VARIABILITY IN BITUMINOUS CONCRETE PAVEMENT CONSTRUCTION

Final Report

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NOTICE

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VARIABILITY IN BITUMINOUS CONCRETE PAVEMENT CONSTRUCTION

SUMMARY

Knowledge of the variability in acceptable bituminous concrete pavement materials and construction in Oklahoma is a prerequisite for the development of successful QA specifications. Toward this end, the ODOT commissioned this study to: (1) develop reliable estimates of the overall variability in the quality characteristics, (2) determine the components of variation due to materials and processes, sampling, and testing, (3) assess the tolerances of both the existing and proposed QA specifications, (4) investigate the capability of HMA production/construction processes, (5) evaluate the adequacy of the nuclear density gauge and the nuclear asphalt content gauge for process control and product acceptance purposes, and (6) recommend changes to the QA specifications and/or the QA system, if warranted.

More than 11,000 measurements of aggregate gradation, asphalt content, air voids, roadway density, stability, and other volumetric properties of HMA were obtained from four construction projects during the period 1990 through 1995. An effort was made to ensure experienced contractors with good process control and that none of the projects involved unusual materials or construction. Sampling was conducted both at the production plant and the roadway independent of acceptance sampling and process control sampling. Because testing was performed by several operators using different pieces of equipment in different laboratories, the measures of variability determined in this study are representative of the between-laboratory variation which is usually larger than that found in a single laboratory.

Based on the findings of the various analyses performed in this study, the following conclusions and recommendations have been reached:

Overall Variability

Measures of the overall variability in the quality characteristics for each individual construction project as well as the pooled variation found in all four projects have been determined based on the principles of random sampling and statistical experimental design. In general, the levels of variability in HMA pavement materials and construction

in Oklahoma are within the national ranges for the respective quality characteristics. Nevertheless, the variability found in many states is less than that in Oklahoma, which suggests that there is an opportunity for improving the quality of construction products in Oklahoma through the systematic reduction in variation. This can be accomplished only by contractor's process control which involves collecting production performance data and developing control charts of these data.

Evidence from the four construction projects indicates that the standard deviation of a given quality characteristic is by itself a variable. Therefore, the development of acceptance plans and payment schedules should be based on variability-unknown methods similar to those described in the 1995 AASHTO Quality Assurance Guide Specification [1].

Components of Variability

Estimates of the components of total variation in each quality characteristic due to materials, sampling, and testing have been made using analysis of variance techniques. The contribution of each source of variation is given in terms of the standard deviation of the respective component.

The standard deviation of the materials component is an estimate of the expected variability in a single lot of HMA due to lack of uniformity in the material or construction when the production process is running smoothly. Likewise, the standard deviation of the sampling component is representative of the variation which is introduced during field sampling -- it does not include the variation caused by reducing large portions of the material to test specimens by splitting and quartering which is considered by ODOT to be part of testing. Finally, the standard deviation of the testing component is a measure of the precision of the test method and how sensitive the test method is to changes in the measured property of the material. It should be emphasized that testing was performed by several operators using different testing apparatus in different laboratories. Therefore, the multilaboratory standard deviation of the testing component reported in this study is expected to be greater than the single laboratory standard deviation.

Preliminary estimates of the variability associated with new test methods such as the binder ignition test for asphalt content and those which resulted from the SHRP program indicate a great deal of promise in controlling testing variability [13]. Another positive development is the technician certification program developed by ODOT and AGC to provide uniform training and certification in sampling and testing for ODOT, contractor, and supplier personnel. Although the issues of certification and training were not addressed in this research, the program will ensure that meaningful comparisons can be made between the ODOT's and the contractor's test results.

Process Capability and Specifications

An assessment of the capability of each of the four HMA construction and production processes has been made with respect to the requirements of JMF, existing QA specifications, and proposed QA specifications. In terms of the C_p, C_{pk}, and C_{pm} indices, process capability ranges from marginally acceptable to unacceptable by usual standards. Likewise, estimates of the percent within specification limits indicate that, except the aggregate passing large sieves, none of the other quality characteristics met the specification limits 100% of the time in all four projects.

One reason for this inferior performance is that the majority of the quality characteristics were not centered on the specified target. Another reason is that the variability in the quality characteristics was often larger than the window of variation permitted by the specifications. Opportunities for improving process performance can be realized through the use of statistical process control charting.

QA Specification Tolerances

The existing QA specification tolerances for aggregate gradation are somewhat large, whereas the tolerances of the new QA specifications seem to be more focused and adequate for accommodating the overall variation in these quality characteristics. For asphalt content, tolerances of $\pm 0.6\%$ (average of the $\pm 0.7\%$ in the existing QA specifications and $\pm 0.5\%$ in the proposed specifications) are realistic and attainable by a consistent and capable process. For air voids, the $\pm 2.5\%$ tolerances of the existing QA specifications are more reasonable than the $\pm 15\%$ tolerances of the proposed specifications.

Variability in roadway density was considerably higher than what is allowed in both the existing and proposed QA specifications. Although this may be a signal that the specification limits are too restrictive for this quality characteristic, it is more likely that the lack of process control is responsible for the poor level of conformance. More data on roadway density should be gathered and analyzed to verify the specification tolerances for roadway density.

Nuclear Density Gauge

Correlation of individual density measurements by core samples with those obtained by the nuclear gauge ranged from good to fair. The results suggest that an improvement in the prediction of core densities from nuclear gauge measurements can be realized through the use of regression equations. Such equations can be developed based on a reasonable number of core and nuclear density measurements for each project.

Because of its speed and ease of operation, the nuclear gauge is a very useful tool for quality control of pavement density during construction. The relative increase in density following each additional pass of the roller helps determine if the maximum relative density has been obtained.

Nuclear Asphalt Content Gauge

The mean values of asphalt content using the extraction and the nuclear gauge test methods are essentially the same for each of the four construction projects. Nevertheless, the accuracy of either test method was not addressed since the true asphalt content is unknown. In terms of precision, the test results suggest that the NAC gauge has a slightly better precision than the extraction method as evidenced by the smaller standard deviation found in three out of the four projects.

Earlier studies indicate that the type of aggregate used in an HMA affects the NAC gauge readings slightly, and that different gradations produce different results [27]. Asphalt sources were also found to cause differences. Therefore, individual calibration for each particular mix is required to ensure accurate determination of asphalt content using the NAC gauge.

The relatively recent method of determining asphalt content by ignition is an excellent tool for both quality control and acceptance testing. Asphalt content can be measured in approximately 30 minutes, compared to over two hours with solvent extraction methods. Preliminary results of a recent study performed by NCAT suggest that the binder ignition test can accurately measure the asphalt content of HMA mixtures, and that the precision of this method is better than that of solvent extraction methods [7, 25, 26]. Because the ignition oven can slightly change the properties of certain types of aggregates, round-robin studies are warranted to calibrate the test method for local materials [25].

Recommendations

Process control is one of the most important issues which must be stressed by ODOT in order to realize the full potential of the quality assurance system in Oklahoma. In its present form, process control is often limited to having the contractor's personnel verify the results of acceptance testing performed by ODOT. This practice is flawed because it does not address the causes of defective materials or construction in a timely manner. The focus of process control should be on the identification of both sporadic and chronic faults in the process and formulating improvement actions. This requires the contractor to collect, analyze, and interpret data concerning the process to maintain target and to systematically reduce variability.

Fostering the implementation of process control requires increasing awareness within the construction community in Oklahoma of the importance of statistical process control methods and the benefits that can be realized by both contractors and ODOT. This can be ameliorated by providing training and requiring certification on the subject.

Further research is required to address: (1) variability in pavement smoothness and its relationship to process capability and QA specifications tolerances, (2) variability in the binder ignition test method for asphalt content determination and the effect of the test method on local aggregates, (3) evaluation of the pay equations in the new QA specifications for HMA pavement construction using acceptance data from several projects, and (4) variability in roadway density measurements by core samples and nuclear gauge.

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schedules should be based on variability-unknown methods similar to those described in the 1995 AASHTO Quality Assurance Guide Specification.

Components of Variability

Variability due to sampling and testing represents a significant portion of the total variability in the measured quality characteristics of HMA pavement materials and construction. Similar conclusions have been reached by many of the variability studies conducted in other states. It is noteworthy that the testing variation encountered in a particular acceptance or process control testing situation is less than the multilaboratory variation found in this study.

In reviewing the literature, it is apparent that some of the existing test methods, like the extraction test, have problems with the interpretation of the test procedure which increases the variability in test results. In other test methods, like aggregate gradation, the amount of material included in the test specimens is too small to contain the correct proportion of each size of aggregate particles.

Preliminary estimates of the variability associated with new test methods such as the binder ignition test for asphalt content and those which resulted from the SHRP program indicate a great deal of promise in controlling testing variability. Another positive development is the technician certification program developed by ODOT and AGC to provide uniform training and certification in sampling and testing for ODOT, contractor, and supplier personnel. This will ensure that meaningful comparisons can be made between the ODOT's and the contractor's test results.

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Recommendations

Process control is one of the most important issues which must be stressed by ODOT in order to realize the full potential of the quality assurance system in Oklahoma. In its present form, process control is often limited to having the contractor's personnel verify the results of acceptance testing performed by ODOT. This practice is flawed because it does not address the causes of defective materials or construction in a timely manner. The focus of process control should be on the identification of both sporadic and chronic faults in the process and formulating improvement actions. This requires collecting, analyzing, and interpreting data concerning the process to maintain target and to systematically reduce variability.

Fostering the implementation of process control requires increasing awareness within the construction community in Oklahoma of the importance of statistical process control methods and the benefits that can be realized by both contractors and ODOT. This can be ameliorated by providing training and requiring certification on the subject.

Further research is required to address (1) variability in pavement smoothness and its relationship to process capability and QA specifications tolerances, (2) variability in the binder ignition test method for asphalt content determination and the effect of the test method on local aggregates, (3) evaluation of the pay equations in the new QA specifications for HMA pavement construction using acceptance data from several projects, and (4) variability in roadway density measurements by core samples and nuclear gauge.

CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT

Over the last 10 years, the Oklahoma Department of Transportation (ODOT) developed several versions of quality assurance (QA) specifications for bituminous concrete pavement construction -- the latest of which is based on the 1995 AASHTO Quality Assurance Guide Specifications. Among other elements, QA specifications include key materials and construction characteristics that correlate with the long-term performance of the finished product and can be measured during or immediately after construction. For each quality characteristic, tolerances that reflect the allowable variation in that characteristic are established and the resulting specification limits are used to make decisions concerning the lot percent defective and pay factor.

The ODOT recognizes that reliable information on the sources and magnitudes of variability in the measured properties of acceptable bituminous concrete pavement construction is needed for the development of realistic specifications. Available estimates of variability were determined from data collected under the method specifications where sampling was not performed at random. In addition to eliminating bias, random sampling allows probability-based analysis of the data -- a basic concept in the development of QA specifications.

Another concern about the available estimates of variability is that they are not up-to-date. Technological advances in construction processes, improvements in testing methods, and the increased awareness by the highway industry that variability is inversely proportionate to quality are among the reasons for expecting a reduction in the overall variability in construction products. Nevertheless, these positive developments may have been offset by the loss of experienced personnel, reduction in staff, and increased complexity of construction projects.

Although specification limits for a given quality characteristic are established based on the overall reported variation in that characteristic, the three components of variation due to materials, sampling, and testing should be quantified to determine their relative contributions to the total variation. The standard deviation -- an estimate of overall variability -- is computed from a set of numbers which are influenced by variation in the measurement process just as they are influenced by variation in the quality characteristic being measured. Each component of variation should be examined to ensure that it does not bias the overall variation and ultimately the specifications.

OBJECTIVES AND SCOPE

The overall objective of this research project was to develop a better understanding of the sources and relative magnitudes of variation in the quality characteristics of acceptable bituminous concrete pavement materials and construction in Oklahoma. The specific objectives of the research were as follows:

- Provide estimates of the overall variation in the quality characteristics of HMA materials and construction in Oklahoma and compare these estimates with recent measures of variability reported by other states.
- Determine the components of the overall variability due to materials and processes, sampling, and testing through a statistically-based field sampling and laboratory testing program.
- Assess the tolerances of both the existing and proposed QA specifications for HMA pavement construction in relation to the overall variability in quality characteristics.
- Investigate the capability of HMA production/construction processes in terms of meeting the existing and proposed QA specifications.
- Evaluate the adequacy of the nuclear density gauge and calibrate the relationship between nuclear density measurements and core density measurements.
- Correlate the results of the nuclear test method for asphalt content determination with those obtained using the solvent extraction method.
- Recommend changes to the QA specifications and/or the QA system, if warranted.

RESEARCH APPROACH

To meet the objectives of this project, a research plan consisting of six tasks was adopted. These tasks are summarized as follows:

Task 1. Literature Review - Review and document the findings of past research activities related to variability in HMA pavement materials and construction.

Task 2. Planning and Executing Field Sampling Program - The objective of this task was to obtain reliable measurements of the quality characteristics of acceptable HMA pavement construction based on the principles of random sampling and statistical experimental design. The sampling program involved four construction projects which were selected in coordination with ODOT during the time period 1990 through 1995. An effort was made to ensure experienced contractors with good process control and that none of the projects involved unusual materials.

Sampling was conducted both at the production plant and the roadway independent of acceptance sampling and process control sampling. For each construction project, fifty sample units were obtained from a lot of 4,000 tons of HMA production. The lot was divided into 25 equal sublots, and two sample-units were obtained from each sublot 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 sublot. At the conclusion of the nuclear gauge test, two cores were drilled at each sampling location.

Task 3. Field and Laboratory Testing - The sample units obtained in Task 2 were forwarded to the materials laboratories in the different ODOT Divisions where they were tested in duplicate by dividing each sample-unit into two test specimens using approved splitting and quartering methods. Test determinations were made in accordance with the ASTM and AASHTO standard test methods, except as noted in the ODOT Standard Specifications for Highway Construction.

Task 4. Measures of Variability - Analysis of variance was applied to the test results obtained from each construction project to determine the overall variation in each quality characteristic and the components of variation due to materials and processes, sampling, and testing. Pooled estimates of the overall variation were also determined using data from all four projects combined.

Task 5. Process Capability and Specifications - An assessment of process capability with respect to JMF and QA specification tolerances was made using several capability indices representative of each construction project. The percent of measurements within the JMF tolerances, QA specification tolerances, and the 2-sigma and 3-sigma limits was also determined.

Task 6. Evaluation of Nuclear Density Gauge and Asphalt Content Gauge - Statistical analyses were performed to establish confidence intervals and test hypotheses concerning the differences between density measurements obtained from core samples and nuclear gauge readings. Likewise, asphalt content measurements obtained using the centrifuge extraction method and the nuclear gauge method were compared. Because the ignition oven method of measuring asphalt content was not readily available during the course of this study, the accuracy and precision of this relatively new test method were discussed based on the results of a recent study conducted by the NCAT [7, 25, 26].

OVERVIEW OF THE NEXT CHAPTERS

Chapter 2 presents background material on measures of variation, the relationship between quality and variability, common and special causes of variation, measurement errors, and analysis of variance. In Chapter 3, details of the research methodology are described. Chapter 4 summarizes the results of analysis of variance including estimates of the overall variation and its components for each quality characteristic, as well as typical measures of variability which have been found in other studies. Chapter 5 presents an assessment of process capability and specification tolerances. Evaluations of the nuclear density gauge and the nuclear asphalt content gauge are discussed in Chapters 6 and 7. Finally, Chapter 8 presents the conclusions and recommendations of this study. The material presented in these chapters is supplemented by Appendices A through L.

This report should serve as a resource information for decision making by ODOT management and engineers concerning the QA specifications for bituminous concrete pavement materials and construction.

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the findings and recommendations of the study. This report should serve as a resource material for decision making by ODOT management and engineers concerning the ODOT's QA Specifications for PC concrete pavement construction and bridge floor construction.

Quality control and quality assurance procedures for HMA mixtures require rapid testing methods to determine the composition of the mixture during production. and placement (for density)

More than 11,000 measurements of aggregate gradation, asphalt content, air voids, roadway density, stability, and other volumetric properties of HMA were obtained from four construction projects during the period 1990 through 1995.

Perhaps two of the most important issues that should be addressed by ODOT to ensure the success of QA specifications are: 1) the quality of the available information on variability, and 2) the relationship between specification limits, variability, and process capability. Research is needed to determine up-to-date and reliable estimates of the overall variability and its components (inherent, testing, sampling), and to evaluate specification limits relative to process capability. The timing of this study is critical considering that the developed QA specifications are currently being tested on selected projects before they are made official, and the potential cost of making incorrect acceptance decisions.
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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.

Estimates of variability used in the development of QA specifications were determined from data collected under the method specifications where sampling was not performed at random. Experience tells us that human choice by the sample selector often produces samples that systematically misrepresent the population from which the samples were obtained. In addition to eliminating bias, random sampling allows probability-based analysis of the data; a basic concept in the development of QA specifications. Another concern about the available estimates of variability is that they are not up-to-date. Technological advances in construction processes and improvements in testing methods during the last several years make it reasonable to expect a reduction in the overall variability in construction products. Other possible reasons that variability may have decreased include the growing emphasis on statistical process control to improve process capability, and the increased awareness by the highway industry that variability is inversely proportionate to quality.

Although specification limits for a given quality characteristic are established based on the overall reported variation in that characteristic, the three components of variation (inherent, sampling, and testing) should be quantified to determine their relative contributions to the total variation. Each component should be examined to ensure that it does not bias the overall variation and ultimately the specifications. If one component seems to be excessively large based on engineering judgment, every effort should be made to eliminate the causes.

The 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 characteristics, 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

pressures placed on ODOT to scale down their operations are some of the factors

Sampling will be conducted both at the production plant and the roadway independent of acceptance sampling and job control sampling. Fifty sample units will be obtained from a lot of 4,000 tons of bituminous concrete production. The lot will be divided into 25 equal sublots, and two sample-units will be obtained from each sublot at random.

Sampling at the Plant: At the plant, samples will be obtained from two different locations as depicted in Figure 2. The first sampling point will yield samples from the aggregate stream prior to the drum mixer according to AASHTO T2-84 [3]. A sampling platform will be 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), will be obtained from each sublot at random. The sample-units will be identified by labels, placed in cloth sacks, and stored.

Sample-units of the freshly mixed bituminous concrete will be obtained from the hauling trucks containing the preselected random tonnage according to AASHTO T168-90 [3]. Two sample-units, each having a minimum mass of 90 lb (40 kg), will be selected from each sublot. The sample-units will be identified by labels, placed in sacks, and stored.

Sampling at the Roadway: Sampling of the compacted mixture will be conducted at random using a system of coordinates designed for this purpose. Two sampling locations per sublot will be identified by spray paint markings on the pavement. At each sampling location, duplicate density measurements will be made using a thin-lift nuclear gauge according to ASTM D2950-82 [6]. The nuclear gauges will be calibrated for the bituminous mix used in a each construction project. At the conclusion of the nuclear gauge test, two cores will drilled at each sampling location according to AASHTO T168-82 [3]. The cores will be identified by labels and stored in boxes.

CHAPTER 2

BACKGROUND

MEASURES OF VARIATION

A meaningful measure of variation should be large when the individual values vary over a wide range, and should be small when the range of variation is narrow. Perhaps the most widely used measure of variability is the variance or its square root, which is known as the standard deviation. The sample variance, denoted by s_x^2, is defined by:

$$s_x^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \qquad (2.1)$$

where x_i is the ith measurement, $\bar{x}$ is the sample mean, and n is the number of measurements included in the sample. The units of the sample variance s_x^2 are the square of the original units of the data, which is somewhat difficult to interpret. Therefore, the sample standard deviation s_x is preferred since it is expressed in the same units as the data. In QA applications, the sample variance s_x^2 is used as an estimate of the true process or population variance, which is denoted by σ_x^2. Similarly, the sample standard deviation is an estimate of the process or population standard deviation denoted by σ_x.

