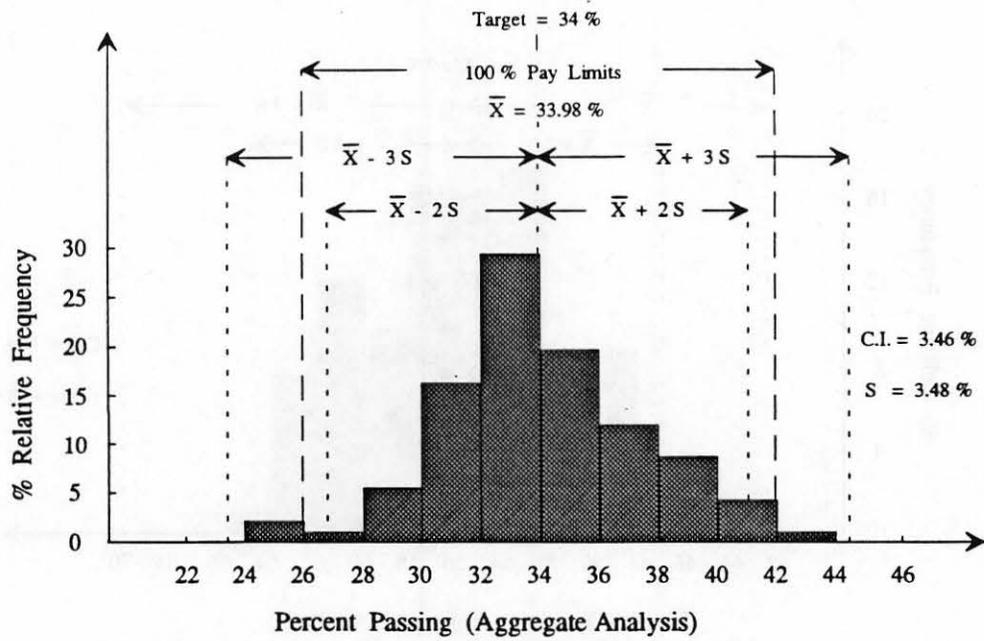


Figure D-6. Percent Passing Sieve No. 4

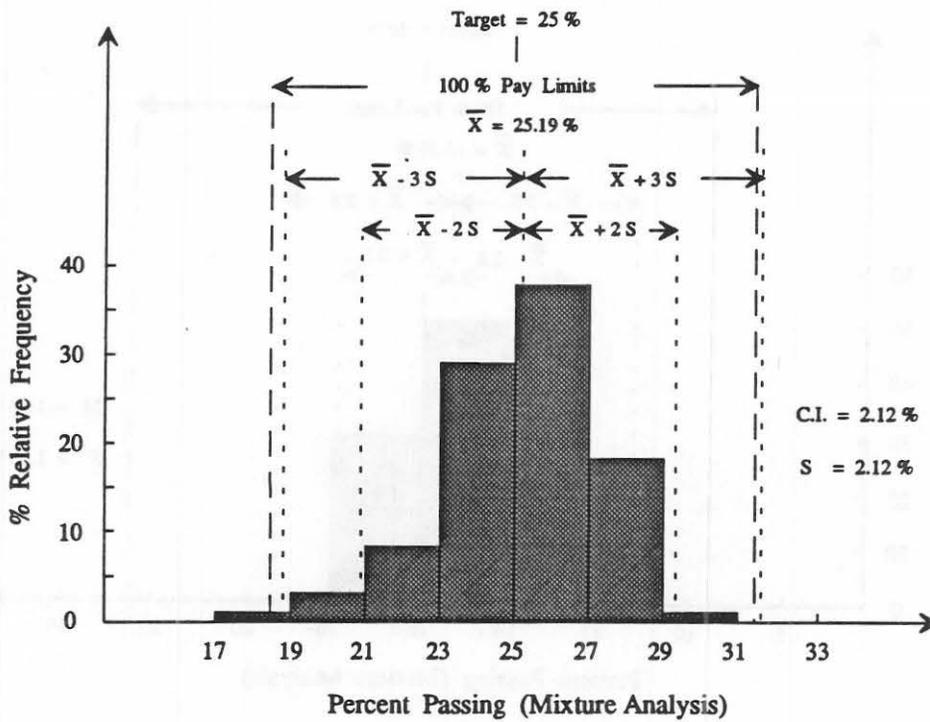
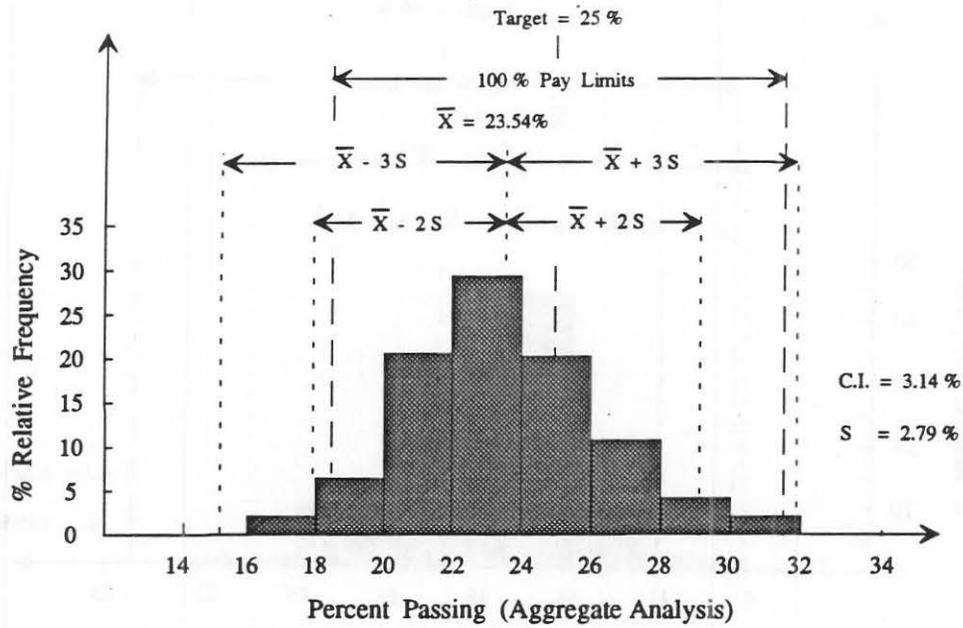


Figure D-7. Percent Passing Sieve No. 10

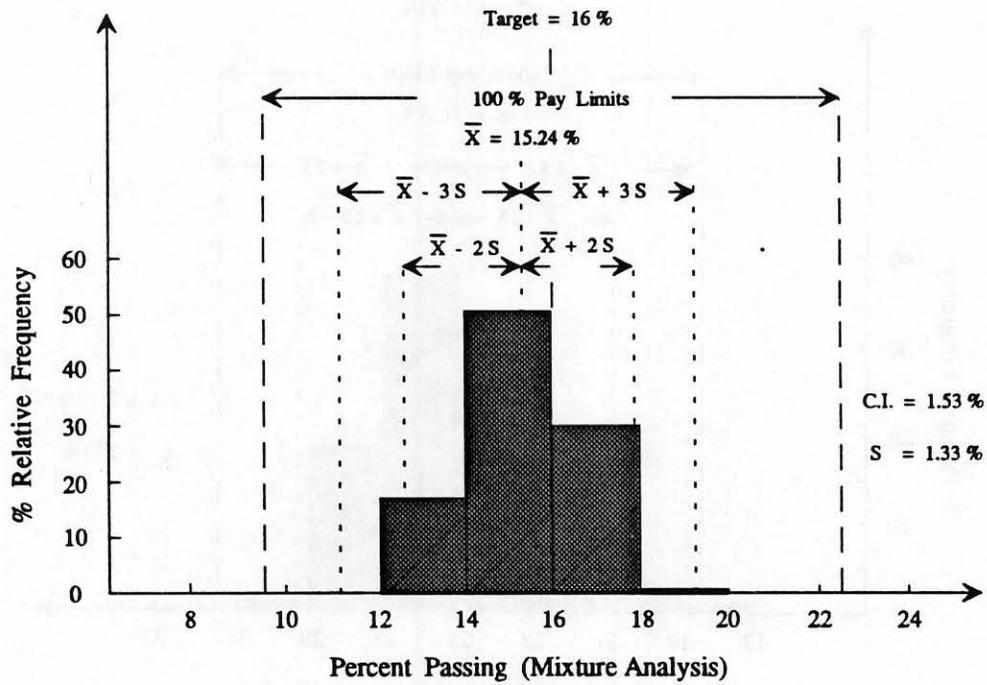
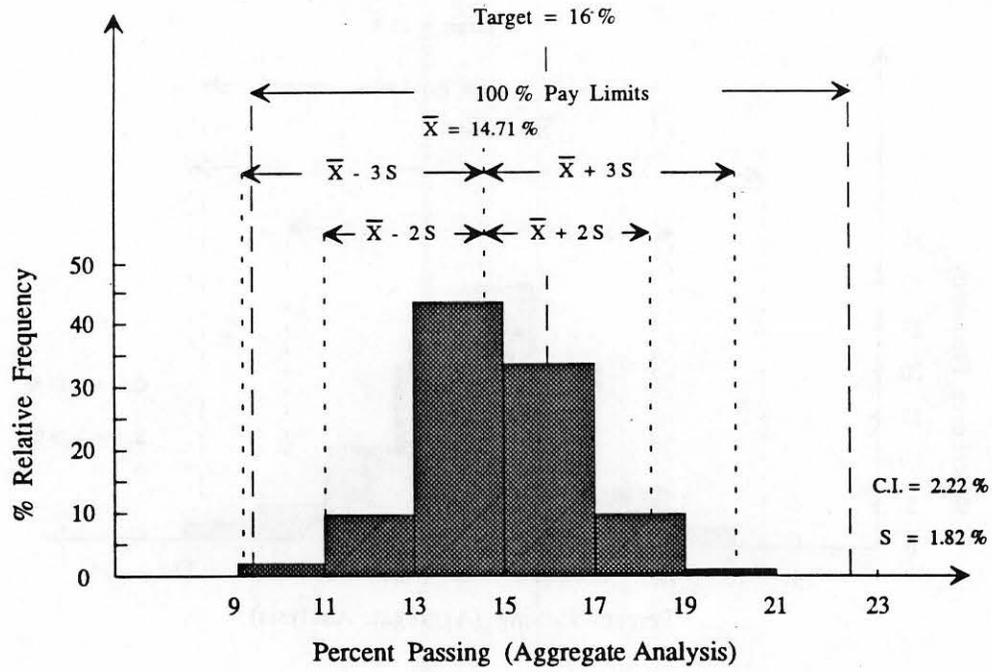


Figure D-8. Percent Passing Sieve No. 40

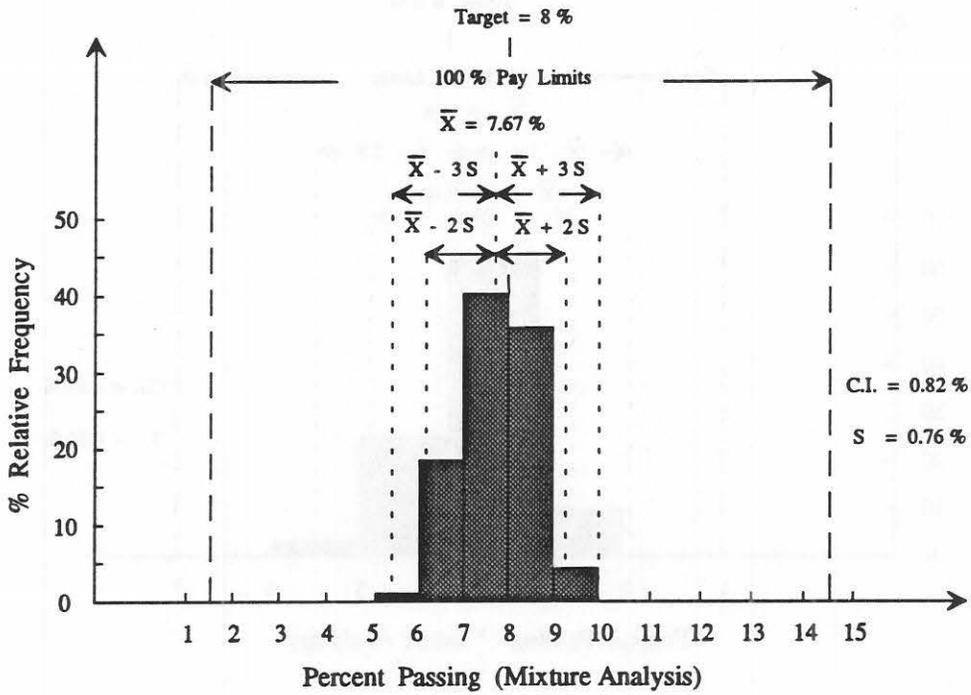
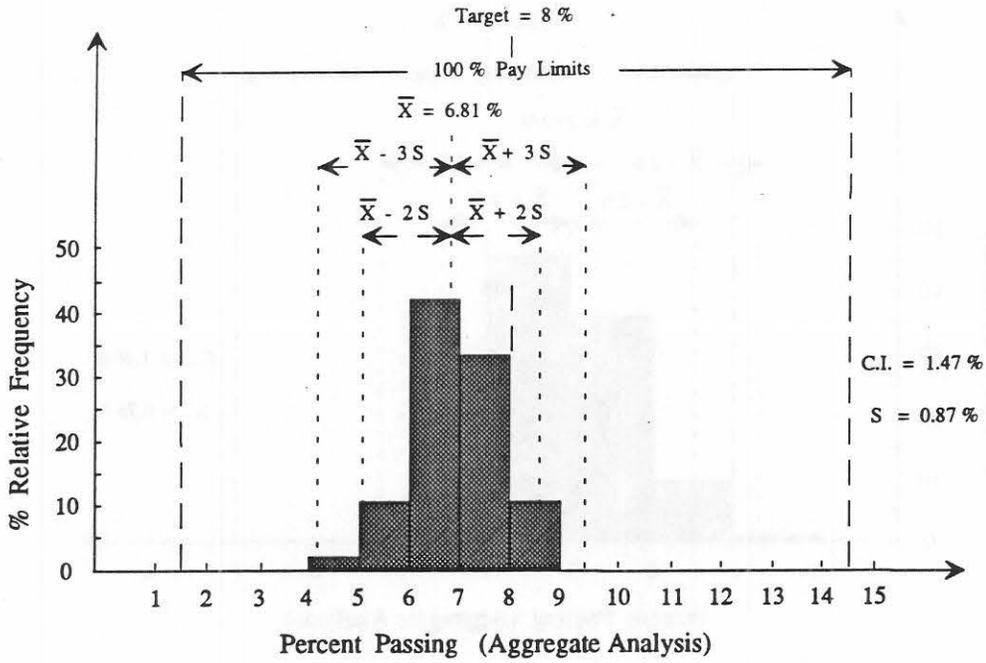


Figure D-9. Percent Passing Sieve No. 80

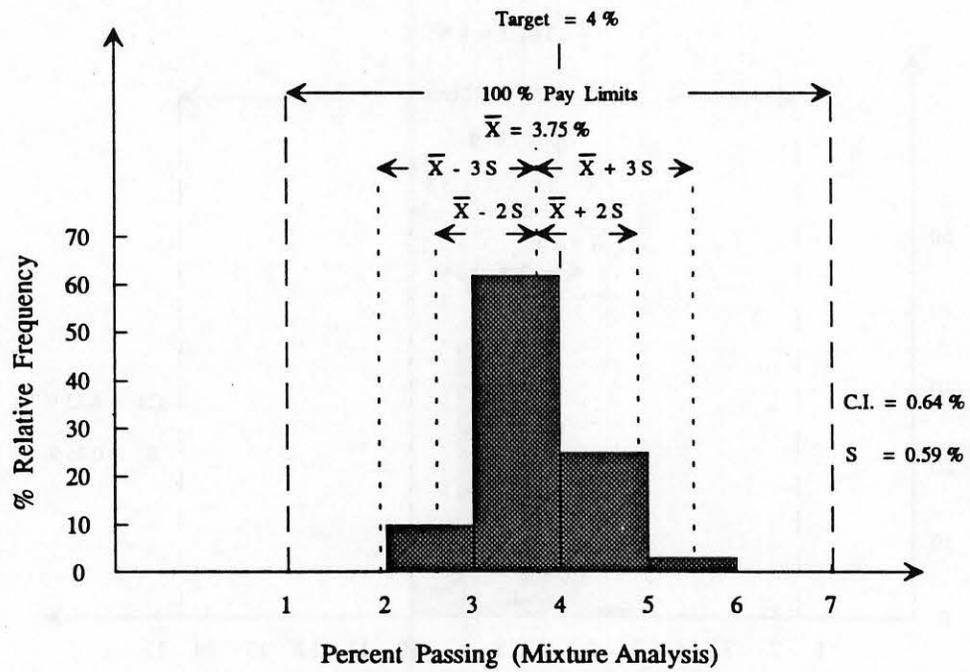
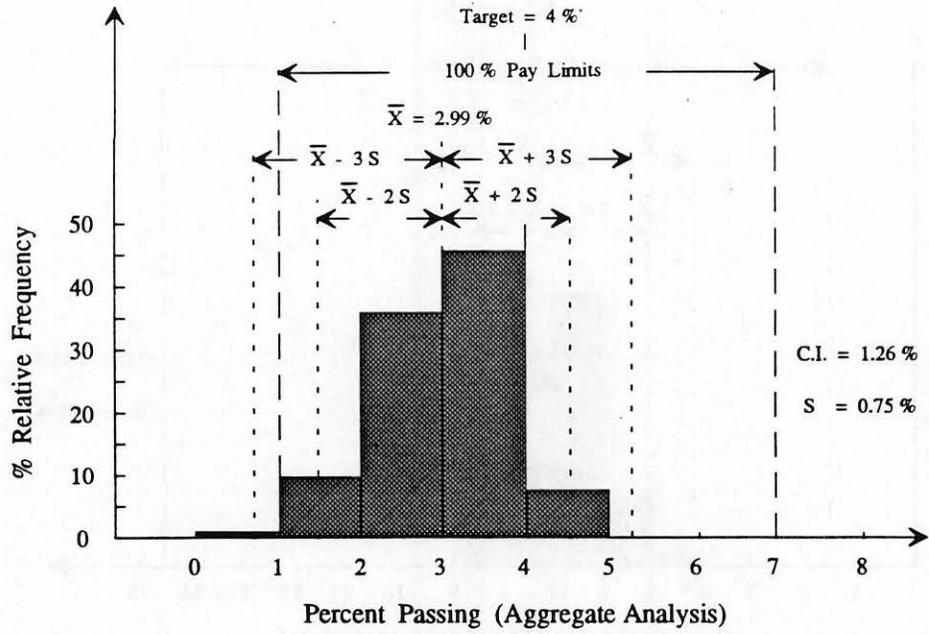


Figure D-10. Percent Passing Sieve No. 200

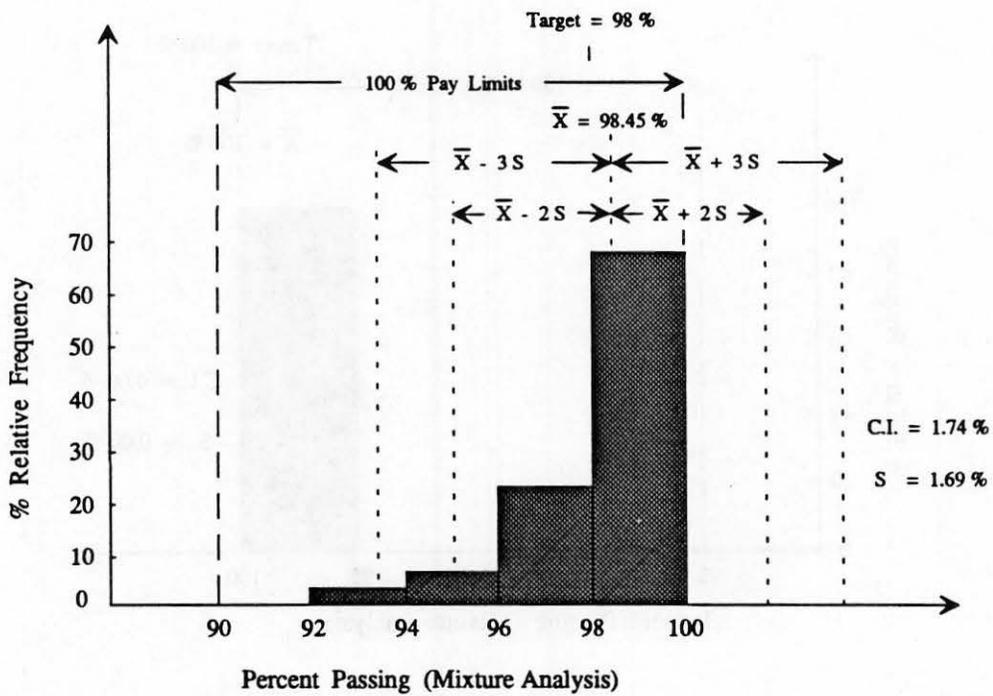
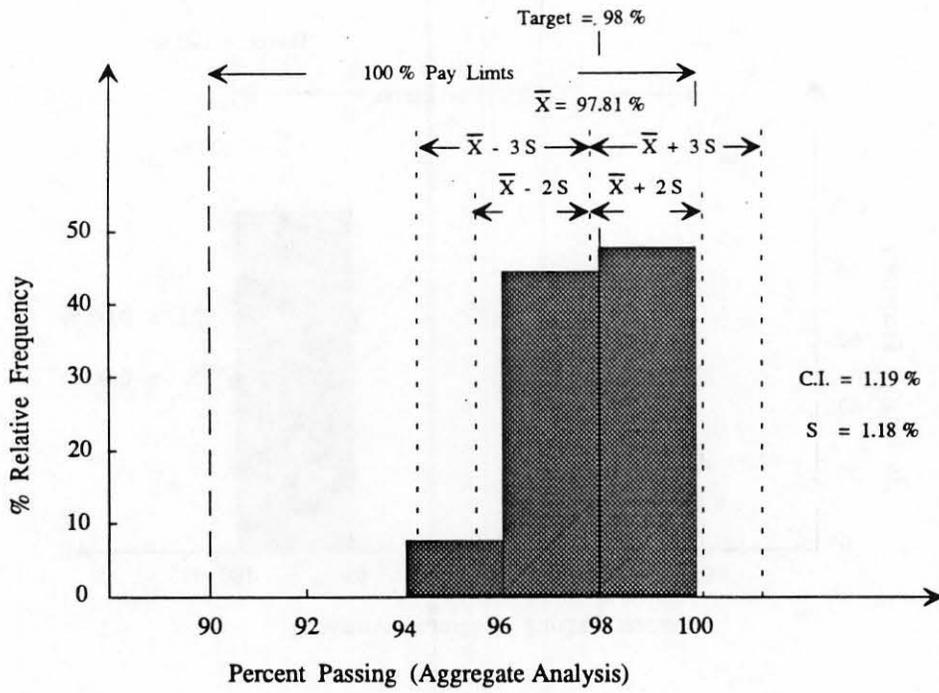


Figure D-2. Percent Passing Sieve 1"

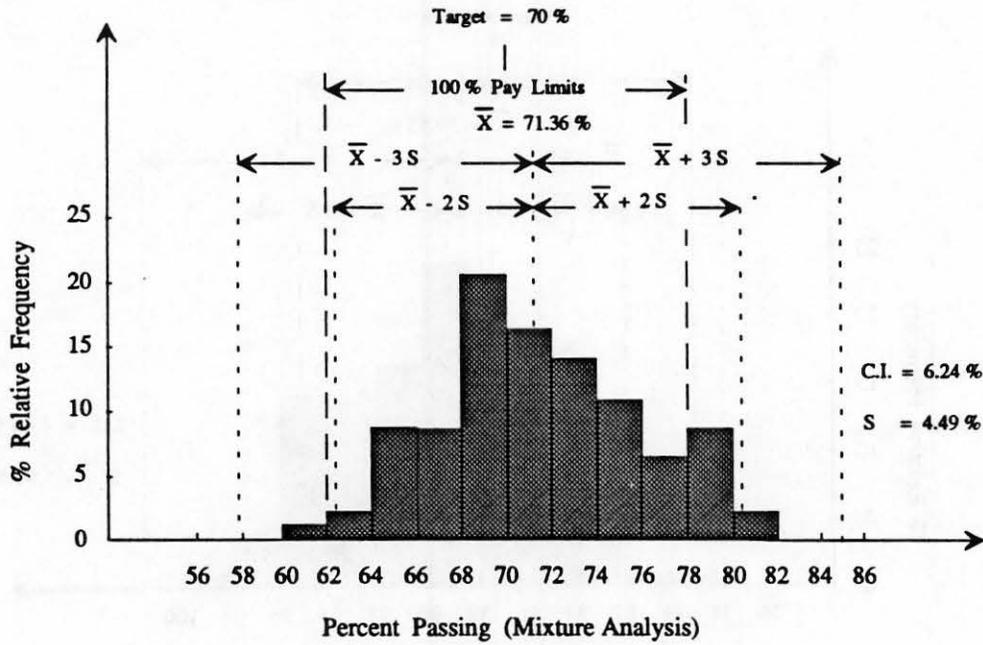
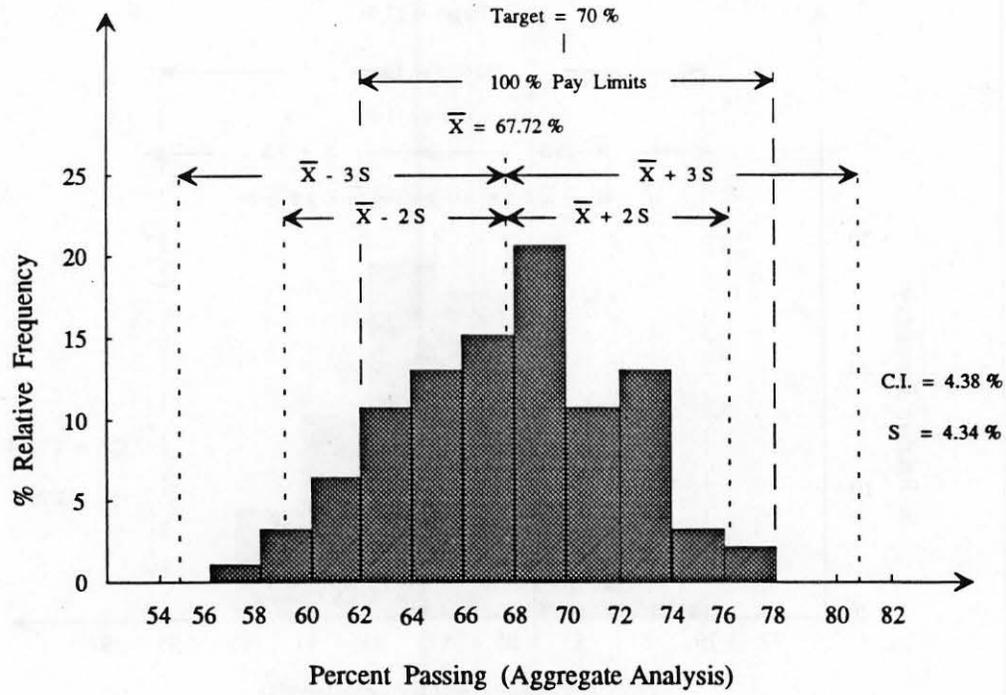