Another measure of variability is the sample range, R, which is the difference between the largest value and the smallest value included in the sample. Because it does not utilize all the information available from the intermediate sample values, use of the sample range is usually limited to small samples. The primary application of sample range is in process control. Under certain assumptions, the true population standard deviation σ_x, may be estimated from the average range $\bar{R}$ (computed from several small samples) using the relationship: $\hat{s}_x = \bar{R} / d_2$, where d_2 is a constant that depends on the sample size n.

In comparing the variability in two or more samples that differ in their means, use of the sample standard deviation may not be meaningful, particularly if variability is expected to increase as the sample mean increases. In this case, the coefficient of variation, denoted by CV, is used as a measure of the relative variation. The coefficient of variation is defined as:

$$CV = \frac{s_x}{\bar{x}} \times 100\% \qquad (2.2)$$

QUALITY–VARIABILITY RELATIONSHIP

Conformance of a product to specifications has traditionally been used to define quality. As shown in Figure 2-1, failure of a product to meet the specifications can result from one or both of two basic causes: 1) shift in the average quality characteristic from the target value required by design, and 2) excessive variation in the quality characteristic about the target. Quality of conformance is influenced by a number of factors including the production processes, the training and supervision of the workforce, and the extent to which process control procedures are followed.

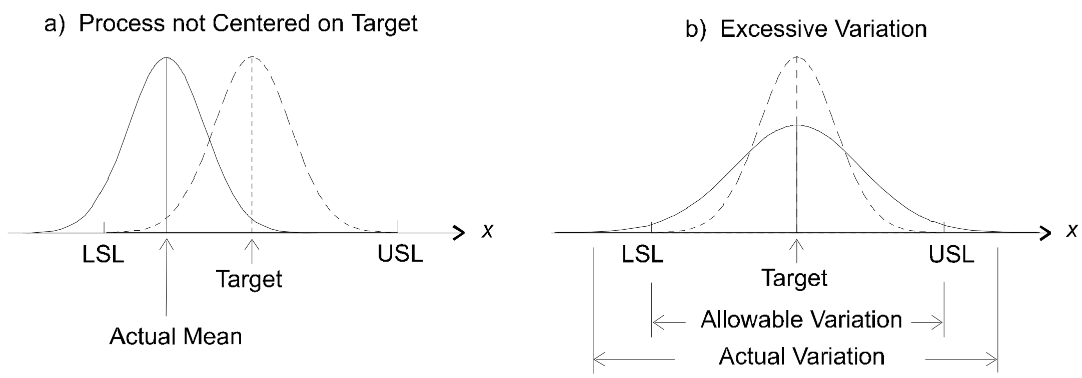


Figure 2-1. Conformance to Specifications View of Quality

A modern view of quality, which has been promoted in recent years, is that of being "on target with the smallest variation". This definition of quality goes beyond associating quality with conformance to engineering specifications and considers quality as inversely proportional to variability. Figure 2-2 illustrates two representations of a process as a statistical distribution of measurements of a particular quality characteristic. According to the traditional view of quality, one would not make much distinction between the two cases in terms of quality; that is, in both cases almost all of the process output conforms to specifications. According to the modern view of quality, however, the bell-shaped process distribution in Figure 2-2(a) would be preferred to the loaf-shaped process distribution in Figure 2-2(b). Focusing attention on the target value while striving for the smallest variation is central to the concept of never-ending quality improvement.

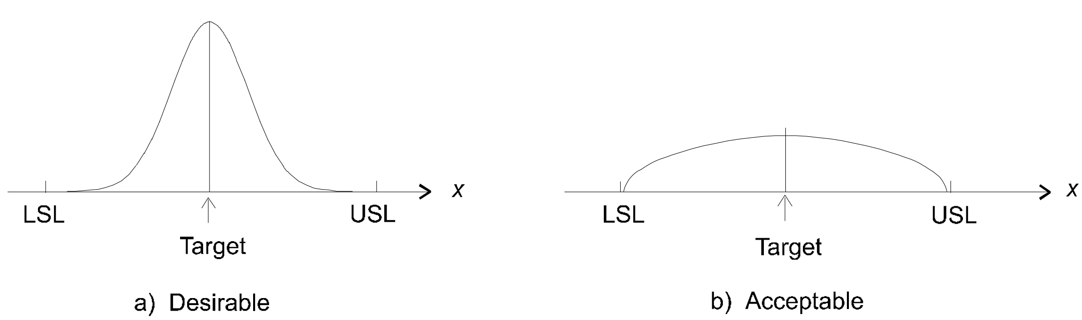
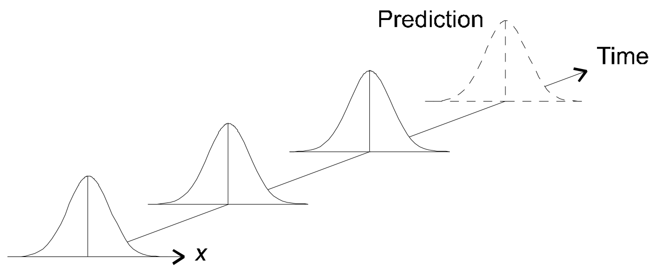


Figure 2-2. Distributions of a Quality Characteristic of a Process

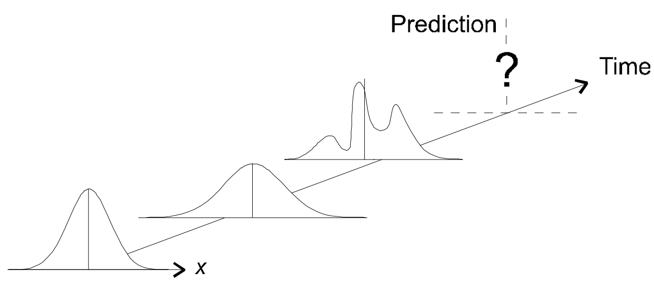
COMMON AND SPECIAL CAUSES OF VARIATION

In any production process, regardless of how well controlled and carefully maintained, a certain amount of inherent or natural variability will always exist. This natural variability is the cumulative effect of many small, essentially unavoidable causes. Anyone who is familiar with a process can identify a large number of factors that contribute, in an unexplainable way, to the variability of the process during its routine operation. In the framework of statistical quality control, such causes are referred to as **common**, **natural**, or **stable system of chance causes**. Experience tells us that natural causes of variation manifest themselves as bell-shaped distributions of the quality characteristics.

A process that is operating with only chance causes of variation present is said to be in a state of **statistical control**. Though the succession of measurements of quality characteristics taken from such a process over time will exhibit variability, these variable measurements tend to fall within predictable limits and to form a predictable pattern of variation that serves as a model for predicting how the process will behave if it continues to be subject only to common causes. Figure 2-3(a) illustrates how such a statistical model may emerge. The process mean and variation stay constant over time, and therefore, the process is said to be stable.



(a) Process is subject only to Natural Causes of Variation



(b) Assignable Causes of Variation Present

Figure 2-3. Process Behavior Over Time

Other causes of variability in a process include defective raw materials, improperly adjusted machines, and operator errors. Such causes of variability that are not part of the chance cause system are called **special** or **assignable causes**. Variability due to assignable causes is generally large when compared to the natural variability in a production process, and it usually represents an unacceptable level of process performance. A process that is operating in the presence of assignable causes is said to be **out of control**. As shown in Figure 2-3(b), the process mean and/or variability change from time to time. Measurements taken from such a process will not conform to the model that describes the predictable pattern of variation associated with the stable system of common causes.

A major objective of statistical process control (SPC) is to quickly detect the occurrence of assignable causes of process shifts so that investigation of the process and corrective action may be undertaken before many nonconforming products are produced. Control charts are effective tools for on-line process control and evaluating process capability. Once assignable causes of variation have been identified and corrective action has been taken, the ultimate goal of SPC is to minimize variability in the process output by attacking the common system of variation causes and improving process capability.

MEASUREMENT ERRORS

Measurements of the quality characteristics 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 quality.

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 quality characteristic and the true value of that characteristic. 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.

A group of measurements can be precise without being accurate, i.e., the measurements may be clustered near each other but bear no relationship to the true value. Conversely, a group of measurements could be accurate, in that their mean is very close to the true value, and yet the individual measurements are 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 2-4. Marksman A 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. The results of marksman B indicate good precision, but poor accuracy; the shots are spaced closely together near one spot some distance from the bull's eye. Marksman C has poor precision and poor accuracy.

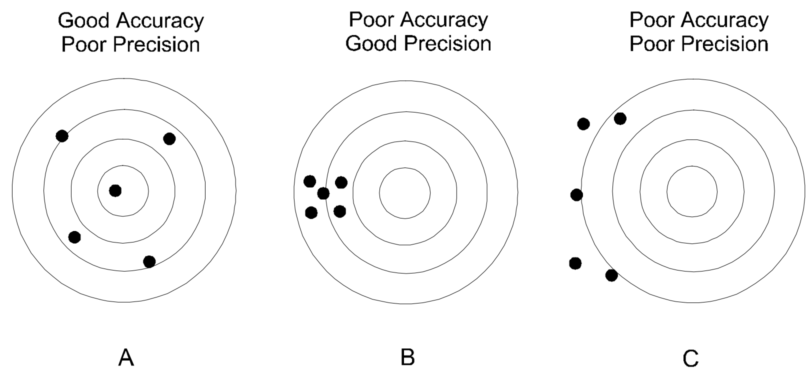


Figure 2-4. Precision and Accuracy of Measurements

COMPONENTS OF VARIABILITY

The overall variability in the measured quality characteristics of a process that is in *state of statistical control* has three components: *inherent variation*, *sampling variation*, and *testing variation*. A brief discussion of these three components is given in the following sections.

<u>*Inherent Variation*</u> - As explained earlier, inherent variation is the true random variation in construction materials and processes. This component of the overall variation that is caused by the unavoidable lack of uniformity is denoted by σ_M^2. It may vary in magnitude depending on the characteristics of materials and processes, but in general, it is one of the smallest sources of variation.

Knowledge of the inherent variability in construction materials and processes is basic to the development of QA specifications. Nevertheless, this source of variation cannot be used by itself as the specification limits. Inherent variation, like other sources of variation, can only be determined by sampling and testing, and this sampling and testing process introduces additional sources of variation.

<u>*Sampling Variation*</u> - Sampling variation manifests itself as differences in the quality characteristics of different sample units taken from the output of a consistent process. The ODOT considers sampling variation to be that component encountered only during field sampling -- it does not include reducing large portions of the material to test specimens by splitting and quartering which is typically performed in the laboratory. The component of variance caused by the method of obtaining sample units is denoted by σ_S^2.

Testing Variation - Testing variation is the lack of repeatability of test results obtained from test specimens that are nearly alike. Operators, test equipment, calibration, and test procedure are some of the factors that cause testing variation. The symbol σ_T^2 is used to denote this component of variance.

Round-robin studies are usually performed according to ASTM C802 standard practice for conducting an interlaboratory test program to determine the precision of test methods for construction materials. Standard practice for preparing precision and bias statements of test methods are described in ASTM C670. The *single-operator one-sigma limit* is an estimate of the standard deviation of a large group of individual test results when tests have been made on the same material by a single operator using the same test equipment in the same laboratory over a relatively short period of time. The *multilaboratory one-sigma limit* is an estimate of the standard deviation of a large group of individual test results when each test determination has been made in a different laboratory and every effort has been made to make the test portions of the material nearly identical. Under normal circumstances, the estimates of one-sigma limit for multilaboratory precision are larger than those for single-operator precision, because different operators and different test equipment are used in different laboratories for which the environment may be different.

Although specification limits for a given quality characteristic are established based on the overall reported variation in that characteristic, the three components of variation (inherent, sampling, and testing) should be quantified to determine their relative contributions to the total variation. Each component should be examined to ensure that it does not bias the overall variation and ultimately the specifications. If one component seems to be excessively large based on engineering judgment, an investigation is warranted to determine if assignable causes are present and every effort should be made to eliminate such causes.

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 is used to determine the variance of the component factors and to test the statistical significance of each factor.

Application of ANOVA requires a well designed statistical experiment that permits analyzing the different factors involved in the experiment. Designing a statistical experiment simply means planning the experiment so that the information obtained will provide satisfactory answers to the questions that prompted the study. 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 2-5 illustrates a sampling plan for a nested design involving three sources of variation (factors) in measurements of some quality characteristic 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 sublot. 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 sublot, and each sample unit is divided into the same number of test specimens, the design is referred to as balanced design.

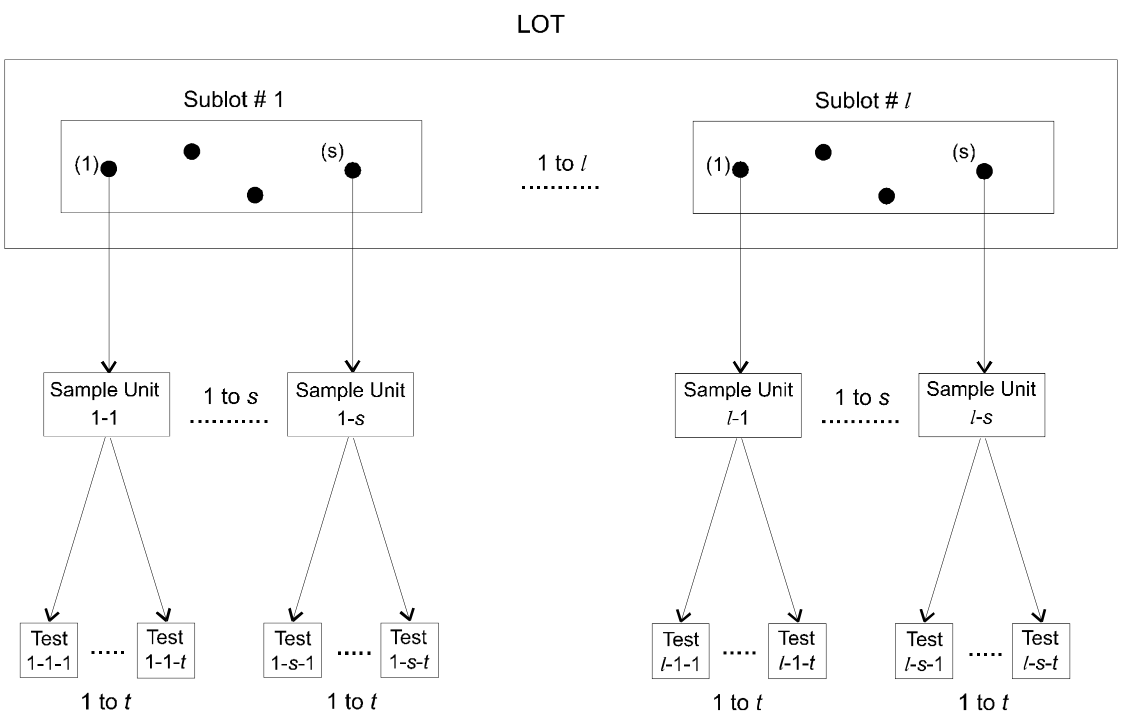


Figure 2-5. Sampling Plan for Nested ANOVA Experiment

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 2-5, *L* represents sublots of HMA pavement, *S* represents sample units taken at random from each sublot, and *T* represents tests performed on specimens prepared from the sample units. It is assumed that factor L has l levels, factor S has s levels, and factor T has t levels.

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

$$y_{ijk} = \mu + L_i + S_{ij} + T_{ijk} \tag{2.3}$$

where:

μ = overall population mean, i.e., mean value of the quality characteristic for the entire lot;

L_i = effect of material and construction process used to produce the *ith* sublot, (i = 1,..., l);

S_{ij} = effect of sampling method used to obtain the *jth* sample unit from the *ith* sublot, (j = 1,..., s);

T_{ijk} = effect of test method on measuring the quality characteristic of the *kth* test specimen taken from the *jth* sample unit in the *ith* sublot, (k = 1,..., 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.

<u>Sums of Squares</u>

The model given by equation 2.3 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:

$$SS_T = \sum_{i=l}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} (y_{ijk} - \bar{y}_{ij.})^2 \tag{2.4}$$

$$SS_S = \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} (\bar{y}_{ij.} - \bar{y}_{i..})^2 \tag{2.5}$$

$$SS_L = \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} (\bar{y}_{i..} - \bar{y}_{...})^2 \tag{2.6}$$

Table 2-1 describes the mathematical notation used in the above equations. Since the sums of squares are additive, the total sum of squares (SS_{Total}) is given by:

$$SS_{Total} = \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} (y_{ijk} - \bar{y}_{...})^2 = SS_L + SS_S + SS_T \tag{2.7}$$

Table 2-1. Mathematical Notation

$$\bar{y}_{ij.} = \frac{1}{t} \sum_{k=1}^{t} y_{ijk} \quad 1$$

$$\bar{y}_{i..} = \frac{1}{st} \sum_{j=1}^{s} \sum_{k=1}^{t} y_{ijk} \quad 2$$

$$\bar{y}_{...} = \frac{1}{lst} \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} y_{ijk} \quad 3$$

where:

$\bar{y}_{ij.}$ = mean value of a quality characteristic of the test specimens in the *jth* sample unit which is taken at random from sublot *i*;

$\bar{y}_{i..}$ = mean value of a quality characteristic of the sample units in the *ith* sublot;

$\bar{y}_{...}$ = mean of the sublot means (or grand mean of a quality characteristic of the lot);

Mean Squares

For analysis of variance purposes, 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: $MS = SS / df$, where *SS* is the sum of squares and *df* represents the degrees of freedom associated with *SS*. In general, the value of *df* can be computed using the expression: $df = N - P$, where *N* is the number of measurements and *P* is the number of parameters estimated using the measurements. The degrees of freedom associated with SS_L, SS_S, and SS_T are: $(l-1)$, $l(s-1)$ and $ls(t-1)$, respectively.

Expected Mean Squares

Estimation of the three components of variance σ_M^2, σ_S^2, and σ_T^2 requires the development of the *expected values* of the mean squares: $E[MS_T]$, $E[MS_S]$ and $E[MS_L]$. It can be shown that the values of these mean squares are given by:

$$E[MS_T] = E\left[\frac{SS_T}{\phi_T}\right] = \frac{1}{ls(t-1)} \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} E\left[y_{ijk} - \bar{y}_{ij.}\right]^2 = \sigma_T^2 \qquad (2.8)4$$

$$E[MS_S] = E\left[\frac{SS_S}{\phi_S}\right] = \frac{1}{l(s-1)} \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} E\left[\bar{y}_{ij.} - \bar{y}_{i..}\right]^2 = t\,\sigma_S^2 + \sigma_T^2 \qquad (2.9)5$$

$$E[MS_L] = E\left[\frac{SS_L}{\phi_L}\right] = \frac{1}{(l-1)} \sum_{i=1}^{l} \sum_{j=1}^{s} \sum_{k=1}^{t} E\left[\bar{y}_{i..} - \bar{y}_{...}\right]^2 = st\,\sigma_M^2 + t\,\sigma_S^2 + \sigma_T^2 \qquad (2.10)6$$

Equations 2.8, 2.9, and 2.10 indicate that MS_T, MS_S, and MS_L are unbiased estimators of σ_T^2, $(t\,\sigma_S^2 + \sigma_T^2)$, and $(s\,t\,\sigma_M^2 + t\,\sigma_S^2 + \sigma_T^2)$, 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,

$$MS_T = \sigma_T^2 \tag{2.11}$$

$$MS_S = t\,\sigma_S^2 + \sigma_T^2 \tag{2.12}$$

$$MS_L = s\,t\,\sigma_M^2 + t\,\sigma_S^2 + \sigma_T^2 \tag{2.13}$$

The simultaneous solution of equations 2.11, 2.12, and 2.13 yields the following expressions of the components of variance:

$$\hat{\sigma}_T^2 = MS_T \tag{2.14}$$

$$\hat{\sigma}_S^2 = (MS_s - MS_T)\,/\,t \tag{2.15}$$

$$\hat{\sigma}_M^2 = (MS_L - MS_S)\,/\,st \tag{2.16}$$

Since the above estimates are obtained by subtraction, it is possible that their values can be negative. If any estimate obtained by subtraction is negative, it is conventionally set equal to zero.