Figure D-4. Percent Passing Sieve 1/2"

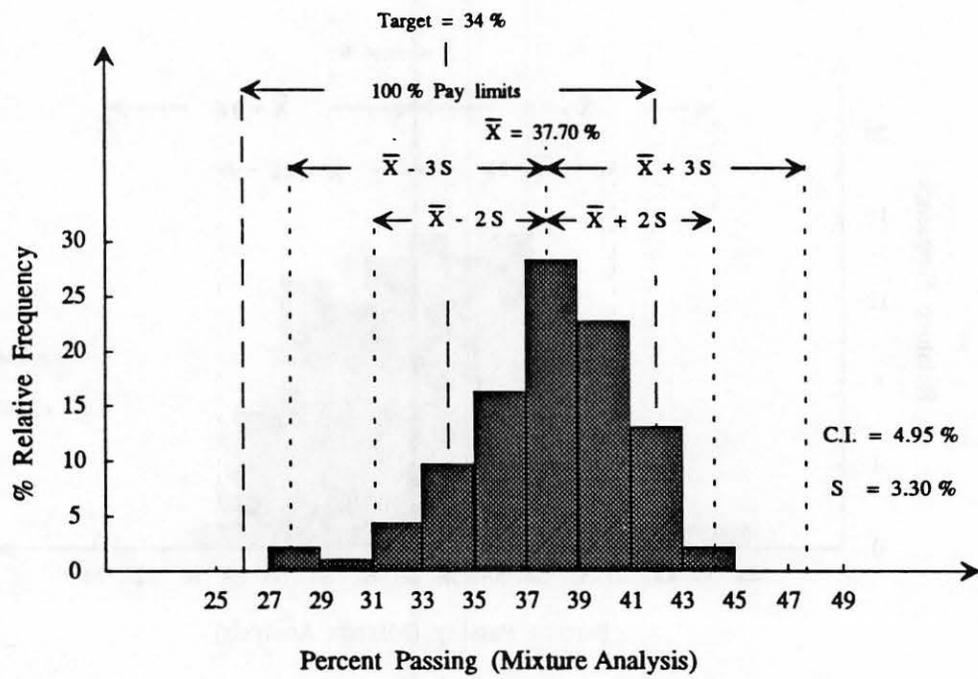
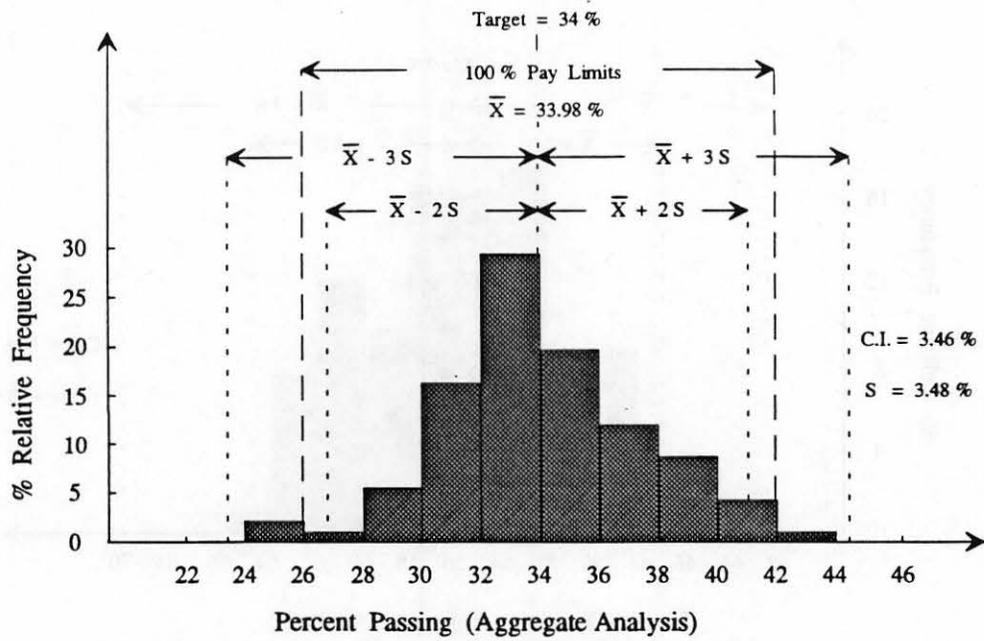


Figure D-6. Percent Passing Sieve No. 4

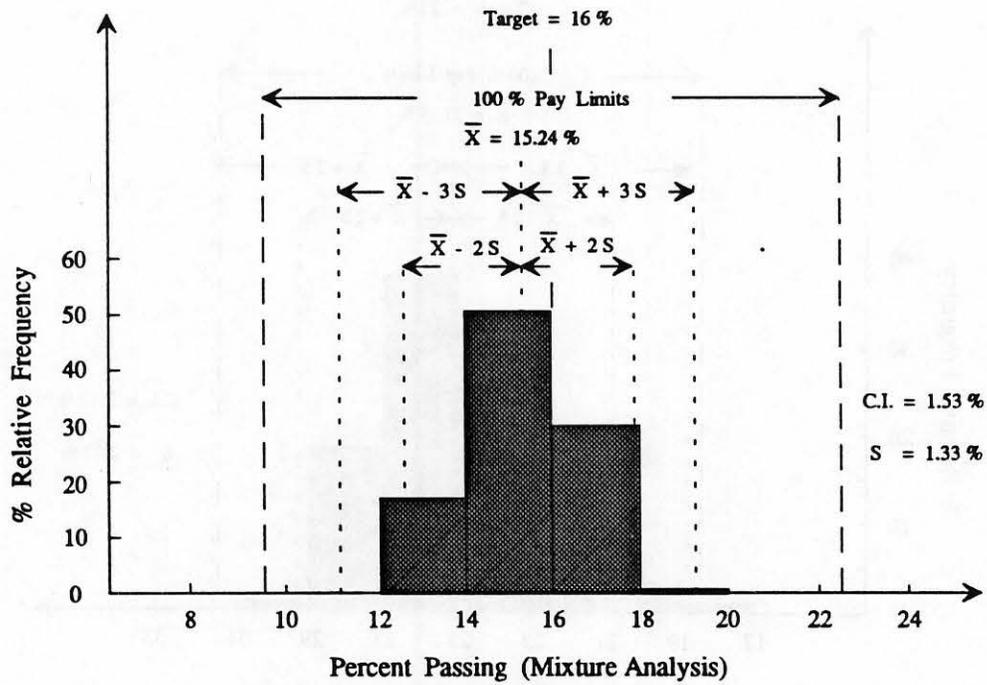
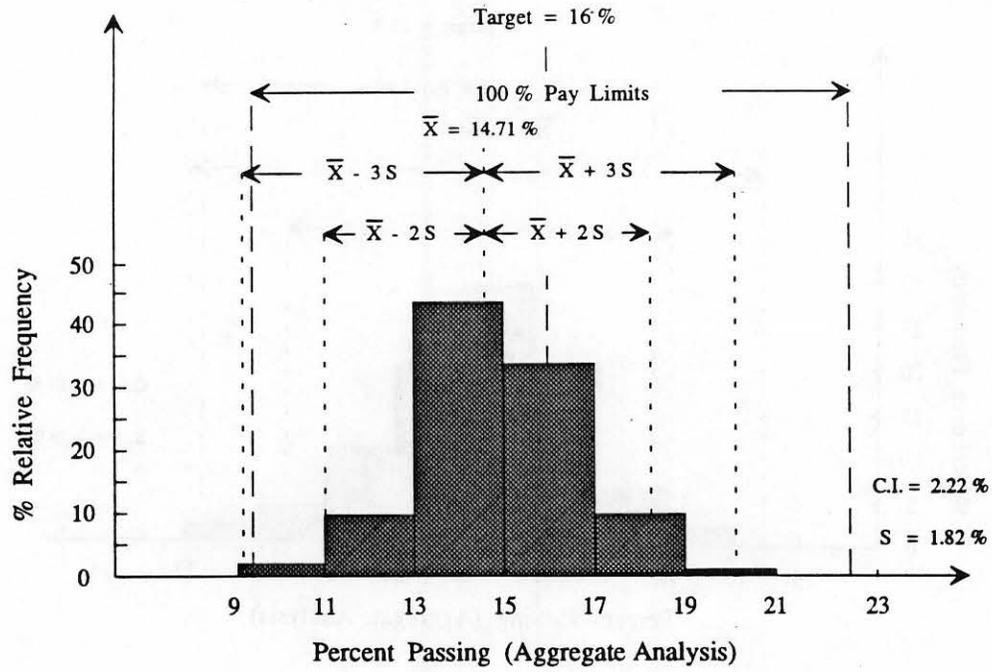


Figure D-8. Percent Passing Sieve No. 40

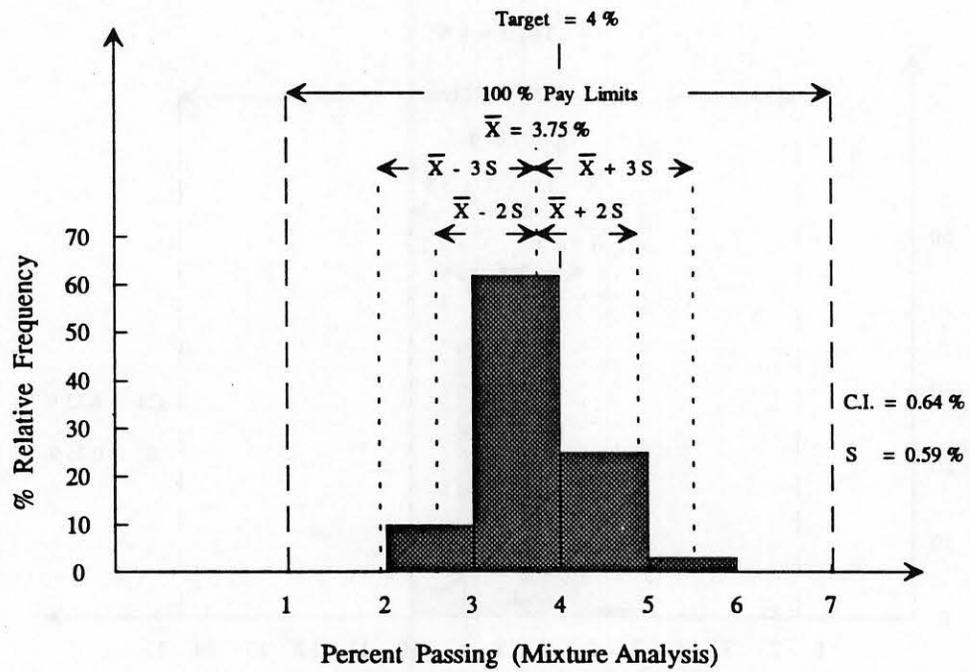
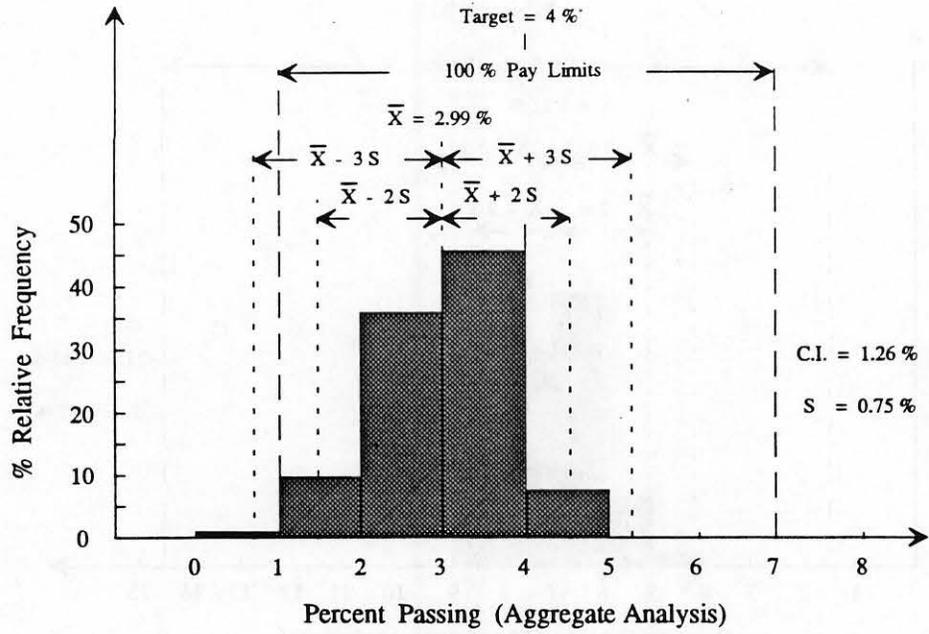


Figure D-10. Percent Passing Sieve No. 200

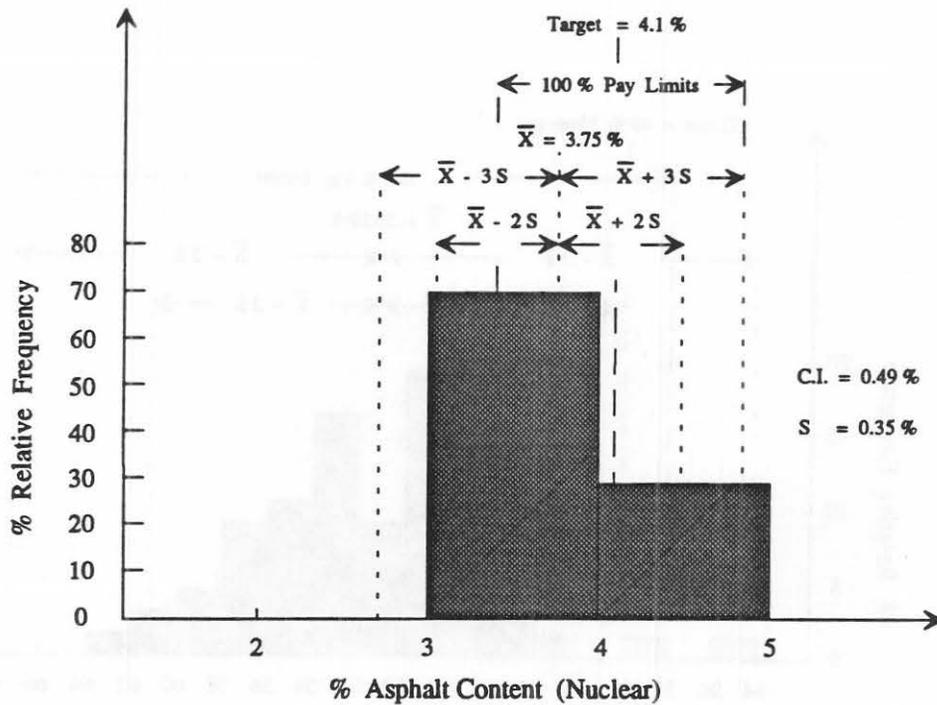
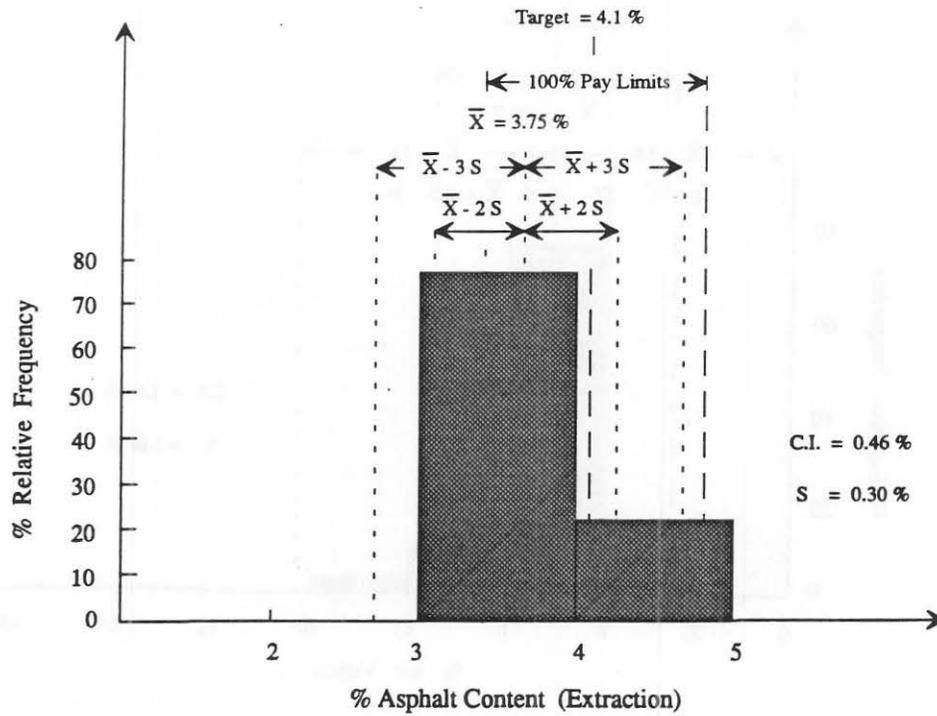


Figure D-11. Asphalt Content (Percent)

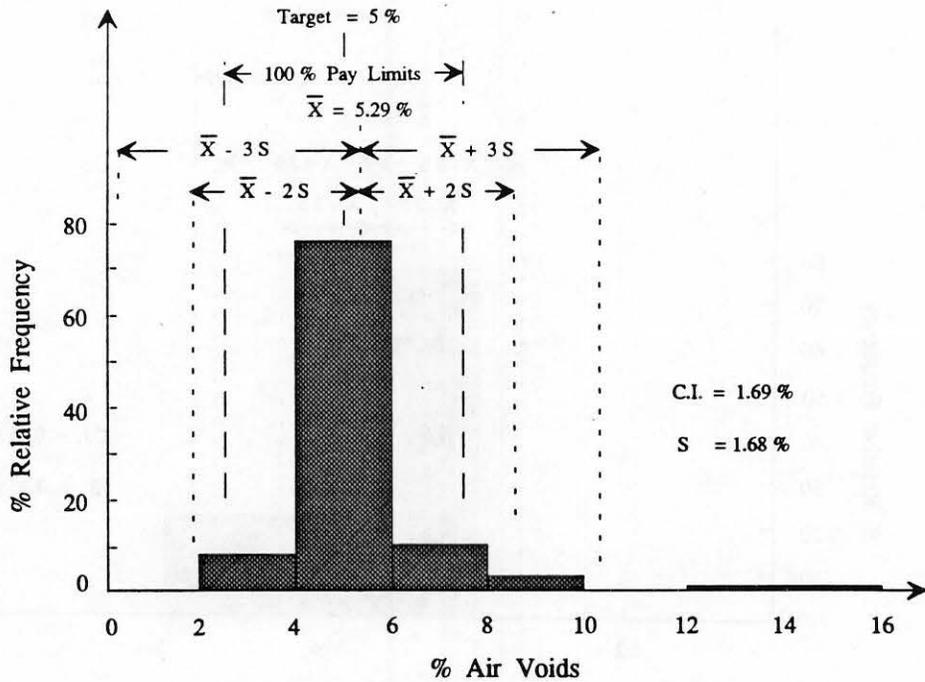


Figure D-12. Air Voids (Percent)