Using the additive property of variances, it can be shown that the estimate of total variance of the measurements is given by:

$$\hat{\sigma}_{Total}^2 = \hat{\sigma}_M^2 + \hat{\sigma}_S^2 + \hat{\sigma}_T^2 \tag{2.17}$$

7

For reference, the foregoing analysis of variance is summarized in Table 2-2.

Table 2-2. 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	$l\,s\,(t-1)$	MS_T	σ_T^2
Total	SS_{Total}	$l\,s\,t - 1$		

Hypothesis Testing

1. Test for Sublot to Sublot Variation

To test the hypothesis: H_0: $\sigma_M^2 = 0$ versus the alternative H_1: $\sigma_M^2 > 0$, the appropriate test statistic is given by:

$$F_M = \frac{MS_L}{MS_S} = \frac{\sigma_T^2 + t\,\sigma_S^2 + s\,t\,\sigma_M^2}{\sigma_T^2 + t\,\sigma_S^2} \qquad (2.18)$$

When H_0 is true (i.e., $\sigma_M^2 = 0$), the above test statistic follows 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 2.18 is compared with a *tabulated-F* value for a given level of significance α. The decision rule for the above hypothesis is as follows:

If $F_M > F_{Tabulated}$ ..... Reject H_0
If $F_M \leq F_{Tabulated}$ ..... Accept H_0

Rejecting H_0 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_0 means that there is no significant variation between the sublots, i.e., the material is reasonably uniform across the lot.

2. Test for Sample-Unit to Sample-Unit Variation

To test the hypothesis: H_0: $\sigma_S^2 = 0$ versus the alternative H_1: $\sigma_S^2 > 0$, the appropriate test statistic is given by:

$$F_S = \frac{MS_S}{MS_T} = \frac{\sigma_T^2 + t\,\sigma_S^2}{\sigma_T^2} \qquad (2.19)$$

When H_0 is true (i.e., $\sigma_S^2 = 0$), the above test statistic follows an *F-distribution* with $l(s-1)$ degrees of freedom for the numerator and $l\,s(t-1)$ 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_0
If $F_S \leq F_{Tabulated}$ ..... Accept H_0

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 significant variation between sample units, i.e., the contribution of sampling is not significant.

With reference to equations 2.18 and 2.19, 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 [23] 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 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.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter summarizes the methods used to obtain representative data on the variability in the quality characteristics of acceptable HMA pavement materials and construction in Oklahoma. The field sampling program required by task 2 and the field and laboratory test methods required by task 3 are briefly described.

DESCRIPTION OF CONSTRUCTION PROJECTS

Four construction projects were selected by ODOT for conducting the sampling and testing program. One of the criteria involved in the selection process was to ensure that each project was carried out by an experienced contractor with good process control. A second criterion was to avoid projects involving unusual materials or construction. Third, the minimum quantity of HMA for a project study should be large enough to allow sufficient time on any one day to obtain the maximum number of sample-units and to make the required field tests. A brief description of the four projects is given in the following paragraphs.

Project 1 - MAF-398(82): This project consisted of 8.88 km (5.52 miles) of overlaying the existing two lanes and constructing two new parallel lanes of highway US-412, Delaware County, Oklahoma. The estimated average daily traffic was greater than 5,000 vehicles per day. The contractor and producer was Cummins Construction Company using a fully automated, drum mix plant.

Existing lanes were overlaid with a 19 mm (¾ inch) layer of asphalt concrete type-E, placed over a layer of asphalt concrete type-F having a minimum thickness of 108 mm (4¼ inches), over fabric reinforcement centered on the existing pavement. Typical cross section of the new construction consisted of 19 mm (¾ inch) of asphalt concrete type-E, over 89 mm (3½ inches) of asphalt concrete type-F, over 203 mm (8 inches) of asphalt concrete type-G, on top of 102 mm (4 inches) of open-graded bituminous base. The type-F asphalt concrete used in the new construction was sampled for this study.

Project 2 - MAF-59(75): The second project provided for widening and overlay of approximately 8.37 km (5.20 miles) of highway US-70 in Marshall County, Oklahoma. The contractor and producer was Gilbert Central Company. The highway is a two-lane facility with an average daily traffic exceeding 2,500 vehicles per day.

A 2.44 m (8 ft) shoulder of asphalt concrete type-A was added on each side of the existing lanes. Fabric reinforcement, 8.53 m (28 ft) wide, was placed on the existing two lanes of travel and two lifts of asphalt concrete type-B were placed full width. The top lift was sampled for this study.

Project 3 - NHY-215(57): This project involved construction of two new lanes and overlay of the existing two lanes of a 7.88 km (4.90 miles) section of highway US-62 in Comanche County, Oklahoma. The average daily traffic exceeded 2,500 vehicles per day. The contractor and producer was Broce Construction Company.

Existing lanes were overlaid with a 38 mm (1½ inches) leveling course of asphalt concrete type-BH, followed by a 7.92 m (26 ft) wide fabric reinforcement centered on the travel lanes, and topped with 51 mm (2 inches) wearing course of asphalt concrete type-BH. The new eastbound lanes were constructed of 51 mm (2 inches) wearing surface of asphalt concrete type-BH, placed on top of 152 mm (6 inches) of asphalt concrete type-AH. There was a 102 mm (4 inches) layer of open graded bituminous base placed over an aggregate base. The type-BH asphalt concrete on the new lanes was sampled for this study.

Project 4 - NH-186(190): This project provided for resurfacing of 10.94 km (6.8 miles) of highway US-69 in McIntosh County, Oklahoma. The highway is a four-lane facility with an average daily traffic exceeding 5,000 vehicles per day. The contractor and producer was Northern Improvement Construction Company.

The existing lanes were overlaid with a 102 mm (4 inches) layer of asphalt concrete type-A, followed by a 7.92 m (26 ft) wide fabric reinforcement centered on the travel lanes, and topped with a 51 mm (2 inches) wearing surface of asphalt concrete type-B. The type-A asphalt concrete on the southbound lanes was sampled for this study.

Table 3-1 summarizes the types and sources of materials used in each project. The job mix formulae are shown in Table 3-2.

FIELD SAMPLING

Sampling was conducted at both the production plant and the roadway independent of acceptance sampling and process control sampling. Stratified random sampling plans were developed to obtain the required sample-units [3]. For the purpose of this research project, the production of approximately 4,000 tons of bituminous concrete was considered as a lot. The lot was divided into 25 sublots of equal size, and two sample-units were obtained from each sublot at random.

Table 3-1. Types and Sources of Materials

Material	Source	% Used
Project 1, US-412		
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	
Project 2, US-70		
Aggregate:		
1) 3/8″ Chips	Meridian Aggregates @ Mill Creek, Oklahoma	23
2) FF Chips	Boorhem & Fields @ Troy, Oklahoma	26
3) Coarse Screenings	Boorhem & Fields @ Troy, Oklahoma	36
4) Fine Sand	J. D. Pratt @ Marshall County, Oklahoma	15
Asphalt Cement (AC-20)	Kerr McGee @ Wynnewood, Oklahoma	
Project 3, US-62		
Aggregate:		
1) 3/4″ Chips	The Dolese Company @ Cooperton, Oklahoma	15
2) 5/8″ Chips	Meridian Aggregates @ Snyder, Oklahoma	30
3) #4 Screenings	Meridian Aggregates @ Snyder, Oklahoma	20
4) #4 Screenings	The Dolese Company @ Cooperton, Oklahoma	25
5) Blow Sand	Sec. 25, T2N, R81W @ Kiowa County, Oklahoma	10
Asphalt Cement (AC-20)	Kerr McGee @ Wynnewood, Oklahoma	
Project 4, US-69		
Aggregate:		
1) 1-1/8″ Rock	Youngman Rock @ Onapa, Oklahoma	30
2) 5/8″ Chips	Youngman Rock @ Onapa, Oklahoma	25
3) Fine Mine Chat	Bingham S&G @ Miami, Oklahoma	22
4) Screenings	Youngman Rock @ Onapa, Oklahoma	8
5) Sand	Pryor Sand @ Whitefield, Oklahoma	15
Asphalt Cement (AC-20)	KOCH Materials @ Muskogee, Oklahoma	
Anti-Strip Agent (Permatac 99)	ScanRoads @ Waco, Texas	

Table 3-2. Job Mix Formula, Project 1 (US-412)

Mix Characteristic	Source 1	Source 2	Source 3	Source 4	Source 5	Combined Aggregate	JMF Target	JMF Tolerances
% Passing Sieve:								
1 1/2"	100					100	100	± 0
1"	97		100			98	98	± 7
3/4"	73	100	74			87	87	± 7
1/2"	39	80	47			67	70	± 7
No. 4	4	5	23		89	34	34	± 7
No. 10	2	4	15	100	63	25	25	± 4
No. 40	2	3	10	80	31	16	16	± 4
No. 80	1	2		23	21	8	8	± 4
No. 200	1	2		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

	Found	Required
Sand Equivalent	68	45 Min.
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 Asphalt Cement

	Found	Required
Specific Gravity @ 25°	1.0241	

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/yd^2/1" thickness
Max. Theoretical Specific Gravity @ 4.1% Asphalt Cement is 2.486 (155.1 pcf)

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

Table 3-2 (continued). Job Mix Formula, Project 2 (US-70)

Mix Characteristic	Source				Combined Aggregate	JMF Target	JMF Tolerances
	1	2	3	4			
% Passing Sieve:							
3/4"	100				100	100	± 0
1/2"	93		100		99	99	± 7
3/8"	44	100	95		86	86	± 7
No. 4	11	71	71	100	63	63	± 7
No. 10	5	5	44	99	33	37	± 4
No. 40	3	1	19	92	22	22	± 4
No. 80	2	1	12	34	10	10	± 4
No. 200	1.6	0.8	8.4	8.0	4.8	4.8	± 2
% Asphalt Cement (AC-20)						4.7	± 0.4
Mix temperature @ discharge from mixer, °F						305	± 20

Tests on Asphalt Cement

	Found	Required
Penetration @ 25° C	74	60-100
Viscosity @ 60° C	1942	2000 ± 400
Viscosity @ 135° C	429	300 Min.
Residue from RTFO		
Viscosity @ 60° C	4462	8000 Max.
Ductility @ 25° C	110+	50 Min.
Specific Gravity @ 25° C	1.0070	

Tests on Aggregates

	Found	Required
Sand Equivalent	57	45 Min.
L.A. Abrasion, (% Wear)	19.5	40 Max.
Durability (DC)	80	40 Min.
Insoluble Residue (Cal)	31.0	30 Min.
Fractured Faces	100	75 w/2
BISG	2.719	
Hveem Weight	1245	

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. %)
4.7	2.413	2.518	95.8		15.4		55	
5.2	2.428	2.498	97.2	95-97	15.3	15.0	54	40
5.7	2.443	2.479	98.5		15.3		53	

Retained Strength 81.7% , 75% Minimum Required

Recommended: 4.7% Asphalt Cement (AC-20)
Compacted Wt.: 111.0 lbs/yd^2/1" thickness
Maximum Theoretical Specific Gravity @ 4.7% Asphalt Cement is 2.518 (157.1 pcf)

Table 3-2 (continued). Job Mix Formula, Project 3 (US-62)

Mix Characteristic	Source 1	Source 2	Source 3	Source 4	Source 5	Combined Aggregate	JMF Target	JMF Tolerances
% Passing Sieve:								
3/4"	100	100				100	100	± 0
1/2"	43	91				89	89	± 7
3/8"	5	50	100	100		71	71	± 7
No. 4	2	6	96	89		54	54	± 7
No. 10	2	2	61	49	100	35	35	± 4
No. 40	1	1	21	19	85	18	18	± 4
No. 80	1	1	12	13	19	8	8	± 4
No. 200	1	0.7	6.9	9.4	2.3	4.3	4.3	± 2
% Asphalt Cement (AC-20)							4.7	± 0.4
Mix temperature @ discharge from mixer, °F							305	± 20
Optimum roadway compaction temperature, °F							290	

Tests on Asphalt Cement

	Found	Required
Penetration @ 25° C	70	60-100
Viscosity @ 60° C	1962	2000 ± 400
Viscosity @ 135° C	411	300 Min.
Residue from RTFO		
Viscosity @ 60° C	3812	8000 Max.
Ductility @ 25° C	100+	50 Min.
Specific Gravity @ 25° C	1.0018	

Tests on Aggregates

	Found	Required
Sand Equivalent	72	45 Min.
L.A. Abrasion, (% Wear)	25.0	40 Max.
Durability (DC)	87	40 Min.
Insoluble Residue (Cal)	54.7	30 Min.
Fractured Faces	100	75 w/2
BISG	2.654	
Hveem Weight	1215	

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. %)
4.3	2.354	2.478	95.0		15.1		45	
4.8	2.368	2.459	96.3	95-97	15.1	15.0	46	40
5.3	2.382	2.441	97.6		15.0		46	

Retained Strength 78.7% , 75% Minimum Required

Recommended: 4.7% Asphalt Cement (AC-20)
Compacted Wt.: 108.4 lbs/yd^2/1" thickness
Max. Theoretical Specific Gravity @ 4.7% Asphalt Cement is 2.463 (153.7 pcf)

Table 3-2 (continued). Job Mix Formula, Project 4 (US-69)

Mix Characteristic	Source 1	Source 2	Source 3	Source 4	Source 5	Combined Aggregate	JMF Target	JMF Tolerances
% Passing Sieve:								
1-1/2"	100					100	100	± 0
1"	92	100				98	98	± 7
1/2"	13	93	100	100	100	72	72	± 7
No. 4	6	23	99	96	97	52	52	± 7
No. 10	5	10	65	69	91	38	38	± 4
No. 40	5	8	9	47	29	14	14	± 4
No. 80	5	7	2	36	1	7	7	± 4
No. 200	3.1	4.3	0.7	20.1	0.4	3.8	3.8	± 2
% Asphalt Cement (AC-20)							4.8	± 0.4
Mix temperature @ discharge from mixer, °F							305	± 20
Optimum roadway compaction temperature, °F							290	
Anti-Strip agent required by weight of asphalt cement							0.5%	

Tests on Asphalt Cement

	Found	Required
Penetration @ 25° C	75	60-100
Viscosity @ 60° C	2166	2000 ± 400
Viscosity @ 135° C	475	300 Min.
Residue from RTFO		
Viscosity @ 60° C	5172	8000 Max.
Ductility @ 25° C	100+	50 Min.
Specific Gravity @ 25° C	1.0375	

Tests on Aggregates

	Found	Required
Sand Equivalent	74	40 Min.
L.A. Abrasion, (% Wear)	37.4	40 Max.
Durability (DC)	50	40 Min.
Fractured Faces	100	75 w/2
BISG	2.484	
Hveem Weight	1145	

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. %)
3.8	2.172	2.359	92.1		15.9		52	
4.3	2.192	2.344	93.5	94-96	15.6	13.0	54	40
4.8	2.212	2.328	95.0		15.2		52	

Retained Strength 84.6% , 75% Minimum Required

Recommended: 4.8% Asphalt Cement (AC-20)
Compacted Wt.: 102.4 $lbs/yd^2/1"$ thickness
Max. Theoretical Specific Gravity @ 4.8% Asphalt Cement is 2.328 (145.3 pcf)

Sampling at the Plant

At the plant, samples were obtained from two different locations as depicted in Figure 3-1. The first sampling point yielded samples from the aggregate stream prior to the dryer drum or drum mixer according to AASHTO T 2 [2]. A sampling platform was installed to facilitate intercepting the entire cross section of the material from the belt discharge. Randomization was based on the time of operation of the aggregate delivery system. Two sample-units, each having a specified minimum mass, were obtained from each sublot at random. For HMA mix types F, A, and B, the minimum mass of the sample-unit is 40 kg (90 lb), 80 kg (180 lb), and 16 kg (35 lb), respectively. The sample-units were identified by labels, placed in cloth sacks, and stored.

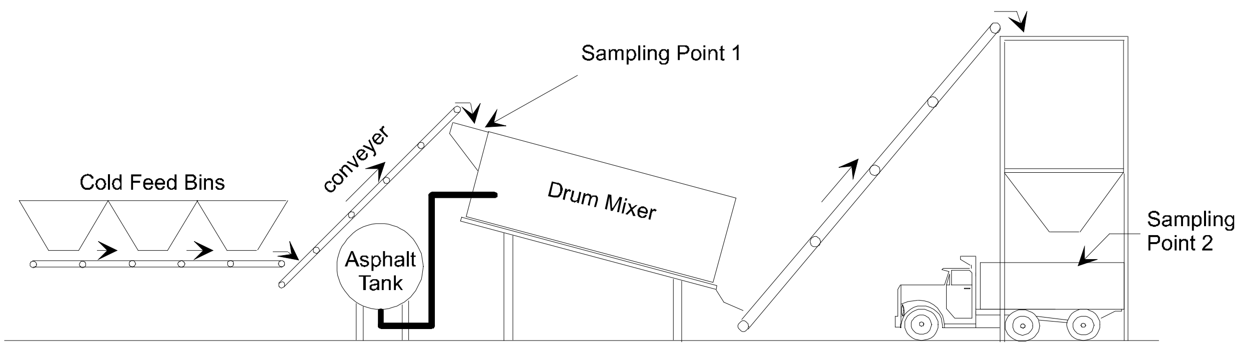


Figure 3-1. Location of Sampling Points at Production Plant

Sample-units of the freshly mixed bituminous concrete were obtained from the hauling trucks (point 2) containing the preselected random tonnage according to AASHTO T 168 [2]. Two sample-units, each having a minimum mass of 40 kg (90 lb), were selected from each sublot. The sample-units were identified by labels, placed in sacks, and stored.

Sampling at the Roadway

Random sampling locations on the compacted mixture were determined at random based on coordinates. Two sampling locations per sublot 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 D 2950. In the first construction project, three types of nuclear gauges were used: Troxler Model 4640, Troxler Model 3440, and Seaman Model C-200. In the other three construction projects, the Troxler Model 4640 was used. Each gauge was calibrated for the bituminous mix used in that project. At the conclusion of the nuclear gauge test, two cores were drilled at each sampling location according to AASHTO T 168 and T 166 [2]. The cores were identified by labels and stored in boxes.

Figures 3-2 through 3-7 show photographs taken at the first construction project. They illustrate the production plant, the aggregate sampling platform, sampling of the fresh mixture from the delivery trucks, and sampling from the compacted mixture.

LABORATORY TESTING

Test determinations were performed in the ODOT materials laboratories around the state in coordination with the ODOT Materials Division. Table 3-3 summarizes the number of laboratories involved in the testing program. 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 T 248 [2]. Thus, for each type of test on the cold feed aggregate, the fresh concrete mixture, and the constructed roadway, 100 test determinations were made for each of the four construction projects.

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 [22]. Samples taken from the aggregate stream at the belt discharge were tested for gradation according to AASHTO T 27 and AASHTO T 11. The test determinations performed on the bituminous mixture were: 1) asphalt content, nuclear method (OHD L-26); 2) asphalt content, extraction method (OHD L-26); 3) gradation of extracted aggregate (AASHTO T 30); 4) density of lab-molded specimens (OHD L-8 and OHD L-14); and 5) Hveem stability (OHD L-16). Cores taken from the finished pavement were tested for density according to OHD L-14.

Table 3-3. Materials Laboratories Involved in Testing

Project No.	Laboratory	No. of Tests per Lab
1	Central Materials Lab	0
	25 Construction Residency Labs	4
2	Central Testing Lab	28
	9 Construction Residency Labs	8
3	Central Testing Lab	20
	10 Construction Residency Labs	8
4	Central Testing Lab	12
	11 Construction Residency Labs	8

Figure 3-2. HMA Production Plant

Figure 3-3. Aggregate Sampling Platform

Figure 3-4. Sampling Fresh Mixture from Hauling Truck

Figure 3-5. Another Photograph of Sampling Fresh Mixture

Figure 3-6. Identifying Coordinates of a Sampling Point

Figure 3-7. Separating Old and New Pavement Layers for Core Density Determination

CHAPTER 4

ANALYSIS OF VARIANCE

This chapter summarizes the results of analysis of variance and other statistical analyses which were performed on measurements of the quality characteristics of acceptable HMA construction materials and processes in Oklahoma to determine the overall variability and its components due to materials, sampling, and testing. Following ASTM recommendations, all available data provided by ODOT were included in the analysis.

OVERALL VARIABILITY

Measures of the overall variability in the quality characteristics are presented in Tables A-1 through A-4 (Appendix A) including the variance, standard deviation, coefficient of variation, and range of test results for each of the four construction projects. Other summary statistics of the test results are also given. It should be noted that testing was performed by several operators using different pieces of equipment in different laboratories. Therefore, the measures of variability determined in this study are representative of the between-laboratory variation which is usually larger than that found in a single laboratory.

Estimates of the pooled variance and pooled standard deviation computed from all four projects are shown in Table A-5 (Appendix A). The pooled variance for a given quality characteristic is the weighted average of the individual variances found in the four projects, with the weights being equal to the number of test results per project less one.

For comparison purposes, Tables 4-1 through 4-4 summarize the results of several studies on variability in HMA materials which were performed in the past 20 years. These tables are reproduced from a 1996 report published by NCHRP on variability in highway pavement construction [13].

In Table 4-1, typical values of the standard deviation of aggregate gradation from extraction test results are shown. The WSDOT data were calculated from a sample of 81 measurements drawn from a single project, the PennDOT data were based on a sample of 49 measurements from a single project, and the BPR data are pooled estimates calculated from several projects. The variability data from Indiana DOT and Arkansas DOT were provided in response to a questionnaire used in the NCHRP study. Examination of these typical measures of variation indicates that the variability in aggregate gradation found in Oklahoma (Tables A-1 through A-4, Appendix A) is within the ranges reported by other states, except sieves 3/8″ and ½″ where the standard deviations exceeded the typical values in two out of the four projects. Nevertheless, the variability found in some states is less than that in Oklahoma, which suggests that there is room for quality improvement through variation reduction. Similar conclusions can be drawn by comparing the typical measures of variability in aggregate gradation from cold feed samples shown in Table 4-2 with those determined in this study.

Table 4-1. Typical Standard Deviations of Aggregate Gradation from Extraction Tests (Percent Passing)

Source	Year	¾″ or ½″	3/8″	No. 4	No. 10	No. 40	No. 50	No. 200
				Surface Mixtures				
Arkansas	1993	1.7	2.6	2.8	1.7	1.3	1.1	0.6
Washington [21]	1993	1.6	2.5	3.0	2.4	1.6	---	0.5
Pennsylvania [9]	1982	2.3	4.4	3.4	2.5	1.5	1.2	1.0
BPR [12]	1969	1.4	2.5	3.5	2.8	1.6	1.2	0.9
Virginia [10]	1968	---	1.9	3.3	3.2	1.6	1.2	0.9
				Binder or Base Mixtures				
Indiana	1989	3.8	---	3.0	---	---	---	0.4
BPR [12]	1969	4.3	4.9	3.9	2.5	1.7	1.2	0.9

Table 4-2. Typical Standard Deviations of Aggregate Gradation from Cold Feed (Percent Passing)

Mix Type	Year	n	3/8″	No. 4	No. 8	No. 30	No. 50	No. 100	No. 200
Surface Mix [42]	1969	36	1.1	8.4	9.6	6.9	3.6	2.4	1.5
Surface Mix [42]	1969	36	0.8	3.9	4.7	4.3	3.9	2.8	1.5
Surface Mix [42]	1969	36	2.3	6.5	5.8	4.1	2.6	1.4	0.9
Binder Mix [42]	1969	36	9.4	8.4	7.9	4.6	2.9	1.5	0.5
Binder Mix (a)	1993	32	3.2	3.3	3.2	1.8	1.0	0.6	0.6
Binder Mix (a)	1993	21	2.4	2.1	1.8	1.0	0.7	0.6	0.5

(a) Data from contractor quality control results in Wisconsin

Comparison of the typical values of the standard deviation of asphalt content shown in Table 4-3 with those found in Oklahoma (Tables A-1 through A-4, Appendix A) indicates that the variability in projects 2, 3, and 4 are within the national range, whereas variability in project 1 exceeded the typical values of variation. Similar comparison of the typical values of the standard deviation of air voids in the compacted pavement shown in Table 4-4 with those found in this study reveals that the variability in this quality characteristic is within the range reported by other states. Again, the variability found in some states is less than that in Oklahoma, which suggests that the capability of the HMA construction processes in Oklahoma can be improved through statistical process control and reduction in natural variation.

Table 4-3. Typical Standard Deviation of Asphalt Content

Source	Year	Test Method	Standard Deviation, %
Arkansas	1994	Extraction	0.21
Virginia [15]	1994	Extraction	0.18
Virginia [15]	1994	Nuclear	0.21
Washington [21]	1993	Extraction	0.24
Colorado [6]	1993	Extraction	0.15
Kansas [11]	1988	Nuclear	0.27
Virginia [14]	1988	Extraction	0.19
Pennsylvania [19]	1980	Extraction	0.25
BPR [12]	1969	Extraction	0.28
Virginia [10]	1968	Extraction	0.25

Table 4-4. Typical Standard Deviations of Air Voids for Roadway Compacted Mixtures

Source	Year	Test Method	Standard Deviation, %
California [5]	1995	Cores	1.9
New Jersey [29]	1995	Cores	1.5
Ontario [4]	1995	Cores	1.6
Colorado [6]	1993	Cores	1.0
Washington [21]	1993	Nuclear	0.9
Virginia [16]	1984	Cores	1.3

Another finding supported by the results in Tables A-1 through A-4 (Appendix A) is that the standard deviation of a given quality characteristic is by itself a variable. This has an implication in developing statistically-based acceptance plans. Early acceptance plans were developed based on the assumption that variability is known, and pay schedules were determined using a set value of the standard deviation from historical data. Variability-known acceptance plans are not considered to be rational because it is rare in highway construction that the standard deviation is actually known. A more logical approach to developing acceptance plans should be based on variability-unknown methods similar to those described in the AASHTO Quality Assurance Guide Specification [1].

COMPONENTS OF VARIABILITY

Summaries of the components of total variation due to materials, sampling, and testing which were found in the four construction projects are presented in Tables A-6 through A-9 (Appendix A). The contribution of each source of variation is shown in terms of the standard deviation of the respective component.

The standard deviation of the materials component is an estimate of the expected variability in a single lot of HMA due to lack of uniformity in the material or construction when the production process is running smoothly. Likewise, the standard deviation of the sampling component is representative of the variation which is introduced during field sampling -- it does not include the variation caused by reducing large portions of the material to test specimens by splitting and quartering which is considered by ODOT to be part of testing. Finally, the standard deviation of the testing component is a measure of the precision of the test method and how sensitive the test method is to changes in the measured property of the material. Again, It should be emphasized that testing was performed by several operators using different testing apparatus in different laboratories. Therefore, the multilaboratory standard deviation of the testing component reported in this study is expected to be greater than the single laboratory standard deviation.

In general, the following might be concluded based on the results in Tables A-6 through A-9 (Appendix A):

Aggregate Gradation

Analysis of the cold feed samples indicates that the average standard deviation for all sieves ranges from 0.74% to 1.44% for the materials component, 0.23% to 1.93% for the sampling component, and 1.55% to 2.65% for the testing component. In addition, the results suggest that the material passing sieves ½" through No. 40 has higher overall standard deviation and higher components of variation than the rest of the sieves.

Extraction test results from the HMA mixture indicate that the average standard deviation for all sieves ranges from 0.49% to 1.13% for the materials component, 0.72% to 1.20% for the sampling component, and 0.98% to 2.25% for the testing component. In general, the standard deviations of the testing component for the material passing smaller sieves were less than those found in cold feed samples, whereas the standard deviations for the material passing larger sieves were greater than those for cold feed samples.

Results of hypothesis testing of cold feed samples and HMA mixture samples were mixed with no evident trends throughout the four projects. Nevertheless, values of the F-statistic for the first hypothesis ($H_0\!:\ \sigma_M^2 = 0$ *vs.* $H_1\!:\ \sigma_M^2 > 0$) suggest that variability due to materials was not significant for the large size sieves, i.e., aggregate gradation was uniform throughout the lot. For the small sieves, variability due to materials was generally significant.

Similar rough conclusions concerning variability due to sampling can be drawn based on values of the F-statistic for the second hypothesis (H_0: $\sigma_s^2 = 0$ *vs*. H_1: $\sigma_s^2 > 0$). The contribution of sampling to overall variability is insignificant for large sieves and is significant for small sieves.

Asphalt Content

The breakdown of overall variation in asphalt content data from extraction tests suggests that the standard deviations of the materials, sampling, and testing components range from 0.00% to 0.20%, 0.13% to 0.19%, and 0.13% to 0.19%, respectively. For the nuclear gauge test results, the standard deviations of the materials, sampling, and testing components range from 0.07% to 0.29%, 0.08% to 0.16%, and 0.09% to 0.13%, respectively.

For both the extraction and nuclear gauge test methods, the F-ratios suggest that variability due to materials was not significant in two out of the four projects, whereas variability due to sampling was significant in all four projects.

The use of chlorinated solvents has become an environmental concern, and many states including ODOT have substituted the solvent extraction test method with the ignition oven test method. Unfortunately, this fairly new technology was not available during the course of this study. Chapter 7 presents detailed discussion of the different test methods for asphalt content determination.

Air Voids in Compacted Pavement

The standard deviation ranges from 0.52% to 1.23% for the materials component, 0.29% to 1.01% for the sampling component, and 0.33% to 0.53% for the testing component. Results of hypothesis testing suggest that the individual components of variability due to materials and due to sampling were significant in all four projects.

Hveem Stability

The standard deviations of the materials, sampling, and testing components range from 4.45% to 18.30%, 0.00% to 7.12%, and 1.49% to 7.80%, respectively. The F-ratios indicate that the individual components of variability due to materials and due to sampling are significant in three out of the four projects.

Roadway Density

Density measurements using core samples suggest that the standard deviations of the materials, sampling, and testing components range from 0.00% to 1.35%, 0.79% to 1.64%, and 0.46% to 1.06%, respectively. For the nuclear gauge test results, the standard deviations of the materials, sampling, and testing components range from 0.15% to 1.47%, 0.46% to 1.72%, and 0.00% to 1.02%, respectively.

Values of the F-ratios computed from core samples suggest that variability due to materials was not significant in three out of the four projects, and that variability due to sampling was significant in all four projects. Density measurements by the nuclear gauge indicate insignificant variability due to materials and significant variability due to sampling in three out of the four projects.

Other Volumetric Properties

Variations in the Rice specific gravity of loose HMA samples indicate that the standard deviation of the materials component is 0.01%, the standard deviation of the sampling component ranges from 0.00% to 0.01%, and the standard deviation of the testing component is 0.01%. Likewise, variations in the bulk specific gravity (lab-molded specimens) indicate that the standard deviation of the materials component ranges from 0.01% to 0.02%, the standard deviation of the sampling component ranges from 0.00% to 0.02%, and the standard deviation of the testing component is 0.01%.

Results of hypothesis testing for the Rice specific gravity and the bulk specific gravity suggest that the individual components of variability due to materials and due to sampling are significant in all four projects.

CHAPTER 5

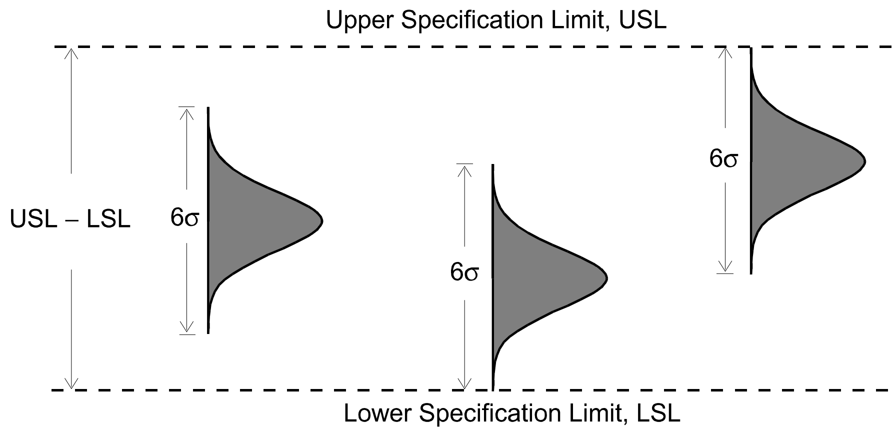
PROCESS CAPABILITY & SPECIFICATIONS

Process capability analysis is the study of the ability of a process to produce products that conform to engineering specifications. The desired performance in terms of a particular quality characteristic is usually specified by a target value *T*, an upper specification limit (*USL*), and/or a lower specification limit (*LSL*). In an ideal production process, the quality characteristic is held at the target setting with no variation. In reality, variation is unavoidable, and the quality characteristic will posses a statistical distribution. The capability of the process depends on the relationship of this distribution that characterizes process performance to the specifications that describe process requirements.

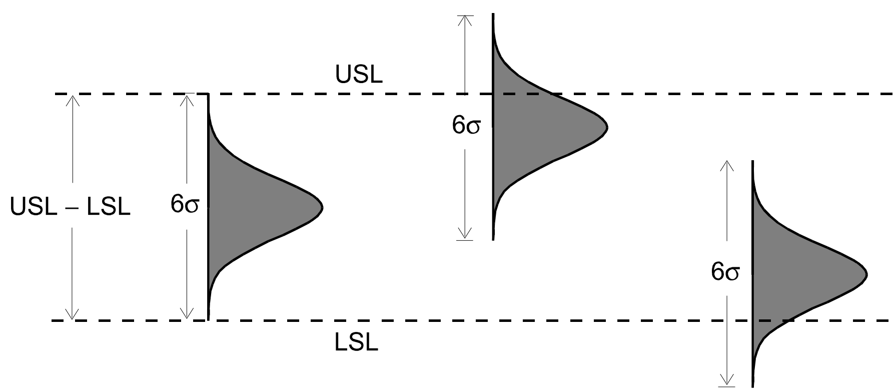
The capability of a process can be assessed only after the process has been brought into a state of statistical control. In other words, a stable and predictable distribution of the process output -- which reflects natural causes of variation -- is a prerequisite for capability analysis. The 6σ spread in the distribution of the product quality characteristic is called the **natural process tolerance** or **basic capability of the process** since a process that is in-control should be able to produce products that fall within that window of natural variation.

Though a process may be in statistical control, a large percentage of the production may not meet the specifications. One reason for this could be that the process is not properly centered on the specified target. If this is the case, the problem can be corrected by adjusting the process to move its mean closer to target. Another possible reason for the lack of conformance to specifications could be that the natural variation is excessively large which jeopardizes process capability. Improving process capability requires reducing those common causes of variation that can possibly be reduced. A third possible reason could be that the specification limits themselves are not realistic, i.e., the specifications do not properly account for the expected natural variation in a stable process.

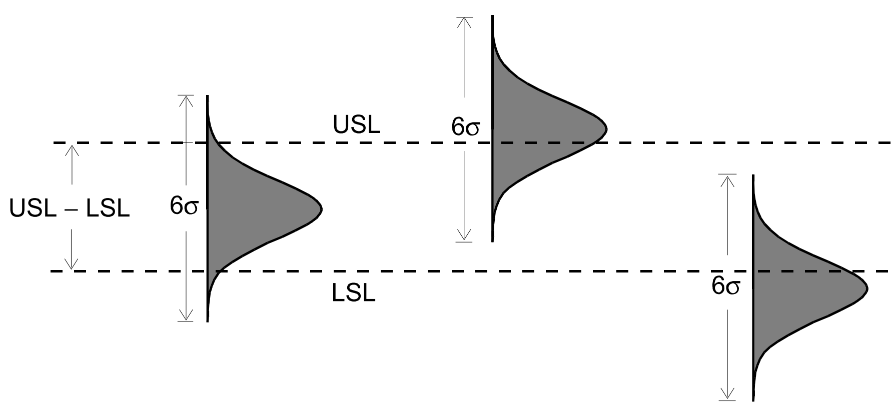
Figure 5-1 illustrates three possible cases that can be encountered in a stable process. In Figure 5-1(a), the natural process tolerance (6σ) is less than the specification range (difference between the upper and lower specification limits). The product will meet the specifications even when there is a substantial shift in the process mean due to an out-of-control condition. It is important, however, to separate the issues of control and conformance. When a process is not in a controlled state, the productivity/efficiency of the process is not guaranteed. The contractor may be making a product that meets the specifications, but he/she is not doing so in the most economical fashion.



a) 6σ < (USL – LSL) -- Process mean can shift without causing process capability to be jeopardized



b) 6σ = (USL – LSL) -- Process must remain centered in order to maintain process capability



c) 6σ > (USL – LSL) -- Process is not capable regardless of process centering

Figure 5-1. Relationship Between Process Variability and Specifications

In Figure 5-1(b), the natural process tolerance is equal to the specification range. As long as the process remains in control and properly centered, and assuming that the quality characteristic is normally distributed, approximately 0.27% of the production will fall outside the specification limits. Therefore assignable causes of variation must be identified and corrected as soon as they occur.

Figure 5-1(c) illustrates the case where the 6σ band is greater than the specification range. Even though the process is in-control, some of the individual measurements will fall outside the specification limits. In this case, the process is incapable of producing a product that will meet the specifications all of the time. To remedy this problem, the process must be improved by reducing its natural variation. Specification limits should also be examined to ensure that they account for the overall natural variation expected when the process is in a state of control.

PROCESS CAPABILITY INDICES

In recent years, a number of process capability indices (PCI's) have been proposed to quantify the performance of production processes. Despite their limitations, these indices have been widely used by many industries and continue to be very popular in quality assurance and control efforts. The most common PCI's are the C_p, C_{pk}, and C_{pm} indices.

Let μ and σ denote the mean and standard deviation of a particular quality characteristic of process output. In addition, let M be the midpoint of the specification range, i.e., $M = (LSL + USL)/2$, which may or may not be equal to the specification target T. The C_p, C_{pk}, and C_{pm} indices are defined by:

$$C_p = \frac{USL - LSL}{6\sigma} \qquad (5.1)$$

$$C_{pk} = \min\left\{\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} = \frac{USL - LSL - 2|\mu - M|}{6\sigma} \qquad (5.2)$$

$$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}} = \frac{C_p}{\sqrt{1 + \left(\frac{\mu - T}{\sigma}\right)^2}} \qquad (5.3)$$

For each of these indices, a larger value implies a more capable process. All three indices are scaled so that the index value is 1.0 if $\mu = T = M$ and $\sigma = (USL - LSL)/6$, in which case approximately 99.7% of the process output will fall within the specification limits, provided that the quality characteristic is normally distributed and the process is in control.

Since the process variance is seldom known, the value of σ is usually estimated using the sample standard deviation *s* given by equation 2.1. In general, a large sample size (120 measurements) will be required. An estimate of σ can also be determined from the *R*-control-chart based on the average range of several small samples taken from the process over time. The estimators of C_p, C_{pk}, and C_{pm} are obtained by replacing μ with $\hat{\mu} = \bar{x}$ and σ with $\hat{\sigma} = s$.

The C_p index has a practical interpretation: 100 ($1/C_p$) is the percentage of the specification range that is used by the process. A process is said to be capable if $C_p \geq 1$. Many industries require a minimum value of $C_p = 1.33$, and for critical quality characteristics, a minimum $C_p = 1.66$.