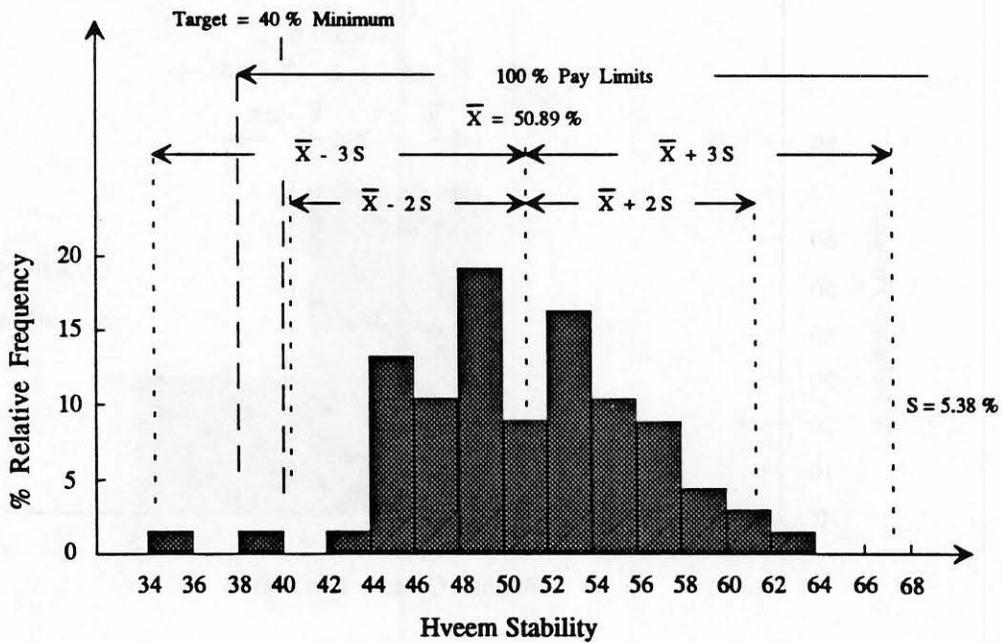


Figure D-13. Hveem Stability

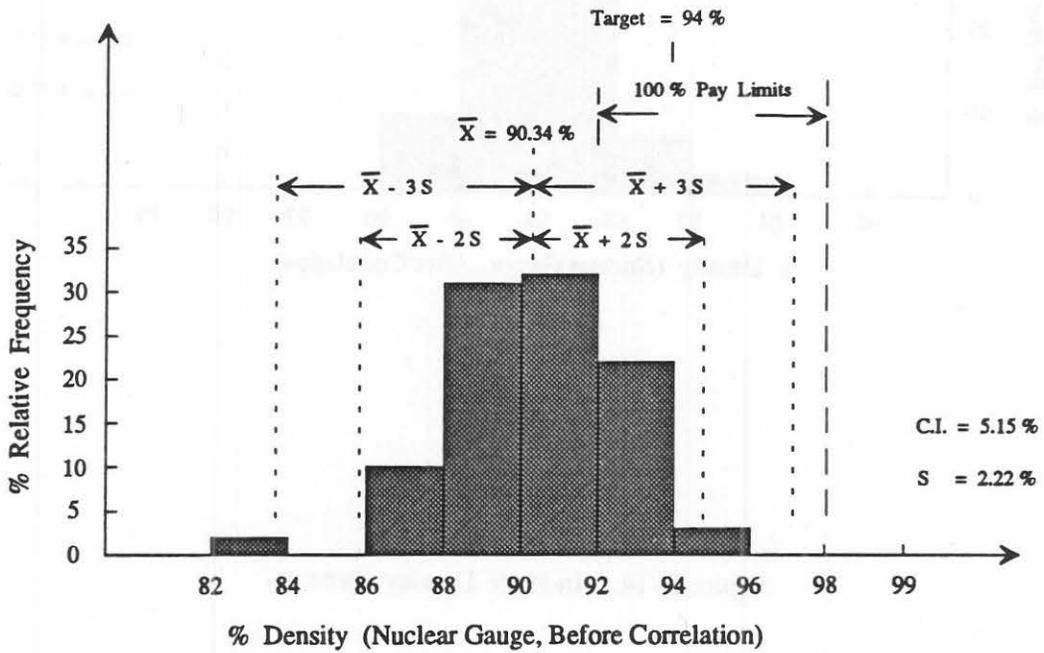
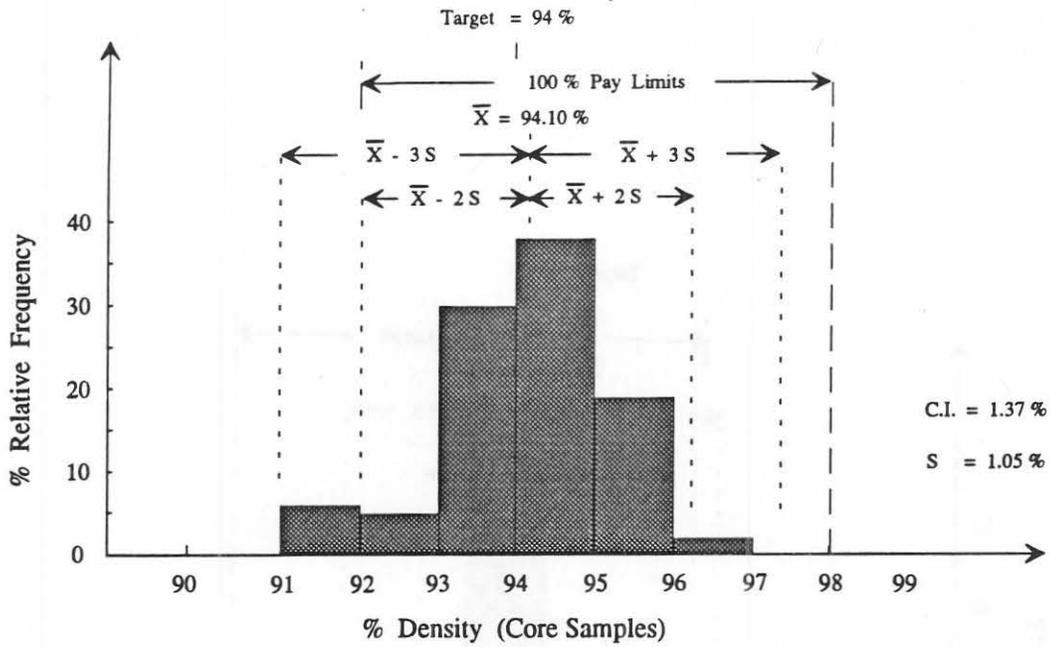


Figure D-14. In-Place Density (Percent)

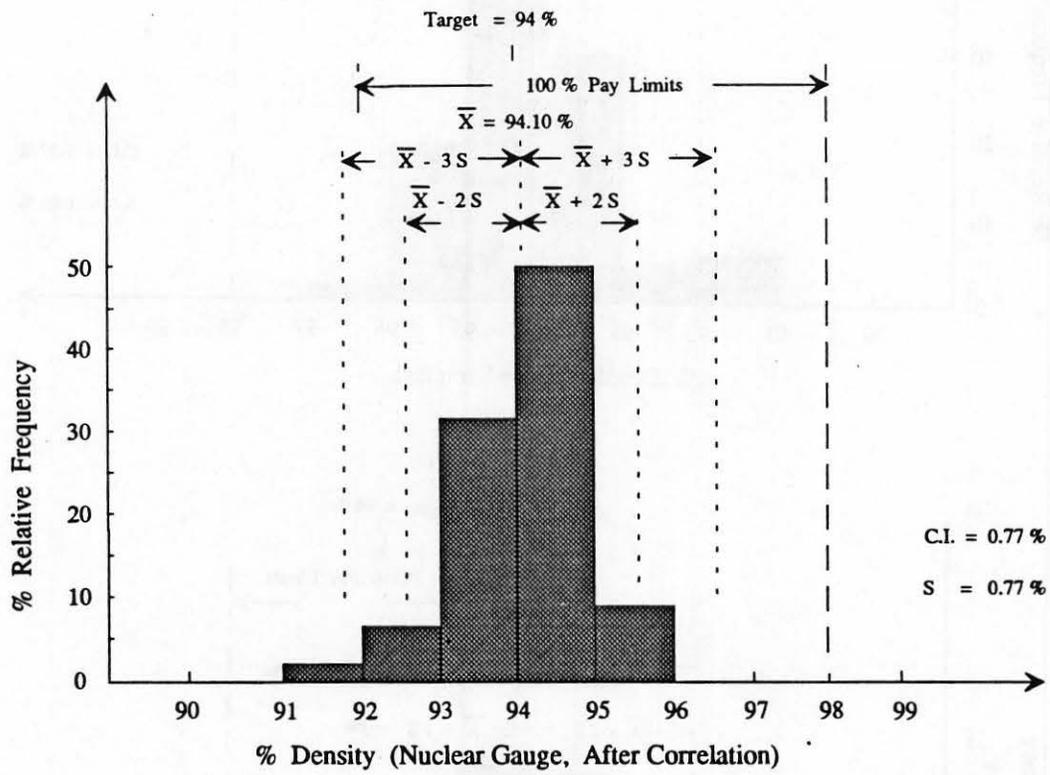
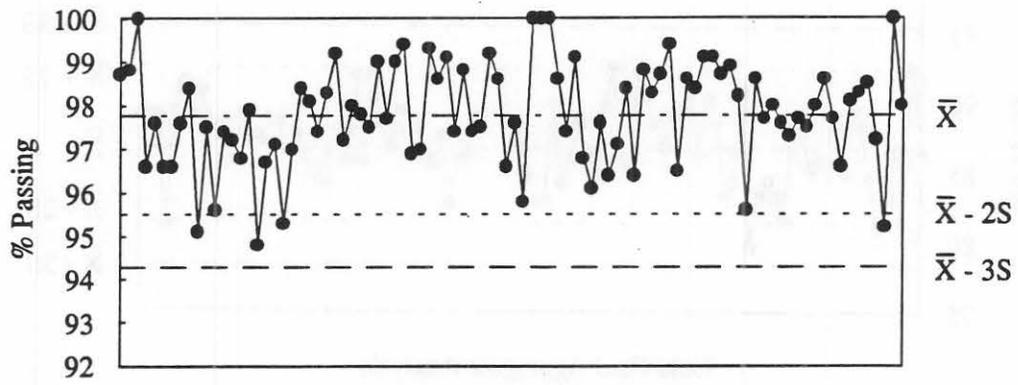


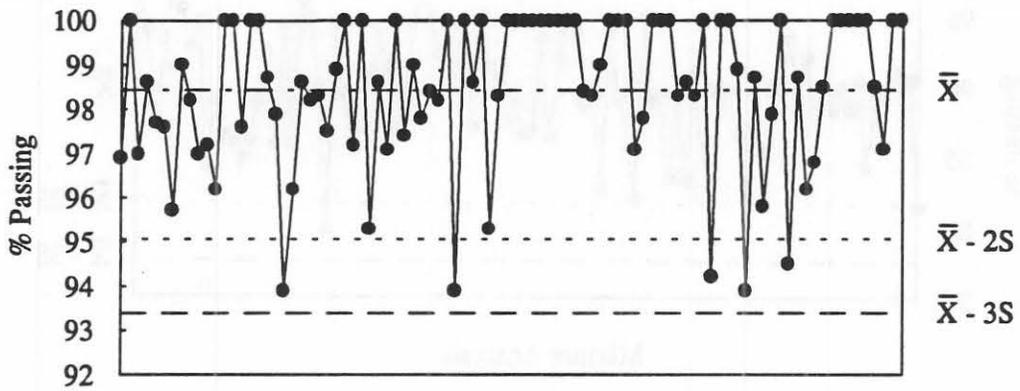
Figure D-14. In-Place Density (Percent)

APPENDIX E

X-CHARTS OF TEST RESULTS



Cold Feed Aggregate Analysis



Mixture Analysis

Figure E-1. Percent Passing Sieve 1"

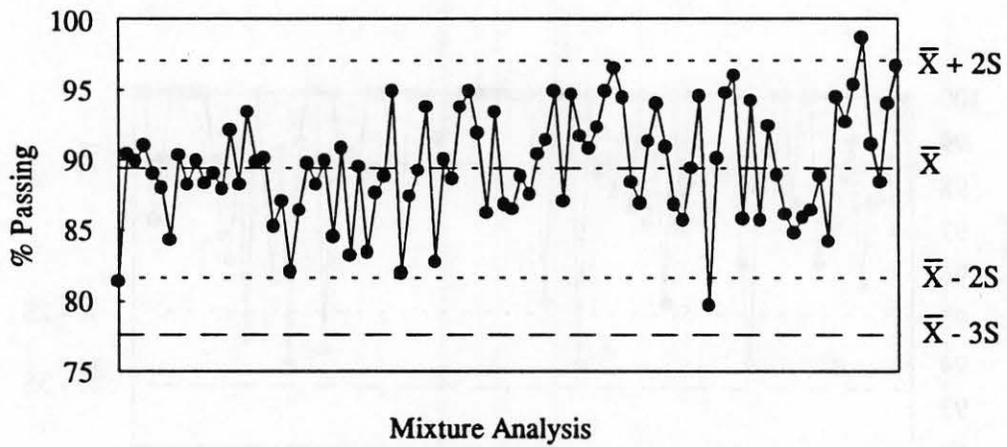
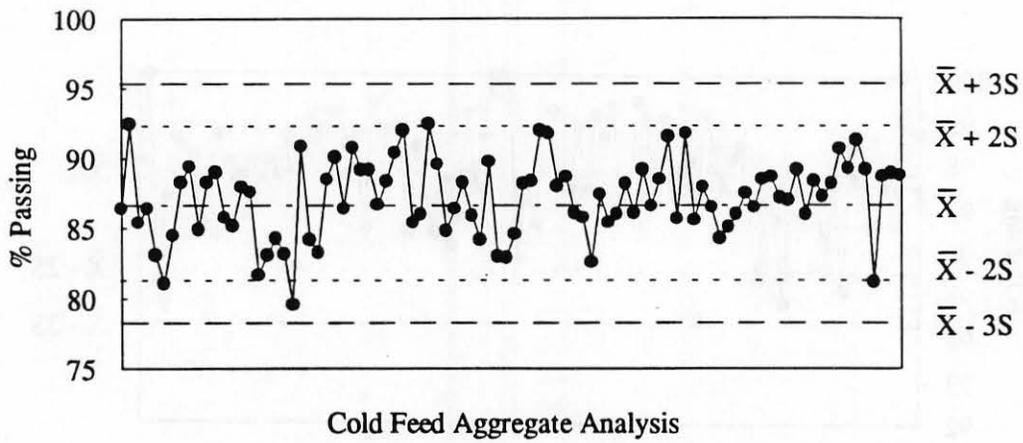


Figure E-2. Percent Passing Sieve 3/4"

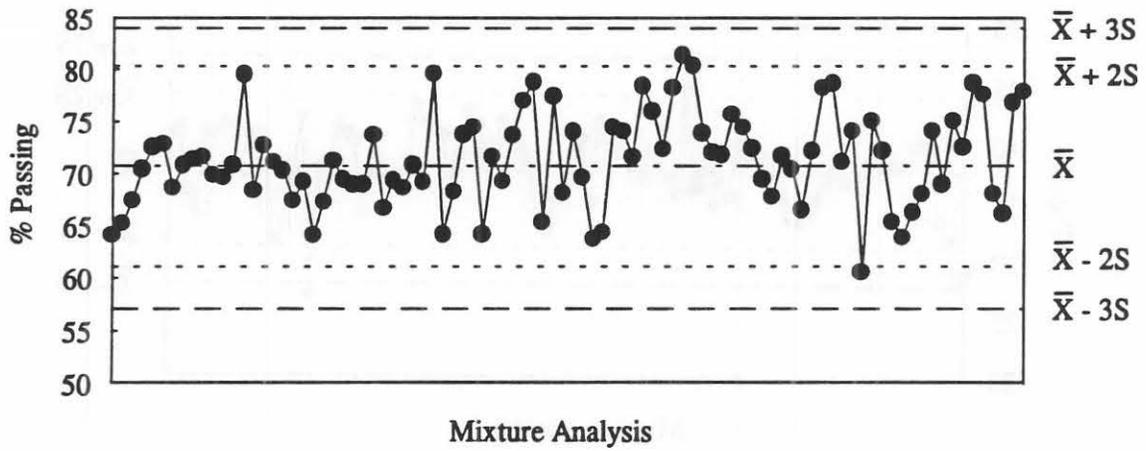
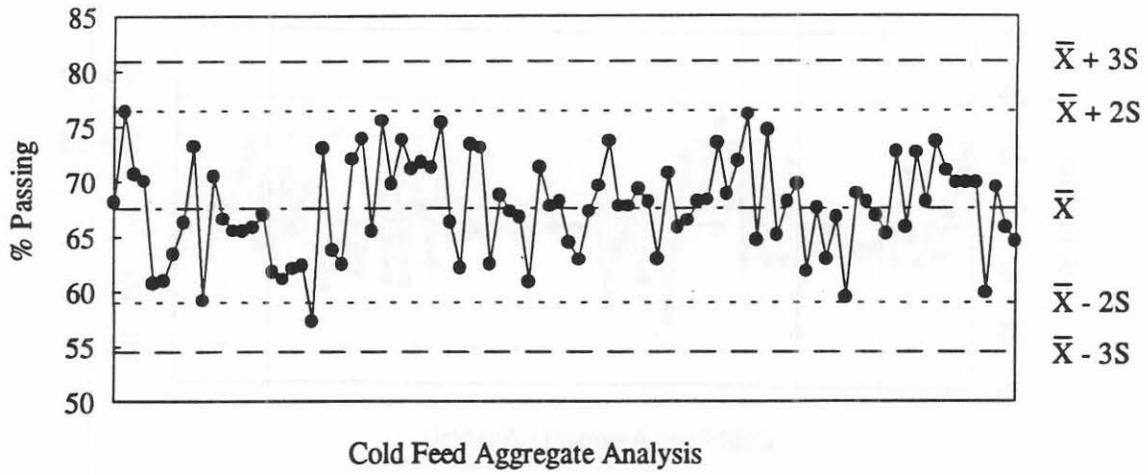
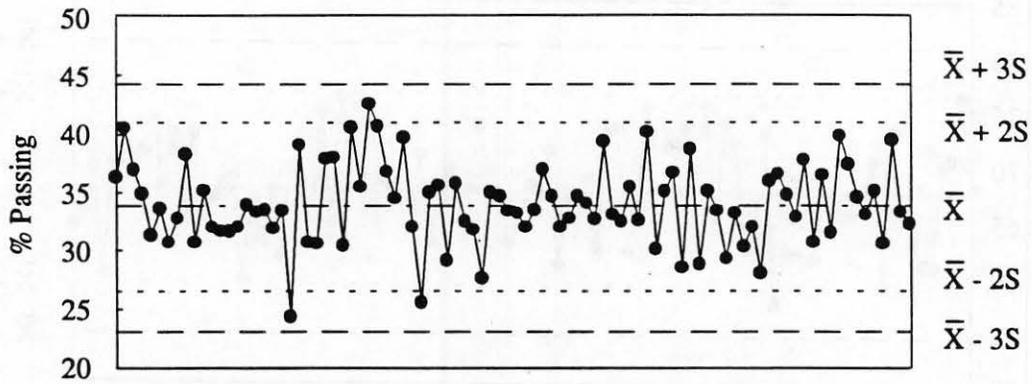
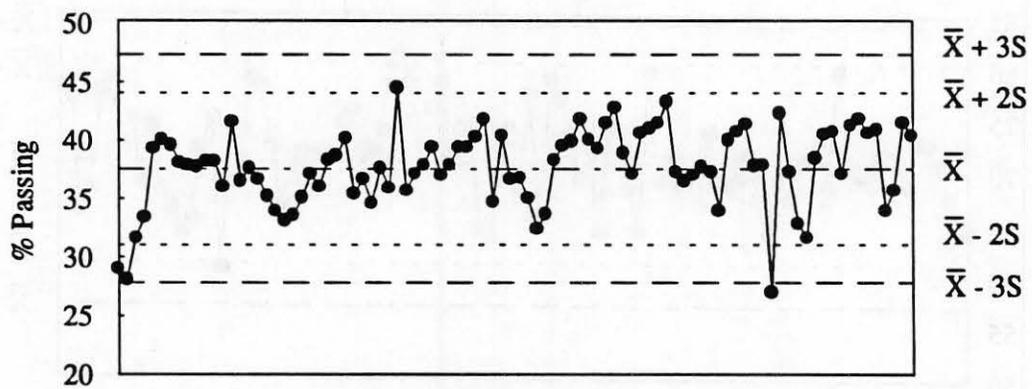


Figure E-3. Percent Passing Sieve 1/2"



Cold Feed Aggregate Analysis



Mixture Analysis

Figure E-4. Percent Passing Sieve No. 4

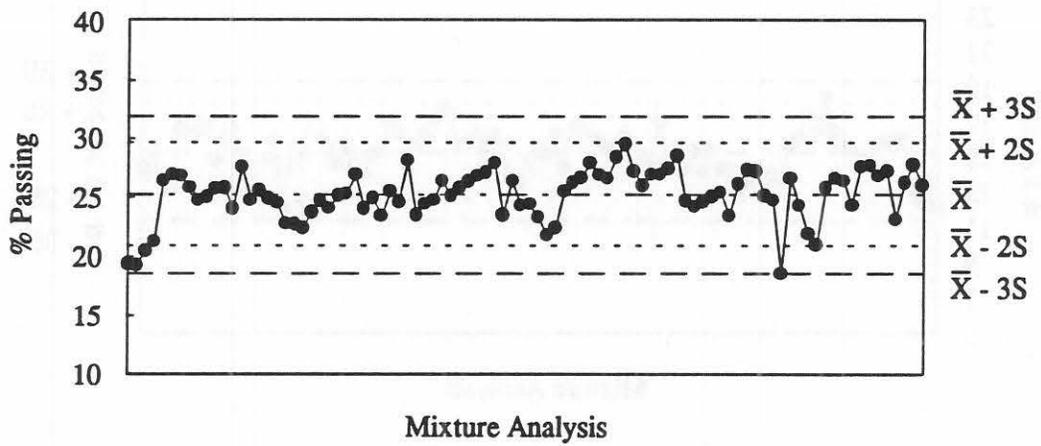
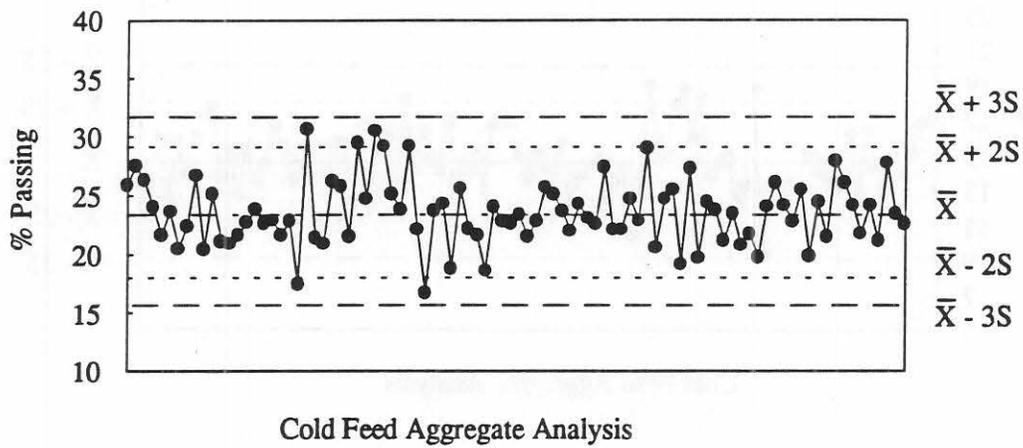


Figure E-5. Percent Passing Sieve No. 10

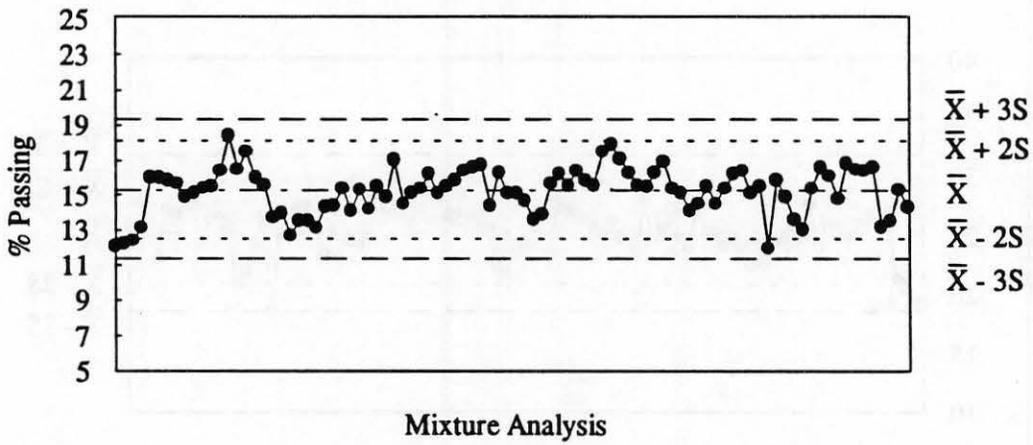
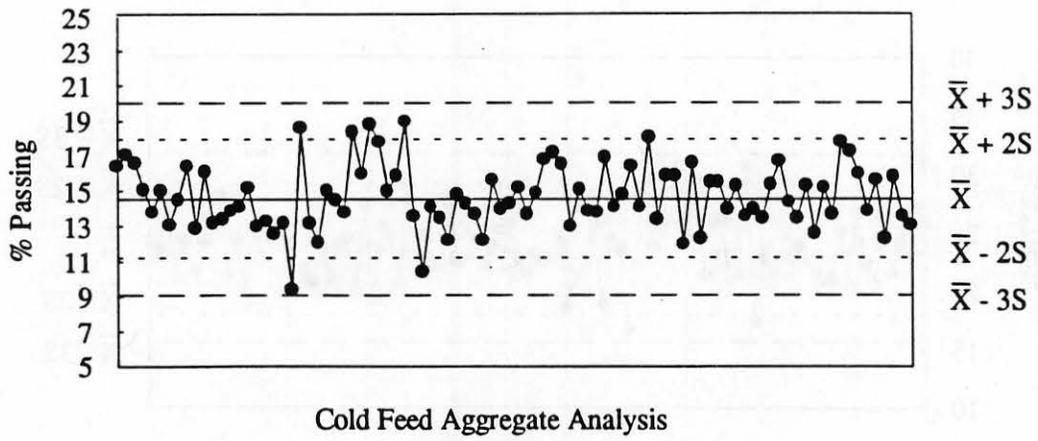
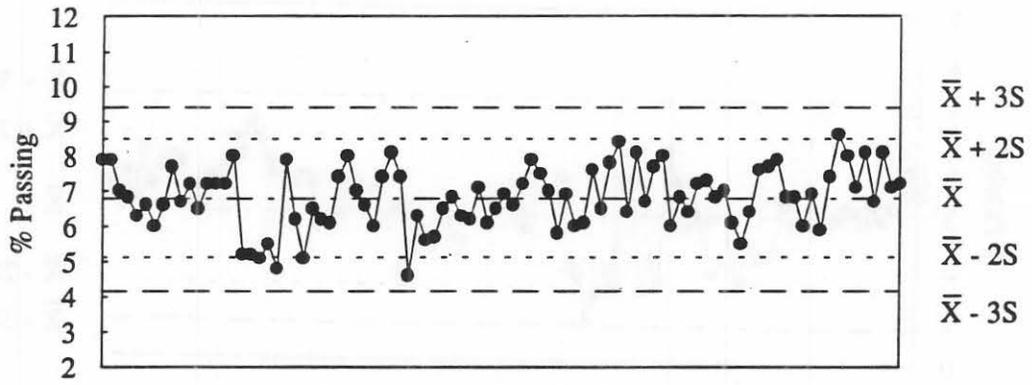
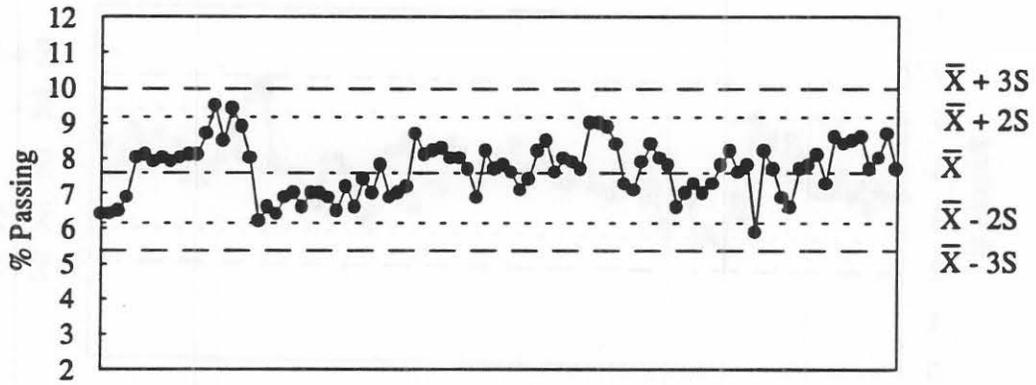