Because the C_p index depends only on the natural variation in a process, its value can be misleading unless it is examined simultaneously with the process mean μ and its relationship to the specified target. With reference to Figure 5-1(a), samples taken from any of the three distributions would yield similar estimates for the C_p index. Since the variances of the populations are much smaller than the specification range, the estimates of C_p would be fairly large, suggesting that all three processes are equally capable. Nevertheless, the distributions of the second and third processes are not centered on target. Therefore, C_p can be thought of as a measure of **potential capability**, that is, capability of the process when centered. In addition, implicit in the definition of C_p is that the specification is two-sided.

The other two indices (C_{pk}, and C_{pm}) account for the location of the process mean μ as well as the natural variation σ. The distinction between C_{pk} and C_{pm} is in the relative importance attached to the specification limits as opposed to the target. For a given process that is in control, the index C_p is never smaller than the other two indices, and the magnitude of the difference between C_p and C_{pk} or C_{pm} reflects the improvement that can be realized by moving the process mean to the specification midpoint or target and/or decreasing the natural variability in the process.

For any fixed value of σ, both C_{pk} and C_{pm} attain their maximum value when $\mu = T = M$, where they become equal to C_p. The value of C_{pk} decreases as μ approaches either *USL* or *LSL*, whereas the value of C_{pm} decreases as μ departs from *T*. In addition, for any fixed value of μ, both C_{pk} and C_{pm} can be increased by decreasing σ. As σ approaches zero, the value of C_{pk} increases without bound, whereas the value of C_{pm} is bounded by:

$$C_{pm} < \frac{(USL - LSL)}{6|\mu - T|} \tag{5.4}$$

Therefore, when $T = M$, a C_{pm} value of 1.0 implies that the process mean μ lies within the middle third of the specification range. Similar interpretations can be made for any C_{pm} value; for example, $C_{pm} = 4/3$ implies that μ falls within the middle fourth of the specification range.

When there is only one specification limit (one-sided specification), the process mean should be as far as possible from that limit. For one-sided specification with a lower limit, the capability index:

$$C_{pL} = (\mu - LSL) / 3\sigma \qquad (5.5)$$

compares the distance between the process mean and the lower specification limit to the 3σ band. Since there is no specified target, the process capability is improved as the process mean is increased.

Similarly, for one-sided specification having an upper limit, the process capability is defined by:

$$C_{pU} = (USL - \mu) / 3\sigma \qquad (5.6)$$

In this case, the process should be operated with the lowest mean value that is realistic.

EVALUATION OF PROCESS CAPABILITY

The estimates of process capability presented in the following sections are based on the assumption that the production/construction process is stable and in a state of statistical control. Inferences about the capability of a process are only relevant if the future performance of the process is predictable. It should also be noted that the reported estimates of process capability are calculated based on samples and, therefore, are subject to sampling error.

Natural Process Tolerances

Table B-1 (Appendix B) presents estimates of the basic process capability ($6\hat{\sigma}$ limits) for each of the four construction projects. Also shown are the $4\hat{\sigma}$ limits and the percentages of the process output that fall within the $6\hat{\sigma}$ and $4\hat{\sigma}$ bands.

Plots of the distributions of the quality characteristics are included in Appendices C through F. Each plot displays the histogram of test results, JMF target, LSL and USL for the existing QA specifications, and the two- and three-sigma limits of natural variation from the process average. Examination of these plots reveals that none of the quality characteristics is centered on the JMF target, except percent passing the ¾″ and larger sieves.

In general, the histograms suggest that the quality characteristics are approximately normally distributed. Notable exceptions include the characteristics of asphalt content measurements by the nuclear gauge which exhibited bimodality in project 1 (US-412), Hveem stability measurements which indicated positive skewness in project 4 ((US-69), roadway density measurements by the nuclear gauge which showed a truncation in projects 3 (US-62). Likewise, the histograms of aggregate gradation for a number of sieves indicate that the percent passing is not normally distributed in some projects.

Capability Indices with respect to JMF Tolerances

A summary of the C_p, C_{pk}, and C_{pm} indices with respect to the JMF tolerances is presented in Table B-2 (Appendix B) for the four construction projects. In general, the following points can be made:

1. **Cold Feed Analysis**

- Sieves 1″ and 1½″ -- Both C_p and C_{pm} are greater than 1 for all four projects.
- No. 80 sieve -- The C_p index varies from 0.98 to 1.54, with two out of the four projects having a C_p greater than 1. Values of C_{pm} range from 0.60 to 1.34 with only one project having a C_{pm} greater than 1.
- All other sieves -- Both C_p and C_{pm} are less than 1 for all four projects.

2. **HMA Mixture Analysis**

- Sieve 1½″ -- Both C_p and C_{pm} are greater than 1 for all four projects.
- Sieve 1″ -- Three out of the four projects have a C_p greater than 1, and two out of the four projects have a C_{pm} greater than 1.
- Sieve ¾″ -- Only one out of the three projects which included this sieve in their JMF has C_p and C_{pm} values greater than 1.
- Sieve ½″ -- The C_p index varies from 0.52 to 1.69, with two out of the four projects having a C_p greater than 1. All four projects have a C_{pm} less than 1, with values ranging from 0.37 to 0.98.
- Sieve 3/8″ – One out of the two projects which included this sieve in their JMF has a C_p greater than 1. Both projects have C_{pm} less than 1.
- No. 4 and No. 10 sieves -- Values of C_p and C_{pm} are less than one for all four projects.
- No. 40 sieve -- The range of C_p is 0.84 to 1.62, with two out of the four projects having a C_p greater than 1. Values of C_{pm} are less than 1 for all four projects.
- No. 80 sieve -- All four projects have C_p greater than 1, with values ranging from 1.19 to 2.50. The range of C_{pm} is 0.71 to 1.61, with two out of the four projects having C_{pm} greater than 1.
- No. 200 sieve -- Values of C_p vary from 0.92 to 2.26, with three out of the four projects having C_p greater than 1. The C_{pm} varies from 0.47 to 1.04 with only one project having C_{pm} greater than 1.
- Asphalt Content – Values of both C_p and C_{pm} are less than 1 for all four projects.
- Air voids -- Values of C_p and C_{pm} are less than 1 for all four projects.
- Hveem Stability -- The range of C_p is 0.54 to 1.86, with two out of the four projects having C_p greater than 1. All four projects have C_{pL} values less than 1.

- Roadway Density -- Both C_p and C_{pm} are less than 1 for all four projects. For project 4 (US-69), the value of C_p is 2.1 based on density measurements obtained by the nuclear gauge. However, this value should be viewed with caution because of problems with testing which were encountered on this project.

Capability Indices with respect to Existing QA Specification Tolerances

Table B-3 (Appendix B) presents a summary of the C_p, C_{pk}, and C_{pm} indices with respect to the existing QA specification tolerances. In general, the following might be concluded:

1. <u>Cold Feed Analysis</u>

- Sieves 1″ and 1½″ -- Both C_p and C_{pm} are greater than 1 for all four projects.
- Sieve ¾″ -- Values of C_p and C_{pm} are greater than 1 for two out of the three projects which included this sieve in their specifications.
- Sieve ½″ -- The C_p values vary from 0.61 to 1.35, with only one out of the four projects having a C_p greater than 1. All four projects have a C_{pm} less than 1, with values ranging from 0.54 to 0.79.
- Sieves 3/8″, No. 4 and No. 10 -- Values of C_p and C_{pm} are less than 1 for all projects that included any of these sieves in their specifications.
- No. 40 sieve -- The range of C_p is 0.42 to 1.19, with only one out of the four projects having a C_p greater than 1. Values of C_{pm} are less than 1 for all four projects
- No. 80 sieve -- All projects have C_p values greater than 1. Values of C_{pm} range from 0.98 to 2.17 with three out of the four projects having C_{pm} greater than 1.
- No. 200 sieve -- The range of C_p is 0.97 to 1.39, with three out of the four projects having C_p greater than 1. Values of C_{pm} vary from 0.42 to 1.13 with only one project having C_{pm} greater than 1.

2. <u>HMA Mixture Analysis</u>

- Sieve 1½″ -- Both C_p and C_{pm} are greater than 1 for all four projects.
- Sieve 1″ -- Three out of the four projects have C_p and C_{pm} values greater than 1.
- Sieve ¾″ -- Two out of the three projects which included this sieve in their specifications have C_p and C_{pm} values greater than 1.
- Sieve ½″ -- The range of C_p is 0.59 to 1.90, and the range of C_{pm} is 0.43 to 1.12. Two out of the four projects have values of C_p and C_{pm} that are greater than 1.

- Sieve 3/8″ -- Both projects which included this sieve in their specifications have C_p values greater than 1. One out of the two projects has a C_{pm} greater than 1.
- No. 4 sieve -- The range of C_p is 0.80 to 1.07, with only one out of the four projects having a C_p greater than 1. Values of C_{pm} vary from 0.54 to 0.81.
- No. 10 sieve -- Values of C_p range from 0.71 to 1.02, and values of C_{pm} range from 0.48 to 1.02. Only one out of the four projects has both C_p and C_{pm} greater than 1.
- No. 40 sieve -- The range of C_p is 1.37 to 2.64. Values of C_{pm} vary from 0.63 to 1.41, with two out of the four projects having C_{pm} greater than 1.
- No. 80 sieve -- Values of both C_p and C_{pm} are greater than 1 for all four projects.
- No. 200 sieve -- All four projects have C_p greater than 1, with values ranging from 1.38 to 3.39. The C_{pm} varies from 0.70 to 1.55 with two out of the four projects having C_{pm} greater than 1.
- Asphalt Content -- Values of C_p computed from extraction test results range from 0.77 to 1.07 with two out of the four projects having C_p greater than 1. The C_{pm} values vary from 0.51 to 0.91. Asphalt content measurements by the nuclear gauge yielded C_p values in the range 0.67 to 1.27, with two out of the four projects having C_p greater than 1. The range of C_{pm} is 0.47 to 1.16, with one out of the four projects demonstrating a C_{pm} greater than 1.
- Air voids -- Values of C_p range from 0.50 to 1.23 with only one project having C_p greater than 1. The C_{pm} values are less than 1 for all four projects.
- Hveem Stability -- The range of C_p is 0.56 to 1.92, with two out of the four projects having C_p greater than 1. Values of C_{pL} are less than 1 for all four projects.
- Roadway Density -- Both C_p and C_{pm} are less than 1 for all four projects. The value of C_p for project 4 (US-69) should be viewed with caution because of problems with testing.

Capability Indices with respect to Proposed QA Specification Tolerances

Table B-4 (Appendix B) presents a summary of the C_p, C_{pk}, and C_{pm} indices with respect to the proposed QA specification tolerances. In general, the following might be concluded:

1. <u>Cold Feed Analysis</u>

- Sieves 1″ and 1½″ -- Both C_p and C_{pm} are greater than 1 for all four projects.
- Sieve ¾″ -- Values of C_p range from 0.72 to 4.06, and values of C_{pm} range from 0.72 to 3.96. Two out of the three projects which included this sieve in their specifications have both C_p and C_{pm} that are greater than 1.

- Sieve ½″ -- The C_p values vary from 0.46 to 1.05, with only one out of the four projects having a C_p greater than 1. Values of C_{pm} range from 0.41 to 0.59.
- Sieves 3/8″, No. 4, No. 10, and No. 40 -- Values of C_p and C_{pm} are less than 1 for all projects that included any of these sieves in their specifications.
- No. 80 sieve -- All projects have C_p values greater than 1. Values of C_{pm} range from 0.68 to 1.51 with two out of the four projects having C_{pm} greater than 1.
- No. 200 sieve -- The range of C_p is 0.65 to 0.93, and the range of C_{pm} is 0.28 to 0.75.

2. <u>HMA Mixture Analysis</u>

- Sieve 1½″ -- Both C_p and C_{pm} are greater than 1 for all four projects.
- Sieve 1″ -- Three out of the four projects have C_p and C_{pm} values greater than 1.
- Sieve ¾″ -- Two out of the three projects which included this sieve in their specifications have C_p and C_{pm} values greater than 1.
- Sieve ½″ -- The range of C_p is 0.45 to 1.47, with only one project having C_p greater than 1. The range of C_{pm} is 0.32 to 0.84.
- Sieve 3/8″, No. 4 and No. 10 -- Values of C_p and C_{pm} are less than 1 for all projects that included any of these sieves in their specifications.
- No. 40 sieve -- The range of C_p is 0.95 to 1.83, with three out of the four projects having C_p greater than 1. Values of C_{pm} are less than 1 for all four projects.
- No. 80 sieve -- All four projects have C_p greater than 1, with values ranging from 1.30 to 2.81. The range of C_{pm} is 0.80 to 1.81 with three out of the four projects having C_{pm} greater than 1.
- No. 200 sieve -- Values of C_p vary from 0.92 to 2.26, with three out of the four projects having C_p greater than 1. The C_{pm} varies from 0.47 to 1.04 with only one project having C_{pm} greater than 1.
- Asphalt Content -- Values of both C_p and C_{pm} are less than 1 for all four projects.
- Air voids -- Values of C_p and C_{pm} are less than 1 for all four projects.
- Roadway Density -- Both C_p and C_{pm} are less than 1 for all four projects.

OTHER MEASURES OF PROCESS PERFORMANCE

In addition to the capability indices described in the previous sections, process performance was evaluated using the conformity index and the percent of process output that falls within tolerances. The following sections present the results of these analyses.

Percent within Specification Limits

Tables B-5 through B-7 (Appendix B) present estimates of the percent of process output that falls within the JMF tolerances, the existing QA specification limits, and the proposed QA specification limits. In general, the following might be concluded:

1. <u>Cold Feed Analysis</u>

- Sieves 1″ and 1½″ -- The aggregate passing these large sieves was within the JMF tolerances, the existing QA specification tolerances, and the proposed QA specification tolerances 100% of the time for all four projects.

- Sieve ¾″ -- The percent within JMF tolerances ranges from 94% to 98.91%. All three projects which included this sieve demonstrated 100% conformance to the existing QA specification limits, whereas the percent within the proposed QA specification limits varies from 89.91% to 100%.

- Sieve ½″ -- Test results indicate that 82.61% to 100% of process output falls within JMF tolerances; 89.13% to 100% falls within the existing QA specification limits; and 76.09% to 100% falls within the proposed QA specification limits. Of the four construction projects, only one project demonstrated 100% compliance with JMF, and three projects demonstrated 100% compliance with both the existing and the proposed QA specifications.

- Sieve 3/8″ -- One out of the two projects which included this sieve in their specifications had 87% of the material within the JMF tolerances, 92% within the existing QA specification limits, and 84% within the proposed QA specification limits. The other project had 79.35% within the JMF tolerances, 85.87% within the existing QA specification limits, and 68.48% within the proposed QA specification limits.

- No. 4 sieve -- Conformance to JMF tolerances ranges from 78% to 96.74%, conformance to existing QA specification limits ranges from 84% to 96.74%, and conformance to proposed QA specification limits ranges from 69% to 91.30%.

- No. 10 sieve --The material passing this sieve was within JMF tolerances 59.78% to 82% of the time. The percent within existing QA specification limits was 80.43% to 97.83%, and the percent within proposed QA specification limits was 64.13% to 88.04%.

- No. 40 sieve -- 75% to 97.83% of the process output was within JMF tolerances, 94.57% to 98.91% was within the existing QA specification limits, and 82.61% to 97.83% was within the proposed QA specification limits.

- No. 80 sieve -- The percent within JMF tolerances ranges from 97% to 100%. All four projects demonstrated 100% compliance with the existing QA specification limits, whereas conformance to the proposed QA specification limits ranges from 98.91% to 100%.

- No. 200 sieve -- Test results indicate that 44% to 95% of process output falls within JMF tolerances; 78% to 98.91% falls within the existing QA specification limits; and 44% to 95% falls within the proposed QA specification limits.

2. <u>HMA Mixture Analysis</u>

- Sieves 1″ and 1½″ -- Aggregate passing these sieves was within the JMF tolerances, the existing QA specification tolerances, and the proposed QA specification tolerances 100% of the time for all four projects.

- Sieve ¾″ -- For the three projects which included this sieve, the percent within JMF tolerances ranges from 82.61% to 100%, the percent within the existing QA specification limits ranges from 94.57% to 100%, and the percent within the proposed QA specification limits ranges from 76.09% to 100%.

- Sieve ½″ -- 72.83% to 100% of the process output falls within JMF tolerances; 81.52% to 100% falls within the existing QA specification limits; and 63.04% to 100% falls within the proposed QA specification limits. Of the four construction projects, only one project demonstrated 100% compliance with JMF, and two projects demonstrated 100% compliance with both the existing and proposed QA specifications.

- Sieve 3/8″ -- One out of the two projects which included this sieve demonstrated 100% compliance within both the JMF tolerances and the existing QA specification limits, whereas compliance with the proposed QA specification limits was 98%. The other project had 81.82% within the JMF tolerances, 89.77% within the existing QA specification limits, and 73.86% within the proposed QA specification limits.

- No. 4 sieve -- Conformance to JMF tolerances ranges from 85.87% to 98.86%, conformance to existing QA specification limits ranges from 94.57% to 100%, and conformance to proposed QA specification limits ranges from 70.65% to 93.18%.

- No. 10 sieve --The material passing this sieve was within JMF tolerances 56.52% to 94.57% of the time. The percent within existing QA specification limits was 88.04% to 100%, and the percent within proposed QA specification limits was 70.65% to 95.65%.

- No. 40 sieve -- The range of percent within limits was 75% to 100% for JMF tolerances; 89.91% to 100% for the existing QA specification limits; and 86.96% to 100% for the proposed QA specification limits. Two out of the four projects demonstrated 100% compliance with JMF tolerances, existing QA specification limits, and proposed QA specification limits.

- No. 80 sieve – Data from the four projects indicate that 97.83% to 100% of the process output was within JMF tolerances, 98.91% to 100% was within the existing QA specification limits, and 98.91% to 100% within the proposed QA specification limits.

- No. 200 sieve -- Conformance to JMF tolerances ranges from 86% to 100%, with two out of the four projects having 100% compliance. All four projects demonstrated 100% conformance to the existing QA specification limits. The percent within the proposed QA specification limits varies from 86% to 100%, with two projects having 100% compliance.

- Asphalt Content -- Extraction test results indicate that 60.87% to 89% of asphalt content measurements fall within JMF tolerances, 84.78% to 100% fall within the existing QA specification limits, and 72.83% to 98% fall within the proposed QA specification limits. Nuclear gauge results show that 51.14% to 95.83% of asphalt content measurements fall within JMF tolerances, 81.82% to 100% fall within the existing QA specification limits, and 60.23% to 98% fall within the proposed QA specification limits.

- Air voids -- Conformance to JMF tolerances ranges from 26% to 76.14%, conformance to existing QA specification limits ranges from 80% to 93.18%, and conformance to proposed QA specification limits ranges from 47% to 84.09%.

- Hveem Stability -- The percent within JMF tolerances ranges from 95.31% to 100%, and the percent within existing QA specification limits ranges from 96.88% to 100%.

- Roadway Density -- Core test results indicate that 0% to 92% of density measurements fall within JMF tolerances, 0% to 94% fall within the existing QA specification limits, and 0% to 94% fall within the proposed QA specification limits. Nuclear gauge results show that 0% to 27% of density measurements fall within JMF tolerances, existing QA specification limits, proposed QA specification limits. Test results obtained by the nuclear gauge for project 4 (US-69) were subject to errors and, therefore, the percent within limits (0%) for this project should be viewed with caution.

Conformity Index

As discussed in Chapter 2, the modern view of quality goes beyond conformance to specification limits and places more emphasis on being on target with the smallest variation. One measure of the degree of accordance of process output with the specified target is the conformity index (*CI*) which is defined by:

$$CI = \sqrt{\sum_{i=1}^{n} \frac{\left| x_i - T \right|^2}{n}} \tag{5.7}$$

where x_i is the ith measurement on the quality characteristic under consideration, T is the target value, and n is the sample size. Like the standard deviation, the conformity index is a measure of variation in a sample of measurements obtained from the process. Nevertheless, the standard deviation is a measure of the deviation from the sample mean, whereas the conformity index is a measure of the deviation from target. The relationship between the standard deviation and the conformity index is given by:

$$CI = \sqrt{\frac{(n-1)\,\sigma^2 + n\,d^2}{n}} \tag{5.8}$$

where d is the deviation of the sample average from the target value.