Figure E-6. Percent Passing Sieve No. 40



Cold Feed Aggregate Analysis



Mixture Analysis

Figure E-7. Percent Passing Sieve No. 80

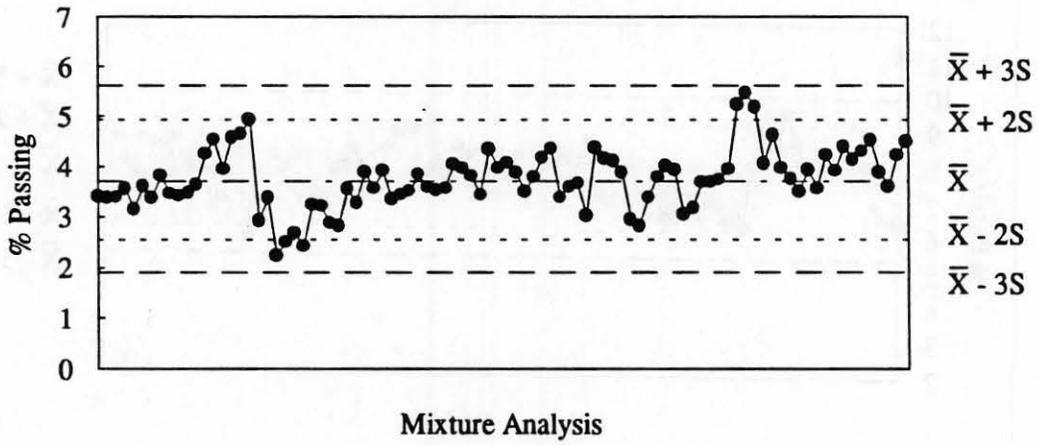
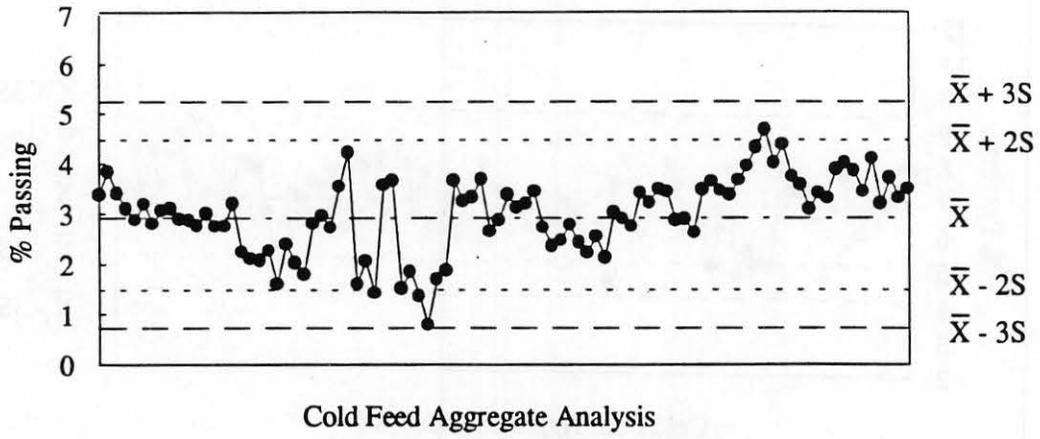


Figure E-8. Percent Passing Sieve No. 200

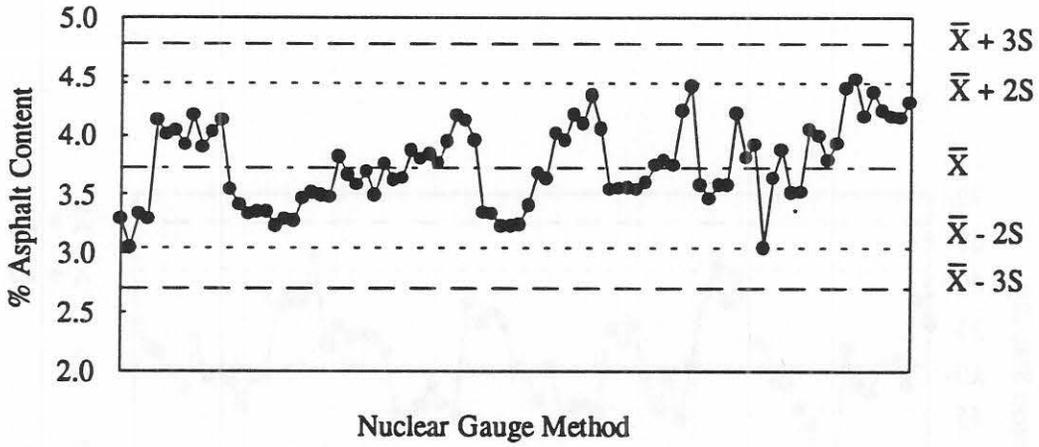
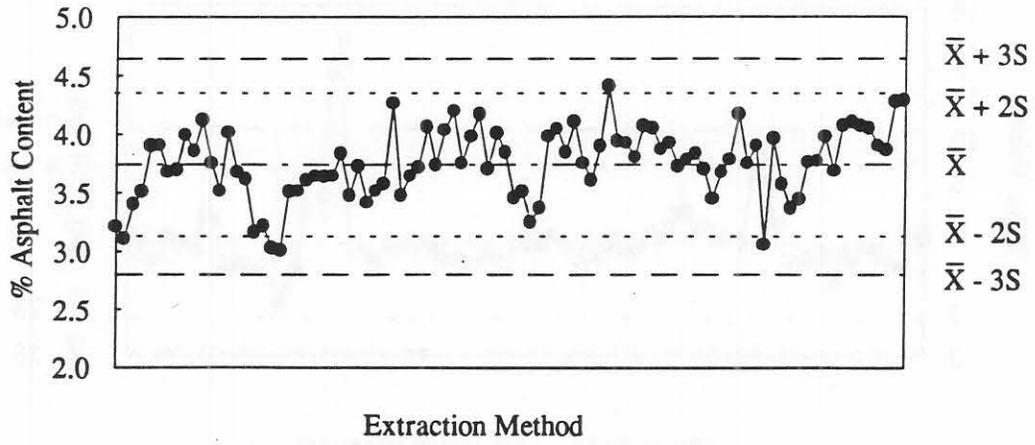


Figure E-9. Asphalt Content (Percent)

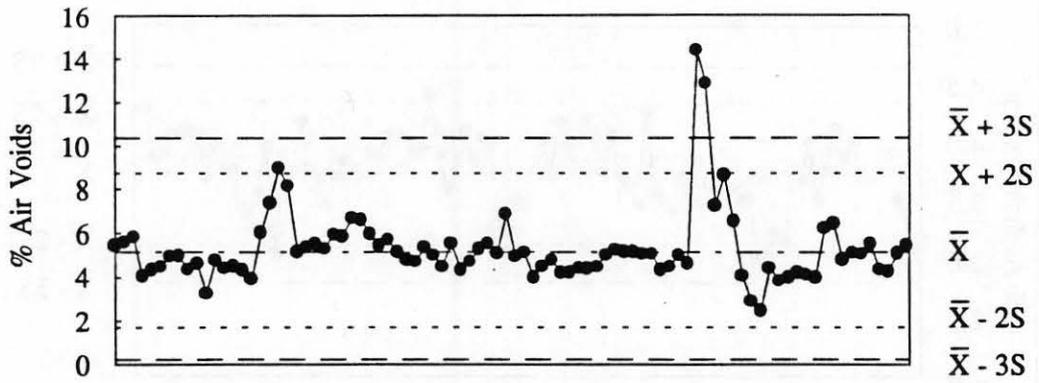


Figure E-10. Air Voids (Percent)

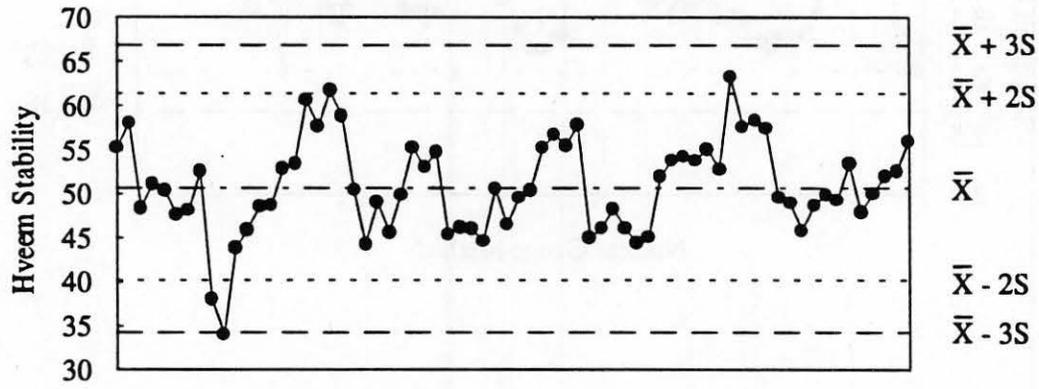
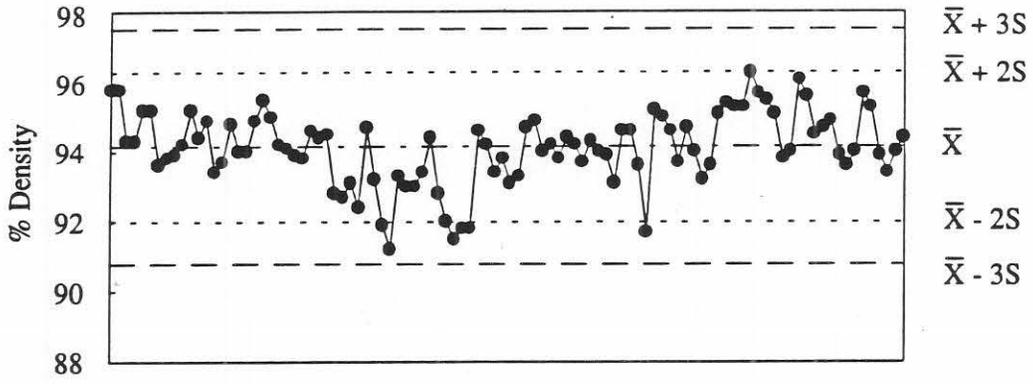
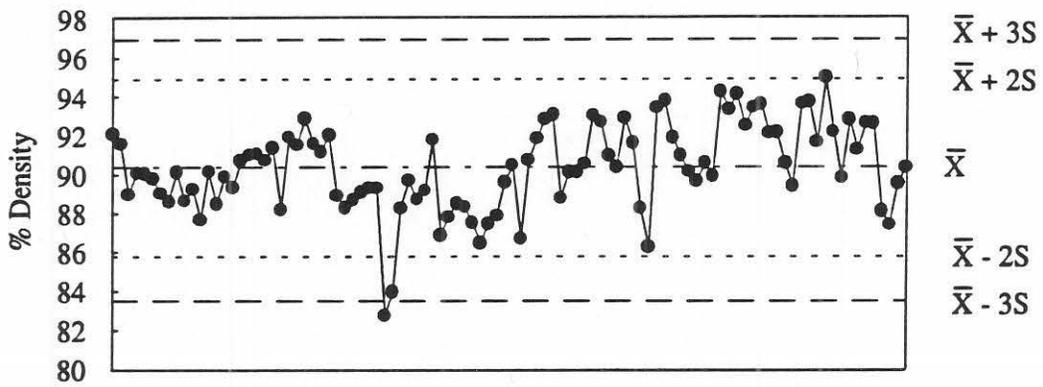


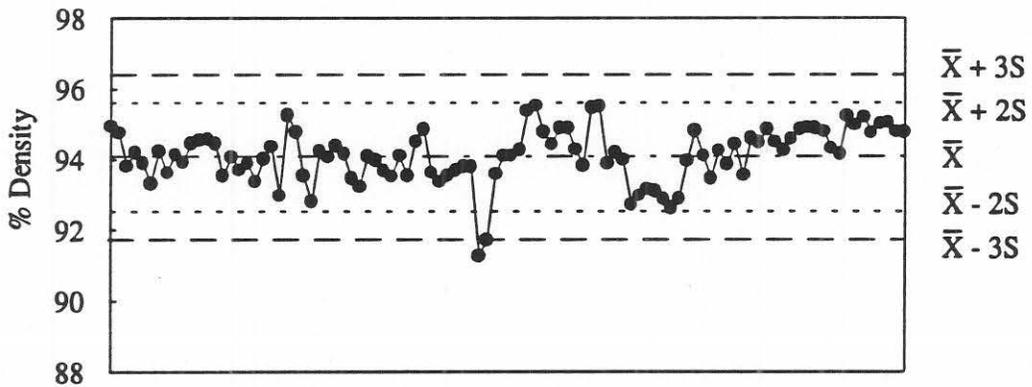
Figure E-11. Hveem Stability



Core Samples



Nuclear Gauge, Before Correlation



Nuclear Gauge, After Correlation

Figure E-12. In-Place Density (Percent)