Values of the conformity indices for each of the four projects are summarized in Table B-8 (Appendix B). In general, the conformity indices for the majority of the quality characteristics are greater than the corresponding standard deviations shown in Tables A-1 through A-4 (Appendix A) which suggests a shift in the process average from the specified target. This is particularly noticeable for the percent passing sieves ¾″ through No. 40, asphalt content, and roadway density where the conformity indices were consistently larger than the standard deviations in all four construction projects.

SPECIFICATION TOLERANCES

Tolerances that include approximately 85% of the process output for each individual project are presented in Table B-9 (Appendix B). These values should serve as reference against which the tolerances of JMF, existing QA specifications, and proposed QA specifications might be compared.

Likewise, Table B-10 lists tolerances based on pooled estimates of natural process variation which were determined in Chapter 4. As indicated, the tolerances for the material passing sieves ½″ through No. 40, asphalt content, air voids, and roadway density are unrealistically high due to the excessive natural variability in the production/construction processes.

For comparison purposes, Table B-11 shows the tolerances of the existing and proposed QA specifications. Examination of the data in Tables B-9, B-10, and B-11 suggests the following:

- Aggregate gradation -- For sieves No. 4 and larger, the $\pm 8\%$ tolerances of the existing QA specifications are somewhat large, whereas the $\pm 6\%$ tolerances of the proposed specifications seem to be more reasonable for a process that is in statistical control. Likewise, the $\pm 4.5\%$

tolerances of the proposed QA specifications for sieves No. 10 through No. 100, and $\pm 2\%$ for the No. 200 sieve seem to be adequate for accommodating the overall variation in these quality characteristics.

- Asphalt Content -- Tolerances of $\pm 0.6\%$ (average of the $\pm 0.7\%$ in the existing QA specifications and $\pm 0.5\%$ in the proposed specifications) seem to be realistic and attainable by a consistent and capable process.
- Air voids -- The $\pm 2.5\%$ tolerances of the existing QA specifications seem to be more reasonable than the $\pm 1.5\%$ tolerances of the proposed specifications.
- Roadway Density – For all four construction projects, variability in roadway density was considerably higher than what is allowed in both the existing and proposed QA specifications. Although this may be a signal that the specification limits are too restrictive for this quality characteristic, it is more likely that the lack of process control is responsible for the poor level of conformance. More data on roadway density should be gathered and analyzed to verify the specification tolerances for roadway density.

CHAPTER 6

EVALUATION OF NUCLEAR DENSITY GAUGE

The volume of air between the coated aggregate particles in a compacted HMA mixture expressed as a percent of the bulk volume of the compacted mixture is referred to as "voids in total mix" or simply "air voids". For a given aggregate gradation, the air voids content depends on asphalt content, compaction 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.

Density of the compacted HMA mixture is directly related to the air void content in the mix. Compaction increases density by compressing a given amount of the mixture into a smaller volume and forcing the asphalt-coated aggregates closer together, which increases aggregate interlock and inter-particle friction and reduces air voids in the mix. Therefore, density must be closely controlled to ensure that the air void content in the freshly compacted mixture falls within an acceptable range. The method used by ODOT for specifying the in-place density requires that the compaction process must achieve a prescribed minimum percentage of the maximum theoretical density of the mix determined from a laboratory test (the Rice method, ASTM D 2041).

MEASUREMENT OF DENSITY

The two primary methods of measuring in-place density are: 1) removing and testing cores from the compacted pavement, and 2) using nuclear gauges. Density determination from core samples requires drilling a 150 mm (6 inch) 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 at the designated sampling points 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 gauges measure density by transmitting gamma rays into the compacted mixture and recording the amount of radiation reflected back to the device during a given time period. Count data obtained from the gauge are related to the relative density of the pavement. The accuracy of the nuclear density gauge is influenced by the chemical composition of the bituminous mix, layer thickness, and surface texture. To mitigate these effects, correction factors must be determined for the particular mix being used. This is accomplished by developing a correlation between the nuclear gauge readings and the actual unit weight of the pavement.

When a thin lift of HMA is placed over an old pavement, the thickness of the top layer and the density of the underlying material are keyed into a microprocessor built into the gauge which computes the relative density of the top layer. Some gauges employ two detectors which are placed at different distances from the radiation source and require only inputting the thickness of the top layer. Recent studies concerning field evaluation of nuclear density gauges have concluded that with experienced gauge operators, proper corrections, and a statistically adequate number of gauge readings, the nuclear gauges are capable of measuring density of thin lifts with an acceptable degree of accuracy [20, 28].

Nuclear density gauges have become excellent testing tools for quality control. In addition to being 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. Nuclear gauge readings can be obtained after each pass of each roller, and the rate of increase in density after each pass is determined. When no appreciable increase in density is obtained with the application of additional roller passes, the maximum relative density for that mix has been obtained.

In addition to its use in quality control, the nuclear gauge has also been used by some state DOT's for acceptance purposes. 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 [24].

STATISTICAL ANALYSIS OF DENSITY MEASUREMENTS

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. Three types of nuclear density gauges were used: Troxler Model 3440, Troxler Model 4640, and Seaman Model C-200.

Summary statistics of the test results for each gauge are given in Table 6-1. The results of the nuclear gauge obtained from projects 3 and 4 should be viewed with caution because, in some instances, testing was not performed in accordance with the prescribed test procedure and some results were combined. In addition, a number of cores obtained from these two projects were broken or damaged in shipment and were not tested.

Table 6-1. Summary Statistics of Roadway Density Results Using Core Samples and Nuclear Gauge

Project No.	Mix Type	Count *n*	Core Samples		Nuclear Gauge		
			Mean	Std. Deviation [1]	Gauge Type	Mean	Std. Deviation [1]
1	F	32	94.02	0.91	Troxler 3440	89.57	1.55
		32	94.06	1.09	Troxler 4640	90.03	2.38
		14	93.48	1.24	Seaman C200	89.81	2.63
		22	94.67	0.79	Troxler 4640	92.25	1.39
		100	94.10	1.05	All Gauges	90.34	2.22
2	B	44	86.62	2.26	Troxler 4640	88.03	1.66
		56	85.83	2.38	Troxler 4640	86.07	2.10
		100	86.18	2.35	All Gauges	86.93	2.15
3	BH	66	90.56	1.85	Troxler 4640	90.45	1.75
4	A	94	90.51	1.42	Troxler 4640	90.57	0.48

(1) Because testing was performed at several laboratories, the standard deviation shown is an estimate of the multilaboratory variability which is usually larger than that of a single laboratory.

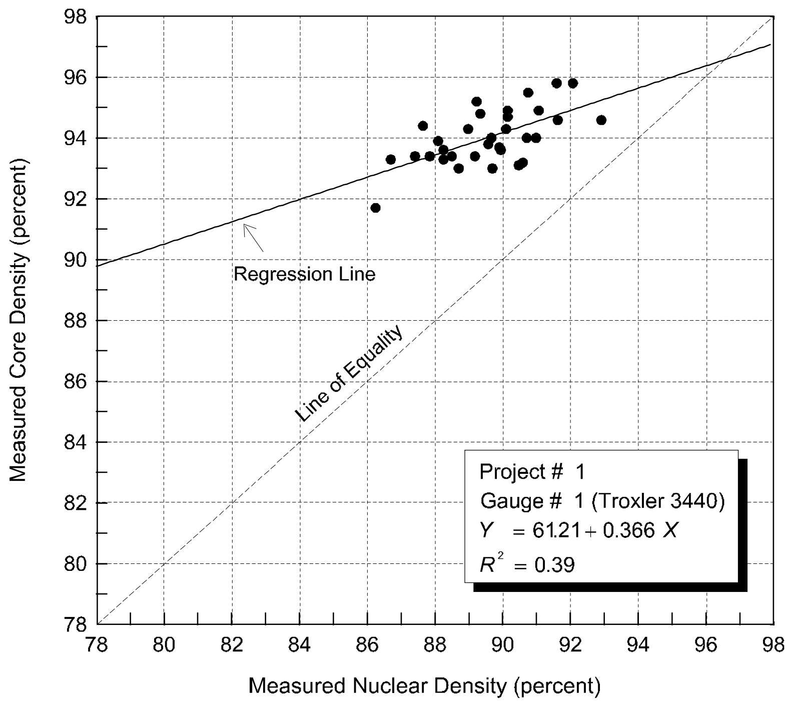
The following sections present comparisons between density measurements obtained using core samples with those of the nuclear gauge. To explore how well the core densities could be predicted from the nuclear gauge densities, regression analysis was used to determine the relationships between density measurements obtained by the two methods. In addition, the differences between core and nuclear densities were analyzed for each project, and confidence intervals for the differences were determined at different confidence levels.

Regression Analysis

Figures 6-1 through 6-4 present scatter plots of the density measurements by the two test methods. Linear equations for predicting core density from nuclear gauge density were developed using regression analysis. The general form of these equations is given by:

$$Y = a + b\,X \tag{6.1}$$

where Y is the expected value of core density, X is the density measurement obtained from nuclear gauge, and a & b are coefficients which are estimated from data based on the principle of least squares.



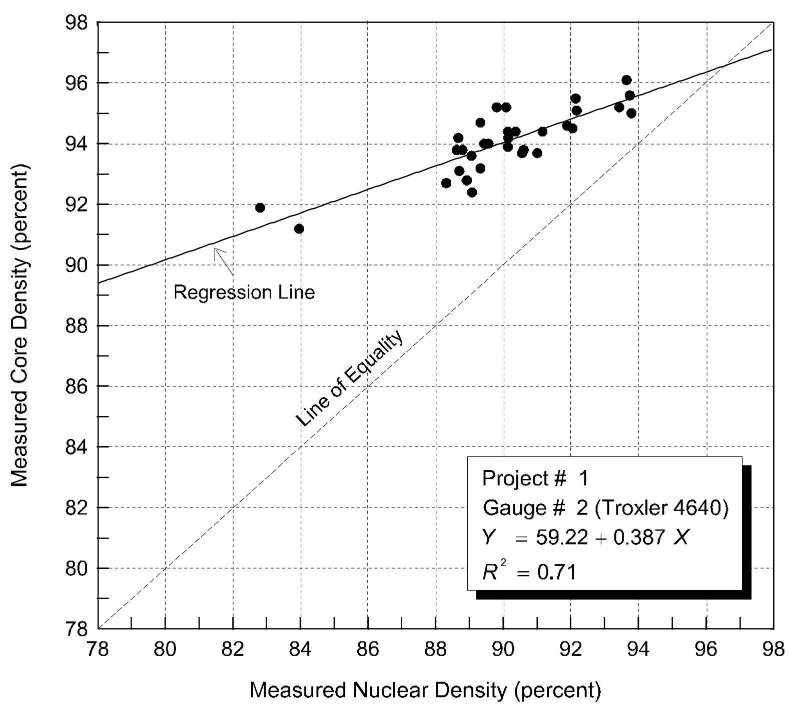
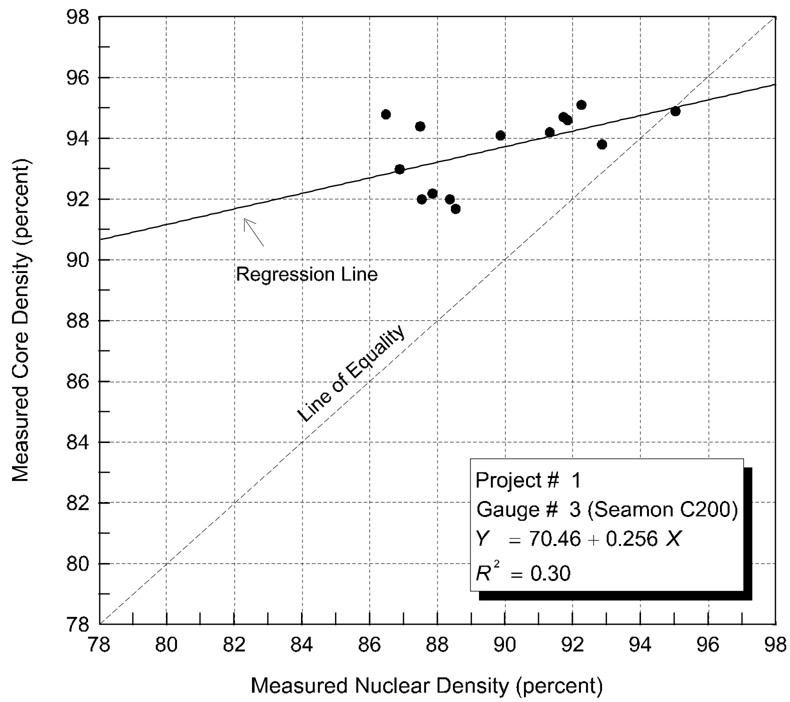


Figure 6-1. Relationship Between Measured Core and Nuclear Densities, Project 1



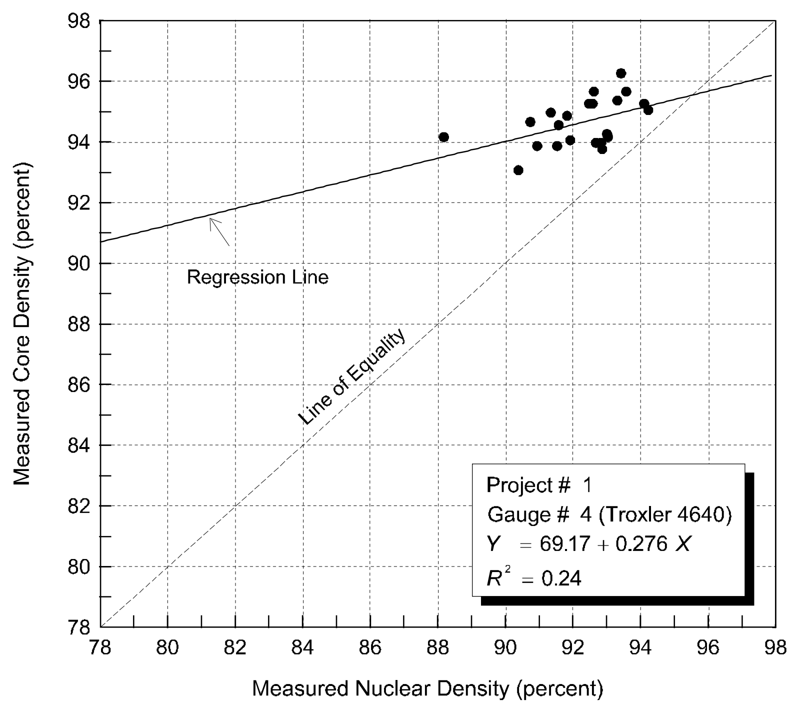
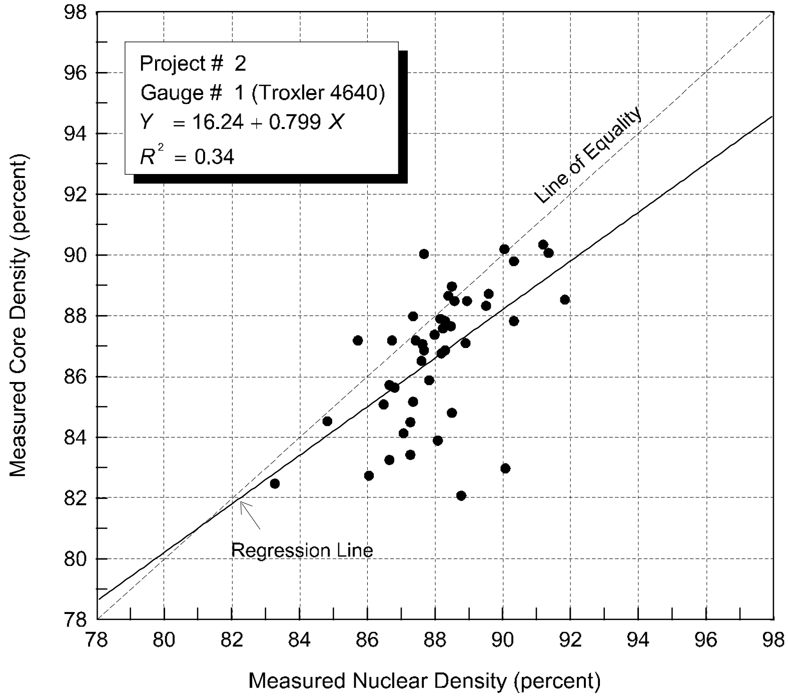


Figure 6-1 (continued). Relationship Between Measured Core and Nuclear Densities, Project 1



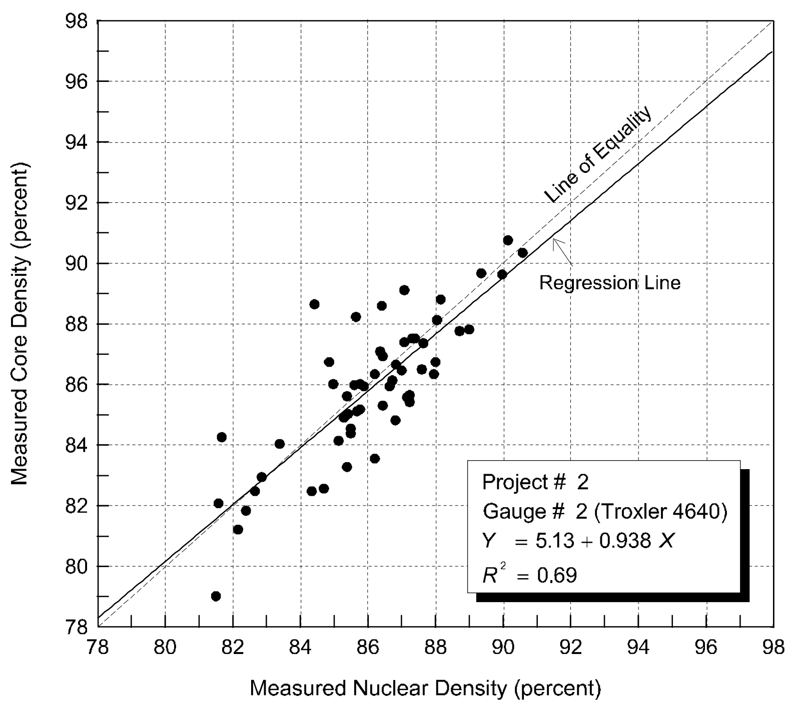


Figure 6-2. Relationship Between Measured Core and Nuclear Densities, Project 2

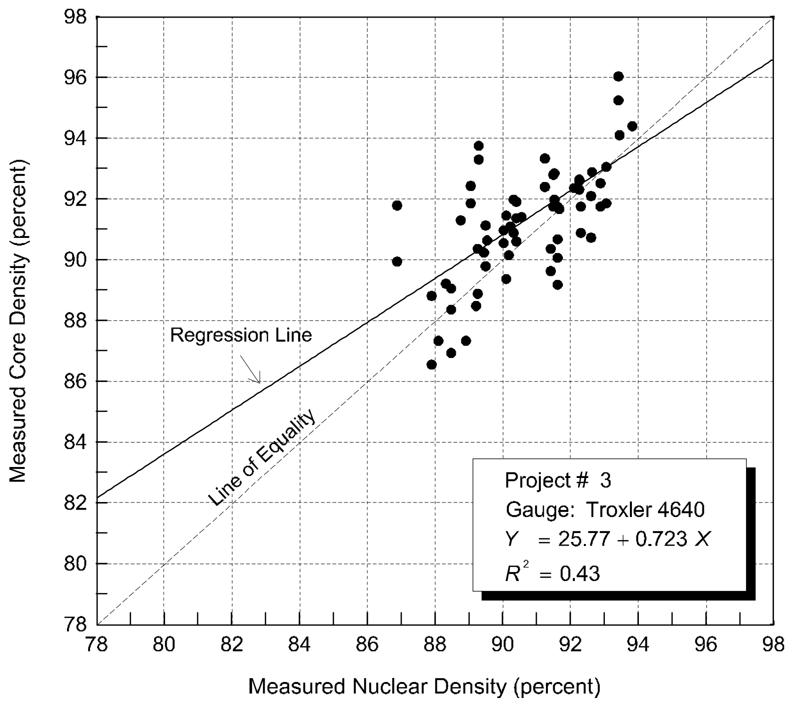


Figure 6-3. Relationship Between Measured Core and Nuclear Densities, Project 3

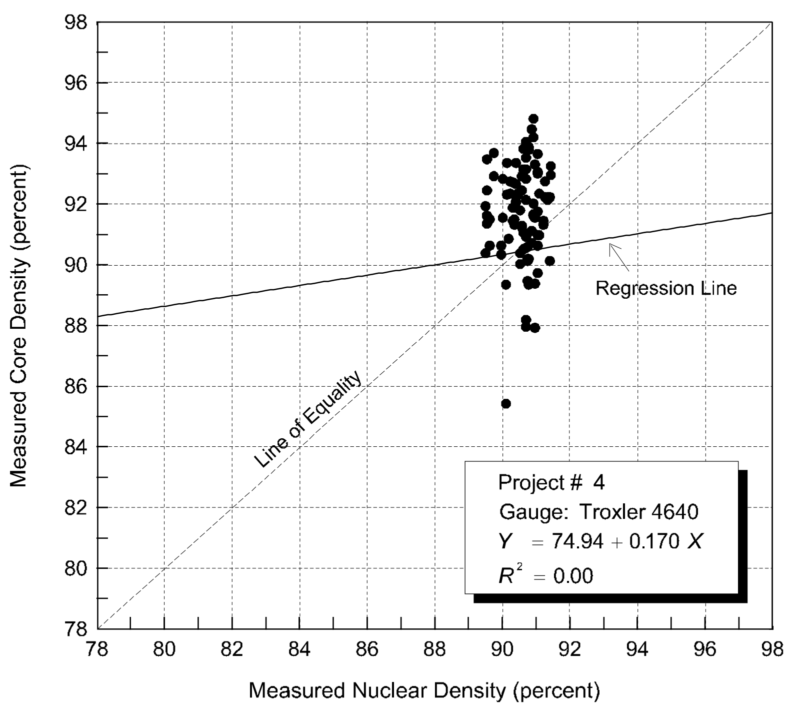


Figure 6-4. Relationship Between Measured Core and Nuclear Densities, Project 4

Table 6-2 summarizes the results of regression analysis. Excluding the data from project 4, the correlation coefficients for the Troxler 4640 gauges vary from 0.49 to 0.84 (R^2 between 0.24 and 0.71), and the values of the standard error of the estimate range from 0.60% to 1.85%. Likewise, the correlation coefficient for the Troxler 3440 gauge is 0.63 (R^2 of 0.39), and the standard error of the estimate is 0.72%. For the Seaman C200 gauge, the correlation coefficient is 0.54 (R^2 of 0.30), and the standard error of the estimate is 1.08%.

Results of hypothesis testing indicate that the regression coefficients for all equations, except project 4, are significantly different from zero at the 95% confidence level. The regression equations are shown on the scatter plots of Figures 6-1 through 6-4.

Table 6-2. Regression Equations Relating Core and Nuclear Density Measurements

Project No.	Gauge Type	Regression Equation	R^2	Correlation Coefficient	Std. Error of Y-Estimate	Std. Error of Regression Coeff.
1	Troxler 3440	$Y = 6121 + 0.366\,X$	0.39	0.63	0.72	0.083
	Troxler 4640	$Y = 59.22 + 0.387\,X$	0.71	0.84	0.60	0.045
	Seaman C200	$Y = 70.46 + 0.256\,X$	0.30	0.54	1.08	0.114
	Troxler 4640	$Y = 69.17 + 0.276\,X$	0.24	0.49	0.71	0.111
2	Troxler 4640	$Y = 16.24 + 0.799\,X$	0.34	0.59	1.85	0.170
	Troxler 4640	$Y = 5.13 + 0.938\,X$	0.69	0.83	1.34	0.086
3	Troxler 4640	$Y = 25.77 + 0.723\,X$	0.43	0.66	1.44	0.104
4	Troxler 4640	$Y = 74.94 + 0.170\,X$	0.00	0.00	1.57	0.329

Analysis of Differences Between Core and Nuclear Density

Table 6-3 presents summary statistics of the differences between core and nuclear densities before and after applying the developed regression equations for each project. Examination of the results in Table 6-3 reveals the there is a slight improvement in predicting core densities using the regression equations over using the nuclear gauge density directly. For example, the differences between the measured core and nuclear densities range from –7.11% to 4.21% for the Troxler 4640 gauge used in project 2. After using the regression equations to calculate core densities, the differences range from –2.16% to 0.05%. In addition, the standard deviations of the differences after applying the regression equations are less than those found when core densities are predicted directly from nuclear densities, which implies better precision.

Table 6-3. Differences Between Core and Nuclear Densities

Project No.	Gauge Type	Minimum Difference	Maximum Difference	Mean Difference $\overline{D}$	Std. Deviation S_D	Std. Error of the Mean, $S_{\overline{D}}$
			Before Applying Regression			
1	Troxler 3440	1.68	6.75	4.45	1.21	0.21
	Troxler 4640	1.23	9.11	4.03	1.58	0.28
	Seaman C200	–0.27	8.16	3.66	2.21	0.59
	Troxler 4640	0.84	6.02	2.42	1.22	0.26
2	Troxler 4640	–7.11	2.38	–1.40	1.86	0.28
	Troxler 4640	–2.66	4.21	–0.23	1.34	0.18
3	Troxler 4640	–2.27	5.04	0.66	1.51	0.19
4	Troxler 4640	–5.97	2.62	–0.19	1.61	0.17
			After Applying Regression			
1	Troxler 3440	2.32	6.56	4.45	0.98	0.17
	Troxler 4640	1.74	8.47	4.03	1.46	0.26
	Seaman C200	–0.17	6.17	3.66	1.95	0.52
	Troxler 4640	0.97	5.37	2.42	1.00	0.21
2	Troxler 4640	–2.16	–0.43	–1.40	0.33	0.05
	Troxler 4640	–0.51	0.05	–0.23	0.13	0.02
3	Troxler 4640	–0.22	1.70	0.66	0.48	0.06
4	Troxler 4640	–0.89	0.71	–0.19	0.41	0.04

Further analyses were performed to establish confidence intervals and to test hypotheses concerning the mean differences between core and nuclear densities. For a confidence level of $100(1-\alpha)\%$, the range of the mean difference is given by:

$$\overline{D} - \frac{S_D}{\sqrt{n}} t_{\upsilon,\alpha/2} \le \mu_D \le \overline{D} + \frac{S_D}{\sqrt{n}} t_{\upsilon,\alpha/2} \qquad (6\text{-}2)$$

where:

μ_D = mean of the population of differences between core and nuclear densities;

$\overline{D}$, S_D = sample mean and standard deviation of the differences between core and nuclear densities;

n = sample size (number of paired observations);

υ = degrees of freedom ($n-1$);

α = probability of type-I error; and

$t_{\upsilon,\alpha/2}$ = value of the t-statistic for an area at the tail of the t-distribution of $\alpha/2$.

The term $S_D / \sqrt{n}$ is referred to as the standard error of the mean, $S_{\bar{D}}$. Values of $\bar{D}$, S_D, and $S_{\bar{D}}$ are given in Table 6-3.

To test the hypothesis that the mean difference between density measurements is equal to zero, that is, H_0: $\mu_D = 0$ against the alternative hypothesis H_1: $\mu_D \neq 0$, the test-statistic is given by:

$$t = \frac{\bar{D}}{S_D / \sqrt{n}} \qquad (6\text{-}3)$$

For a confidence level of $100(1-\alpha)\%$, the computed t-value given by equation 6-3 is compared with the critical t-value $t_{\upsilon,\alpha/2}$ with degrees of freedom $\upsilon = n-1$. If the absolute value of the computed t-statistic is less than $t_{\upsilon,\alpha/2}$, H_0 is accepted. Otherwise, H_0 is rejected.

Table 6-4 presents lower and upper confidence limits for the mean difference μ_D between core and nuclear densities. For example, the table shows that for the Troxler 3440 gauge used in project 1, there is a 95% chance that the mean difference between core and nuclear densities will not exceed 0.87% before applying the regression equation, and 0.71% after applying the equation. Similar conclusions can be drawn for other gauges and other confidence levels.

The results shown in Table 6-4 should be interpreted with caution. Although the mean difference μ_D between core and nuclear densities is expected to fluctuate within a fairly narrow band, the individual differences vary within a much wider range. As shown in Table 6-3, for the Troxler 3440 gauge, the range of differences between the individual density measurements before applying the regression equation is 5.07% (1.68% to 6.75%), compared with 0.87% range for the mean difference.

Summary

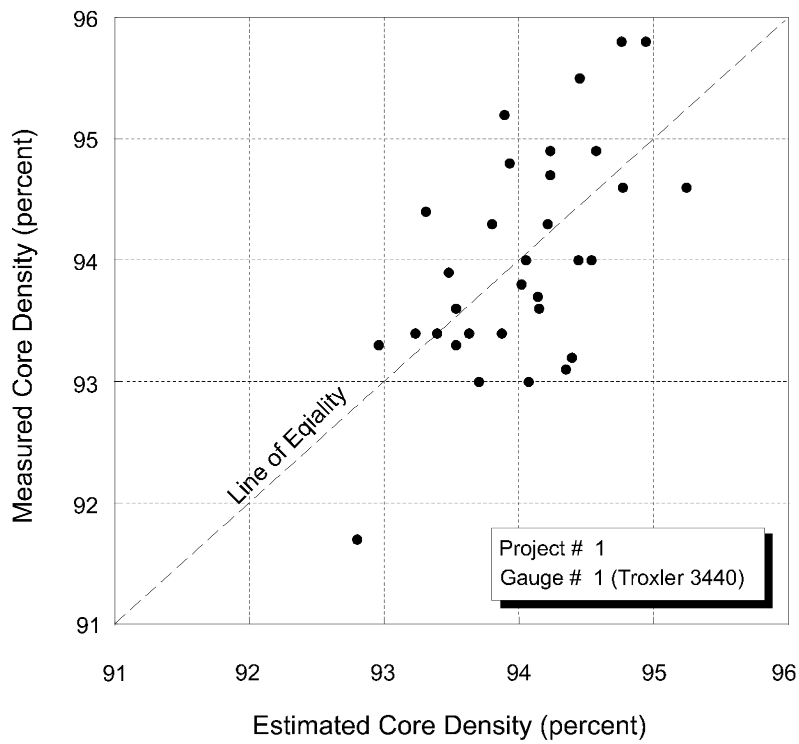
This chapter provided an evaluation of the nuclear gauge as a means of monitoring the density of thin lifts of HMA pavement. Correlation of individual density measurements by core samples with those obtained by the nuclear gauge ranged from good to fair. The results suggest that an improvement in the prediction of core densities from nuclear gauge measurements can be realized through the use of regression equations. Such equations can be developed based on a reasonable number (minimum of 10 per OHD L-4) of core and nuclear density measurements for each project.

Because of its speed and ease of operation, the nuclear gauge is a very useful tool for quality control of pavement density during construction. The relative increase in density following each additional pass of the roller helps determine if the maximum relative density has been obtained.

Table 6-4. Confidence Limits and Hypothesis Testing for Average of Differences Between Core and Nuclear Densities

Project No.	Gauge Type	Confidence Level %	Confidence Limits		Hypothesis Testing	
			Lower Limit	Upper Limit	Computed t-value	Conclusion
			Before Applying Regression			
1	Troxler 3440	90	4.08	4.81	20.74	Significant
		95	4.01	4.88	20.74	Significant
	Troxler 4640	90	3.56	4.50	14.48	Significant
		95	3.46	4.60	14.48	Significant
	Seaman C200	90	2.62	4.71	6.20	Significant
		95	2.39	4.94	6.20	Significant
	Troxler 4640	90	1.97	2.87	9.31	Significant
		95	1.88	2.96	9.31	Significant
2	Troxler 3440	90	–1.87	–0.93	–5.00	Significant
		95	–1.97	–0.84	–5.00	Significant
	Troxler 4640	90	–0.53	0.06	–1.31	Not Significant
		95	–0.59	0.12	–1.31	Not Significant
3	Troxler 3440	90	0.35	0.97	3.55	Significant
		95	0.29	1.03	3.55	Significant
4	Troxler 3440	90	–0.47	0.08	–1.17	Not Significant
		95	–0.53	0.14	–1.17	Not Significant
			After Applying Regression			
1	Troxler 3440	90	4.15	4.74	25.55	Significant
		95	4.09	4.80	25.55	Significant
	Troxler 4640	90	3.59	4.47	15.62	Significant
		95	3.50	4.56	15.62	Significant
	Seaman C200	90	2.74	4.59	7.02	Significant
		95	2.54	4.79	7.02	Significant
	Troxler 4640	90	2.05	2.79	11.29	Significant
		95	1.97	2.86	11.29	Significant
2	Troxler 3440	90	–1.49	–1.32	–27.98	Significant
		95	–1.50	–1.30	–27.98	Significant
	Troxler 4640	90	–0.26	–0.21	–13.37	Significant
		95	–0.27	–0.20	–13.37	Significant
3	Troxler 3440	90	0.56	0.76	11.21	Significant
		95	0.54	0.78	11.21	Significant
4	Troxler 3440	90	–0.26	–0.12	–4.58	Significant
		95	–0.28	–0.11	–4.58	Significant

Variations commonly encountered in HMA production and paving operations require routine calibration of the nuclear gauge to establish the proper bias correction and maintain accuracy of the measurements. Use of the nuclear gauge for acceptance testing can only be recommended when operated by experienced field personnel, when all the parameters affecting the nuclear measurements are precisely known, and when vigorous calibration is performed. Core samples must be taken periodically to validate the nuclear gauge measurements and to check the input parameters.



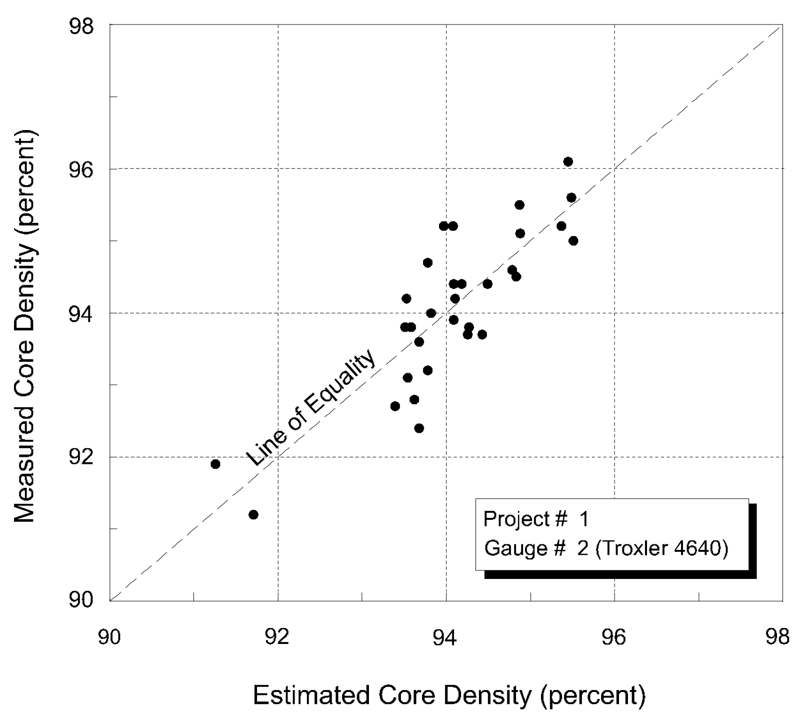
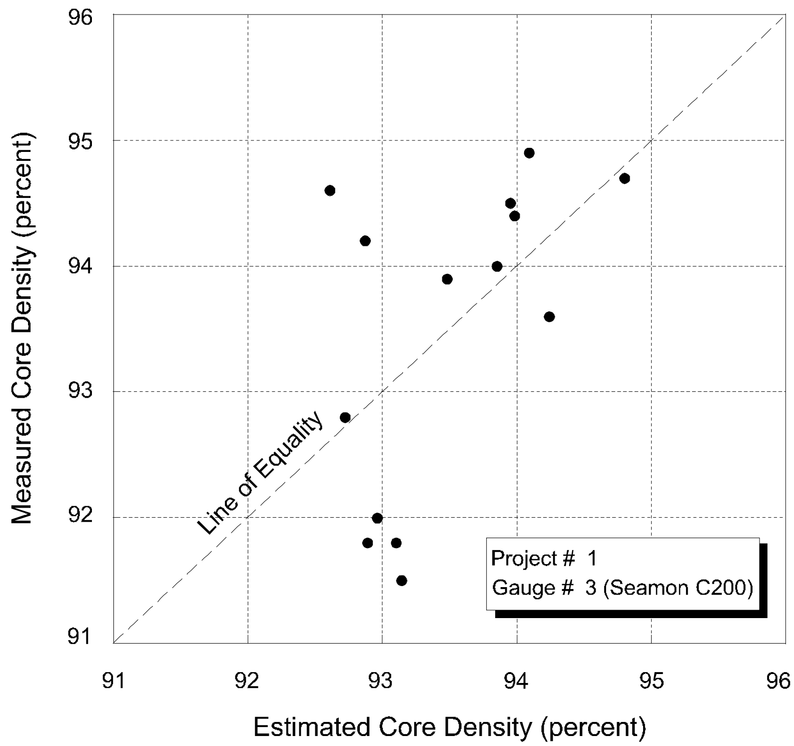


Figure 6-5. Relationship Between Measured and Estimated Core Densities, Project 1