APPENDIX F

ODOT QUALITY ASSURANCE SPECIFICATIONS
ACCEPTANCE SCHEDULE

Mix Characteristics	Pay Factor	Number of Tests			
		1	2	3	4 ^a
Average of Deviations from Target (Without Regard to Signs)					
Asphalt Cement Content (Extraction or Nuclear)	1.00	0.00 - 0.70	0.00 - 0.50	0.00 - 0.40	0.00 - 0.35
	0.95	0.71 - 0.80	0.51 - 0.57	0.41 - 0.46	0.36 - 0.40
	0.90	0.81 - 0.90	0.58 - 0.64	0.47 - 0.52	0.41 - 0.45
	0.80	0.91 - 1.00	0.65 - 0.71	0.53 - 0.58	0.46 - 0.50
Target: JMF-Percent (%)	Unacceptable ^b	Over 1.00	Over 0.71	Over 0.58	Over 0.50
Average of Deviations from Target (Without Regard to Signs)					
Asphalt Cement Content (Digital Print-out)	1.00	0.00 - 0.30	0.00 - 0.21	0.00 - 0.17	0.00 - 0.15
	0.95	0.31 - 0.35	0.22 - 0.25	0.18 - 0.20	0.16 - 0.18
	0.90	0.36 - 0.41	0.26 - 0.29	0.21 - 0.24	0.19 - 0.21
	0.80	0.42 - 0.46	0.30 - 0.33	0.25 - 0.27	0.22 - 0.23
Target: JMF-Percent (%)	Unacceptable ^b	Over 0.46	Over 0.33	Over 0.27	Over 0.20
Average of Deviations from Target (Without Regard to Signs)					
Gradation: No.4 & Larger Sieves ^c	1.00	0.00 - 8.00	0.00 - 5.66	0.00 - 4.62	0.00 - 4.00
	0.98	8.01 - 9.00	5.67 - 6.36	4.63 - 5.20	4.01 - 4.50
	0.96	9.01 - 10.00	6.37 - 7.07	5.21 - 5.77	4.51 - 5.00
	0.94	10.01 - 11.00	7.08 - 7.78	5.78 - 6.35	5.01 - 5.50
	0.92	11.01 - 12.00	7.79 - 8.49	6.36 - 6.93	5.51 - 6.00
	0.90	12.01 - 13.00	8.50 - 9.19	6.94 - 7.51	6.01 - 6.50
	0.88	13.01 - 14.00	9.20 - 9.90	7.52 - 8.08	6.51 - 7.00
	0.85	14.01 - 15.00	9.91 - 10.61	8.09 - 8.66	7.01 - 7.50
	0.82	15.01 - 16.00	10.62 - 11.32	8.67 - 9.24	7.51 - 8.00
	0.79	16.01 - 17.00	11.33 - 12.02	9.25 - 9.82	8.01 - 8.50
	0.76	17.01 - 18.00	12.03 - 12.73	9.83 - 10.39	8.51 - 9.00
Target: JMF-Percent (%)	Unacceptable ^b	Over 18.00	Over 12.73	Over 10.39	Over 9.00
Average of Deviations from Target (Without Regard to Signs)					
Gradation: No. 10 through 100 Sieves ^c	1.00	0.00 - 6.50	0.00 - 4.60	0.00 - 3.75	0.00 - 3.25
	0.98	6.51 - 7.50	4.61 - 5.30	3.76 - 4.33	3.26 - 3.75
	0.96	7.51 - 8.50	5.31 - 6.01	4.34 - 4.91	3.76 - 4.25
	0.93	8.51 - 9.50	6.02 - 6.72	4.92 - 5.48	4.26 - 4.75
	0.91	9.51 - 10.50	6.73 - 7.43	5.49 - 6.06	4.76 - 5.25
	0.88	10.51 - 11.50	7.44 - 8.13	6.07 - 6.64	5.26 - 5.75
	0.85	11.51 - 12.50	8.14 - 8.84	6.65 - 7.22	5.76 - 6.25
	0.82	12.51 - 13.50	8.85 - 9.55	7.23 - 7.79	6.26 - 6.75
	0.79	13.51 - 14.50	9.56 - 10.25	7.80 - 8.37	6.76 - 7.25
	0.76	14.51 - 15.50	10.26 - 10.96	8.38 - 8.95	7.26 - 7.75
Target: JMF-Percent (%)	Unacceptable ^b	Over 15.50	Over 10.96	Over 8.95	Over 7.75

Mix Characteristics	Pay Factor	Number of Tests				
		1	2	3	4*	
Average of Deviations from Target (Without Regard to Signs)						
Gradation: No.200 Sieve ^c	1.00	0.00 - 3.00	0.00 - 2.12	0.00 - 1.73	0.00 - 1.50	
	0.98	3.01 - 3.40	2.13 - 2.40	1.74 - 1.96	1.51 - 1.70	
	0.96	3.41 - 3.80	2.41 - 2.69	1.97 - 2.19	1.71 - 1.90	
	0.94	3.81 - 4.20	2.70 - 2.97	2.20 - 2.43	1.91 - 2.10	
	0.91	4.21 - 4.60	2.98 - 3.25	2.44 - 2.66	2.11 - 2.30	
	0.88	4.61 - 5.00	3.26 - 3.54	2.67 - 2.89	2.31 - 2.50	
	0.85	5.01 - 5.40	3.55 - 3.82	2.90 - 3.12	2.51 - 2.70	
	0.82	5.41 - 5.80	3.83 - 4.10	3.13 - 3.35	2.71 - 2.90	
	0.79	5.81 - 6.20	4.11 - 4.38	3.36 - 3.58	2.91 - 3.10	
	0.76	6.21 - 6.60	4.39 - 4.67	3.59 - 3.81	3.11 - 3.30	
Target: JMF-Percent (%)	Unacceptable ^b	Over 6.60	Over 4.67	Over 3.81	Over 3.30	
Average of Deviations from Target (Without Regard to Signs)						
Air Voids (Lab Molded Specimens)	1.00	0.00 - 2.50	0.00 - 1.77	0.00 - 1.44	0.00 - 1.25	
	0.99	2.51 - 2.58	1.78 - 1.82	1.45 - 1.49	1.26 - 1.29	
	0.97	2.59 - 2.67	1.83 - 1.89	1.50 - 1.54	1.30 - 1.34	
	0.94	2.68 - 2.75	1.90 - 1.94	1.55 - 1.59	1.35 - 1.38	
ADT	Target	0.90	2.76 - 2.83	1.95 - 2.00	1.60 - 1.63	1.39 - 1.42
5000 or more	5%	0.85	2.84 - 2.91	2.01 - 2.06	1.64 - 1.68	1.43 - 1.46
1000 - 5000	4%	0.79	2.92 - 3.00	2.07 - 2.12	1.69 - 1.73	1.47 - 1.50
1000 or less	3%	Unacceptable ^b	Over 3.00	Over 2.12	Over 1.73	Over 1.50
Average Deviations from Target (Considering Signs)						
Hveem Stability (Lab Molded Specimens)	1.00	(-2)	0	0	0	
	0.90	(-3)	(-2)	(-1)	(-1)	
	0.80	(-4)	(-3)	(-2)	(-2)	
	Unacceptable ^b	Over (-4)	Over (-3)	Over (-2)	Over (-2)	
Minimums:						
2500 ADT or more and All city streets	40					
Less than 2500 ADT	35					

Mix Characteristics	Pay Factor	Number of Tests			
		1	2	3	4 ^a
Average of Deviations from Target (Considering Signs)					
Roadway Density ^d	1.00	(+)4.00-(-)2.00	(+)2.83-(-)1.41	(+)2.31-(-)1.15	(+)2.00-(-)1.00
(Core or Nuclear)	0.99	(-)2.01-(-)2.60	(-)1.42-(-)1.84	(-)1.16-(-)1.50	(-)1.01-(-)1.30
	0.98	(-)2.61-(-)3.20	(-)1.85-(-)2.26	(-)1.51-(-)1.85	(-)1.31-(-)1.60
	0.96	(-)3.21-(-)3.80	(-)2.27-(-)2.69	(-)1.86-(-)2.19	(-)1.61-(-)1.90
	0.93	(-)3.81-(-)4.40	(-)2.70-(-)3.11	(-)2.20-(-)2.54	(-)1.91-(-)2.20
	0.89	(-)4.41-(-)5.00	(-)3.12-(-)3.54	(-)2.55-(-)2.89	(-)2.21-(-)2.50
	0.84	(-)5.01-(-)5.60	(-)3.55-(-)3.96	(-)2.90-(-)3.23	(-)2.51-(-)2.80
	0.78	(-)5.61-(-)6.20	(-)3.97-(-)4.38	(-)3.24-(-)3.58	(-)2.81-(-)3.10
	0.70	(-)6.21-(-)6.80	(-)4.39-(-)4.81	(-)3.59-(-)3.93	(-)3.10-(-)3.40
	0.60	(-)6.81-(-)7.40	(-)4.82-(-)5.23	(-)3.94-(-)4.27	(-)3.41-(-)3.70
Target:	0.50	(-)7.41-(-)8.00	(-)5.24-(-)5.66	(-)4.28-(-)4.62	(-)3.71-(-)4.00
94.00% of Maximum	Unacceptable ^b	Over (-)8.00	Over (-)5.66	Over (-)4.62	Over (-)4.00
Theoretical Density		Over (+)4.00	Over (+)2.83	Over (+)2.31	Over (+)2.00

Average of Deviations from Maximum (Considering Signs)		
Surface Smoothness	1.05	Less than 3.0
	1.03	3.0 - 3.6
	1.02	3.7 - 4.2
	1.01	4.3 - 5.4
	1.00	5.4 - 6.5
	0.99	6.6 - 7.7
	0.97	7.8 - 9.0
	0.95	9.1 - 10.0
	0.90	10.1 - 11.0
Maximum:	0.80	11.1 - 12.0
6.0 inches per mile	Unacceptable ^b	More than 12.0

- a If more than four tests are conducted, the allowable deviations will be determined by dividing the allowable deviations for one test by the square root of the number of tests actually conducted.
- b Unless otherwise directed by the engineer, products testing in this range are unacceptable and shall be removed and replaced at no cost to the Department.
When the total adjustment to payment (Combined Pay Factor) is equal to or less than 0.90 the Contractor may, at his option, remove and replace the products at no additional cost to the Department or leave them in place and receive no payment for them.
- c Only the smallest of the gradation pay factors shall be considered in determining adjustment in pat for each lot.
- d It is the intent of this Specification that uniform compaction be obtained. In addition to average density requirements, the allowable range (difference between the highest and lowest densities in the affected lot) is limited to 4.0% on new construction and 5.0% on resurfacing. The density pay factors for lots exceeding these limits shall be limited to 0.98 or the density pay factors shown above, whichever is less.

Table 15 summarizes the results of regression analysis. The correlation coefficient varies from 0.49 to 0.84 (R^2 between 0.24 and 0.71). Hypothesis testing concerning the significance of the regression coefficients ($H_o: \beta = 0$ versus $H_a: \beta \neq 0$) indicated that these coefficients are significantly different from zero at the 95% confidence level. In other words, there is evidence to indicate that core densities are linearly related to nuclear densities. The calibrated relationships are shown on the scatter plots of Figures 13a through 16a. In addition, Figures 13b through 16b show scatter plots of measured core densities versus estimated core densities from the calibrated relationships.

TABLE 15. CALIBRATED RELATIONSHIPS BETWEEN CORE AND NUCLEAR DENSITIES

Nuclear Gauge	N	Equation	R ²	Std. Error of Y Estimate	Std. Error of Regression Coeff.
Troxler 3440 (Muskogee Residency)	32	Y = 61.21 + 0.366 X	0.392	0.720	0.083
Troxler 4640 (Materials Division)	32	Y = 59.22 + 0.387 X	0.708	0.601	0.387
Seamon C200 (Cummins Const.)	14	Y = 70.46 + 0.256 X	0.297	1.078	0.114
Troxler 3440 (Cummins Const.)	22	Y = 69.17 + 0.276 X	0.237	0.706	0.111

Paired-Difference Test

Figure 17 depicts the relationship between measured core density and the difference between density measurements. To test the hypothesis that the average difference between density measurements is equal to zero, that is,

$$H_o: \mu_1 = \mu_2 \quad \text{against} \quad H_a: \mu_1 \neq \mu_2$$

the test-statistic is given by:

$$t = \frac{\bar{D}}{s_D / \sqrt{n}} \quad (28)$$

where:

- μ_1 = population mean of core density measurements;
- μ_2 = population mean of nuclear density measurements;
- n = sample size (number of paired observations);
- s_D = sample standard deviation of the differences between core and nuclear density measurements; and
- D = sample mean of the differences between core and nuclear density measurements.

For a desired confidence level ($1 - \alpha$), the computed t-value given by equation 28 is compared with a critical t-value corresponding to $n - 1$ degrees of freedom ($t_{\alpha/2, df}$). If the absolute value of the