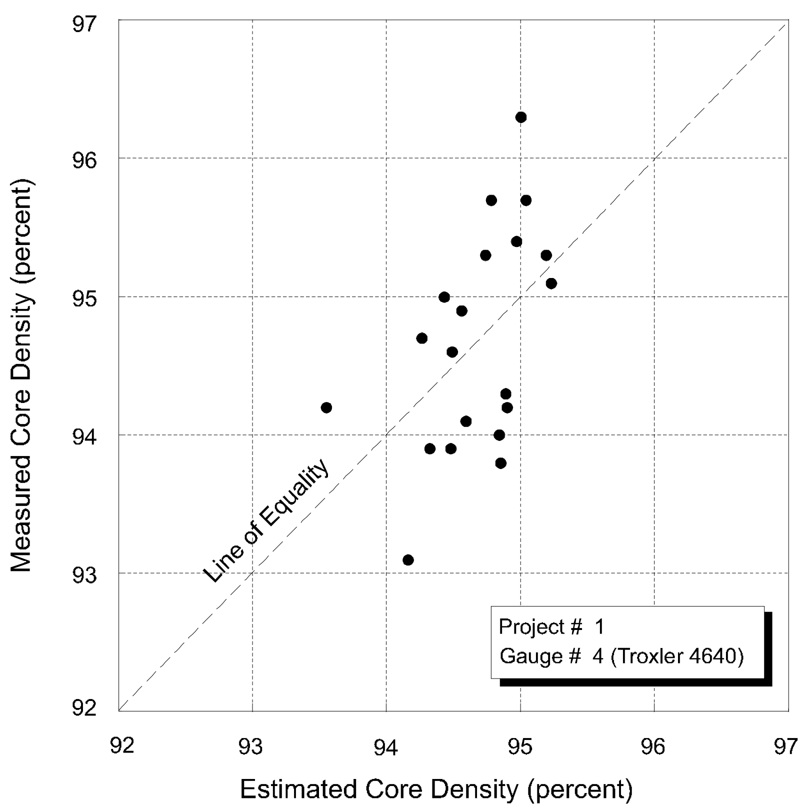
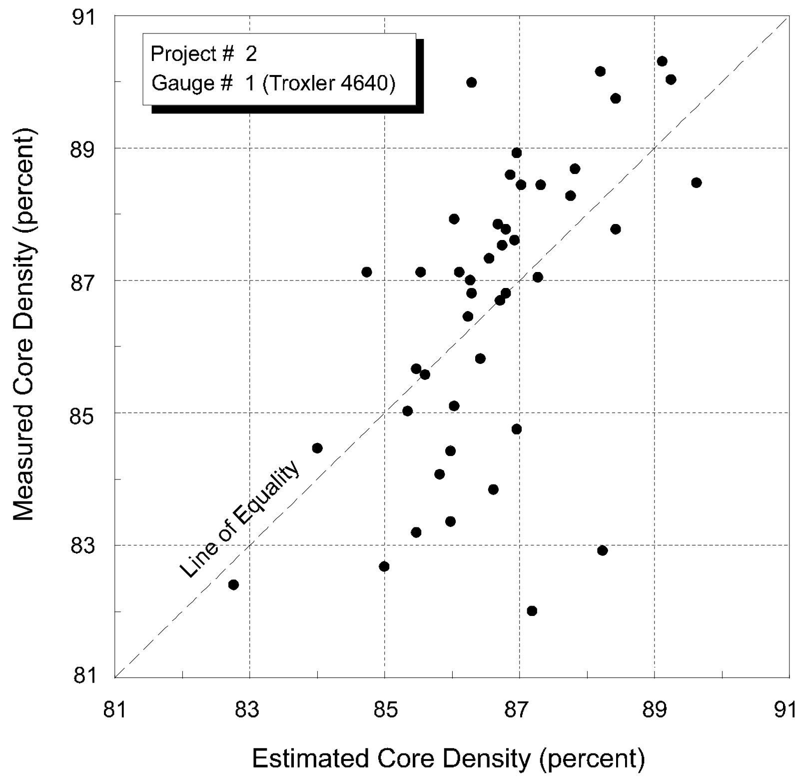


Figure 6-5 (continued). Relationship Between Measured and Estimated Core Densities, Project 1



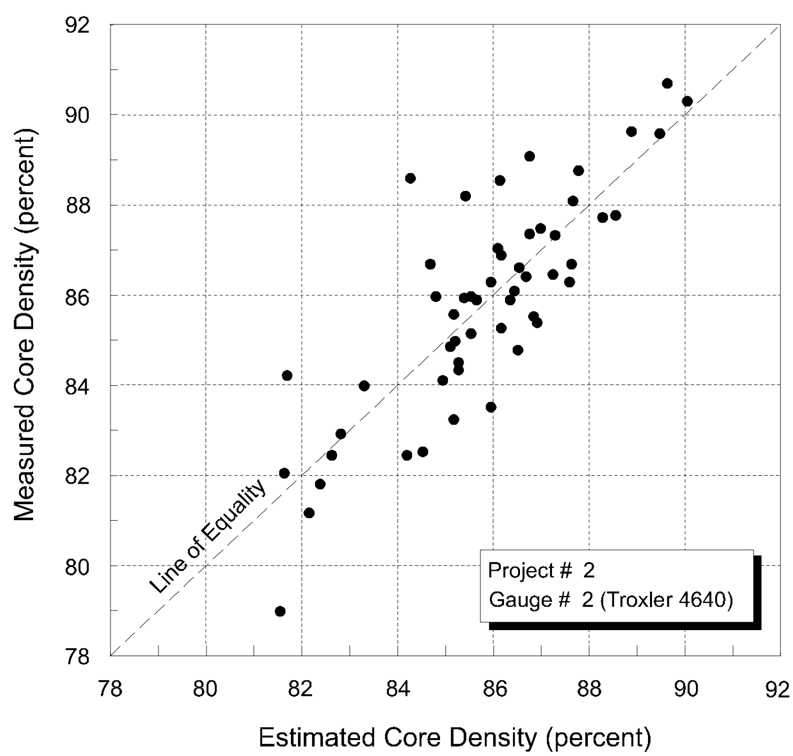


Figure 6-6. Relationship Between Measured and Estimated Core Densities, Project 2

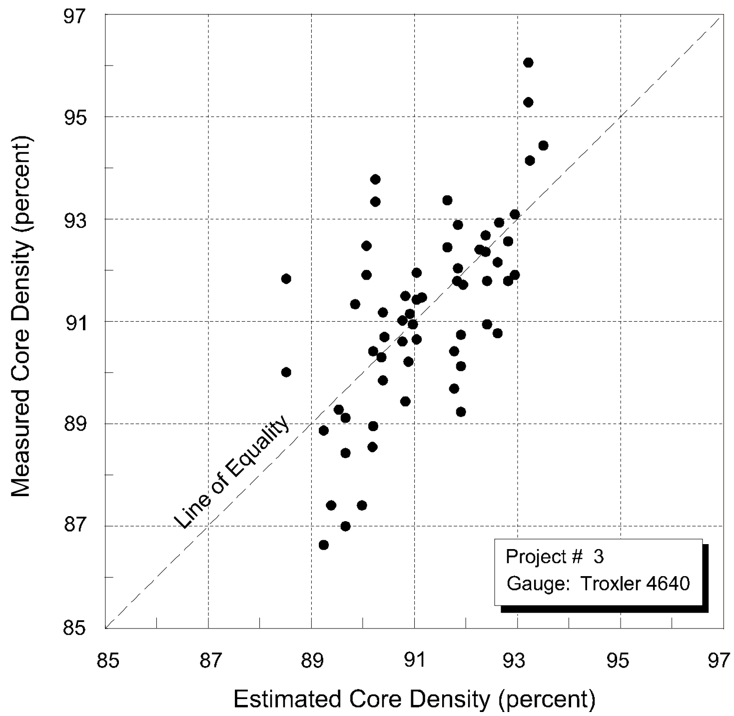


Figure 6-7. Relationship Between Measured and Estimated Core Densities, Project 3

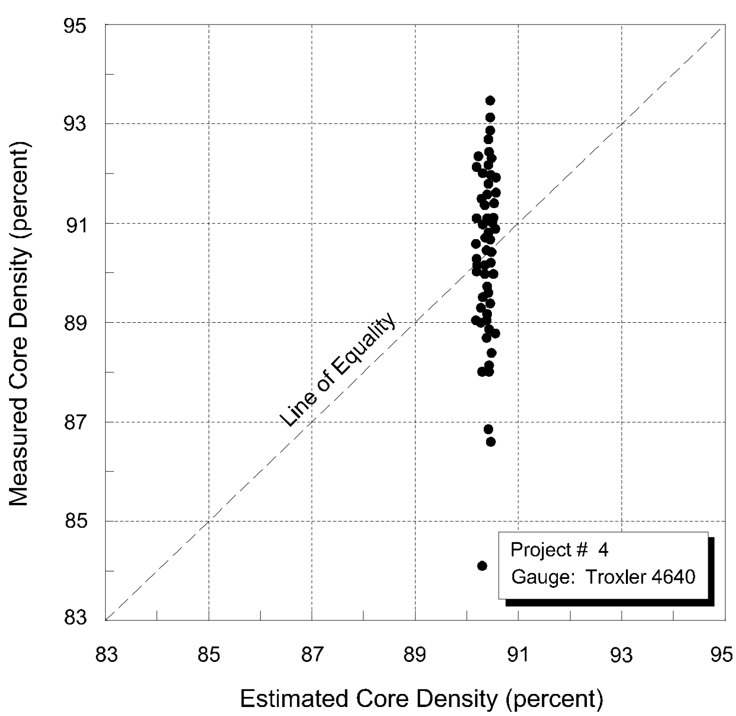
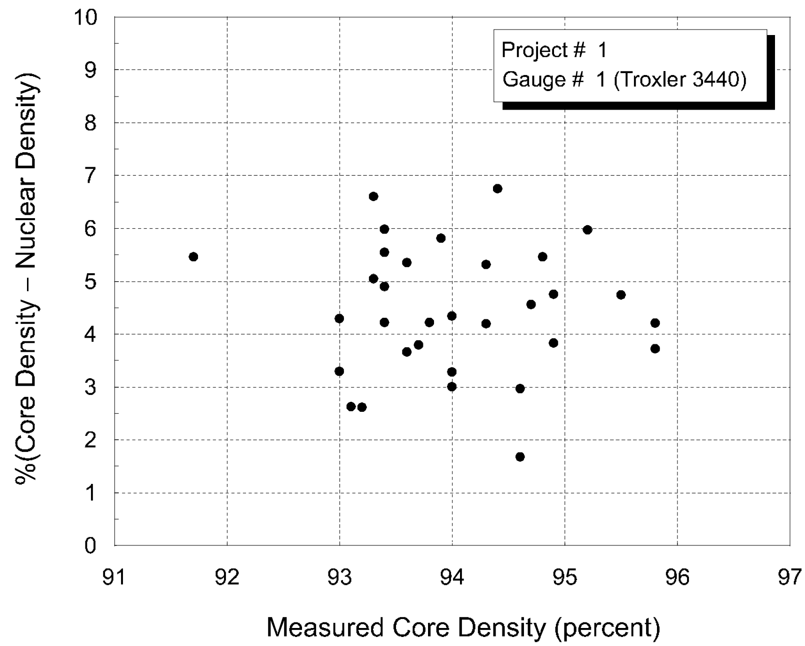


Figure 6-8. Relationship Between Measured and Estimated Core Densities, Project 4



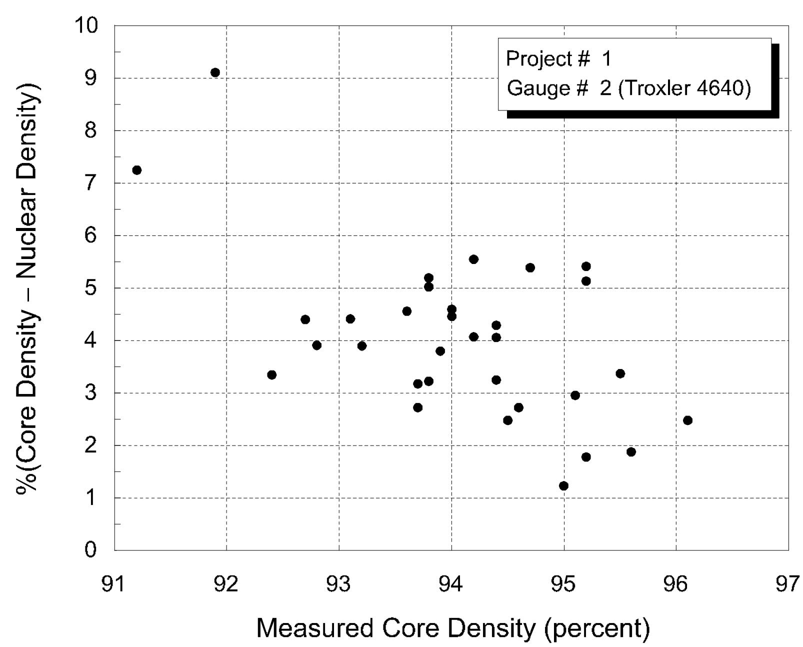
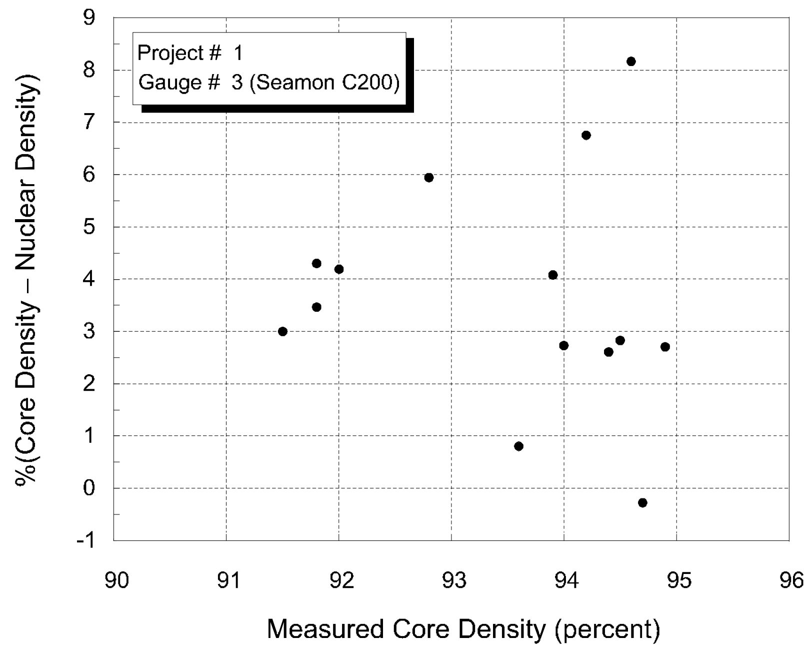


Figure xx. Measured Core Density versus Difference Between Core and Nuclear Density



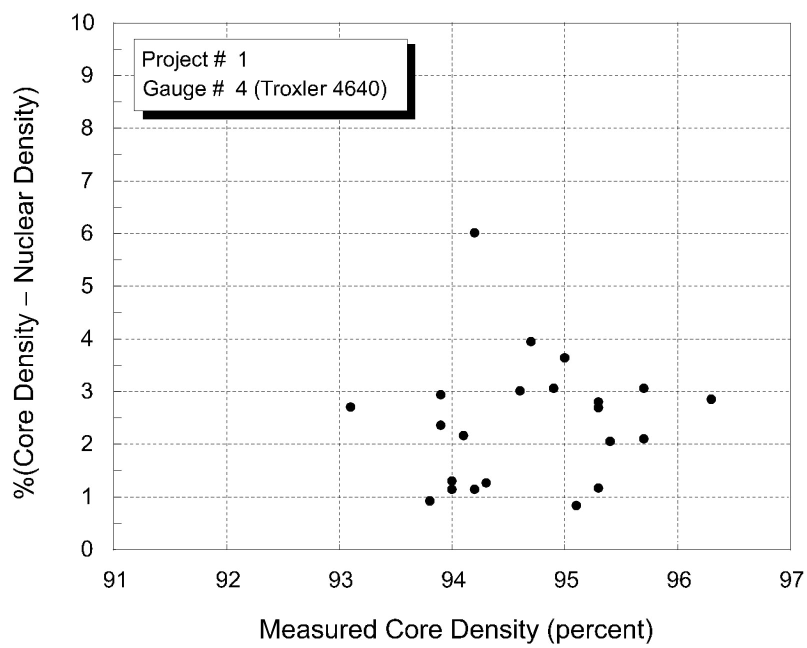
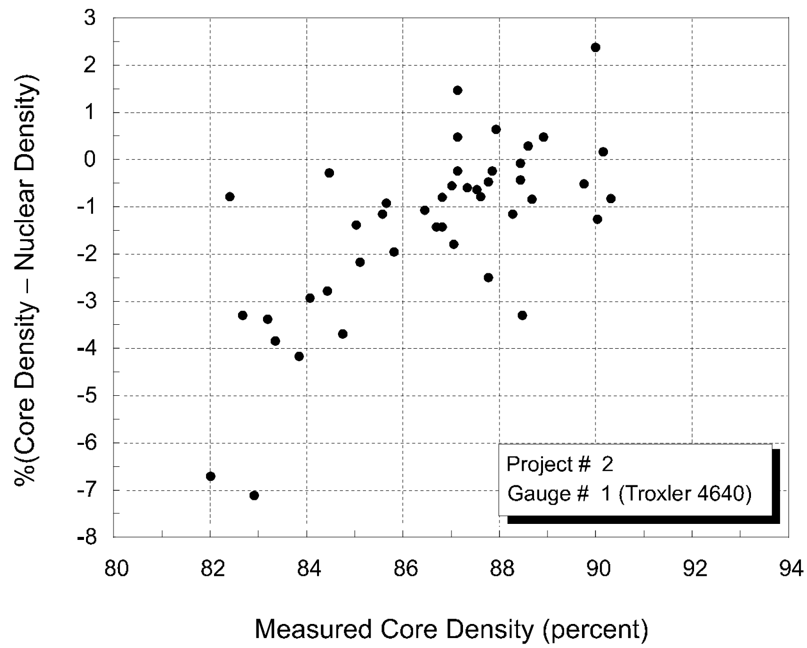


Figure xx (continued). Measured Core Density versus Difference Between Core and Nuclear Density



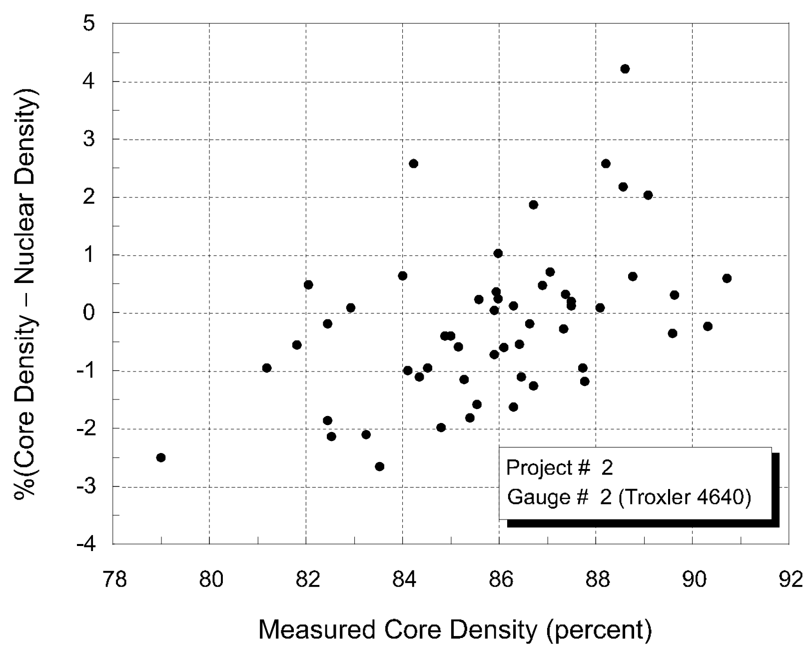
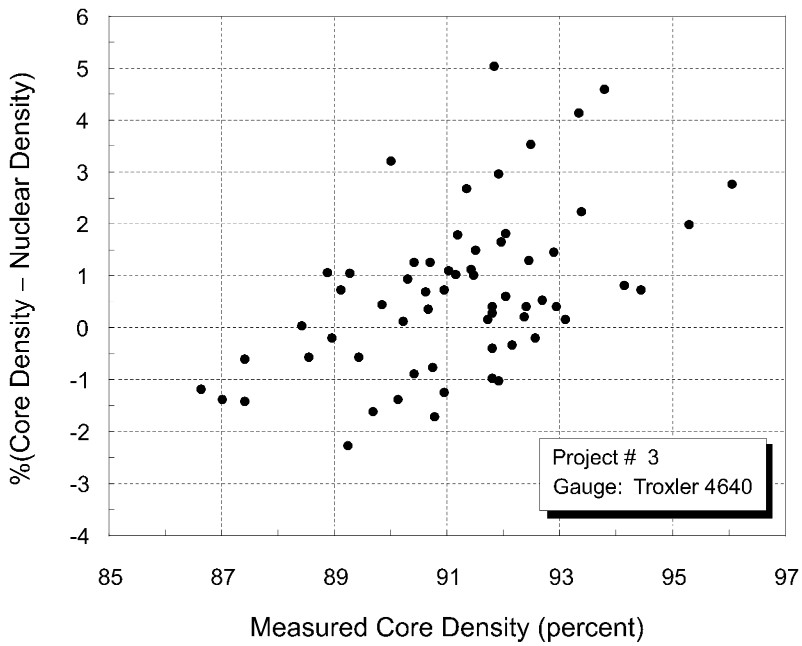


Figure xx (continued). Measured Core Density versus Difference Between Core and Nuclear Density



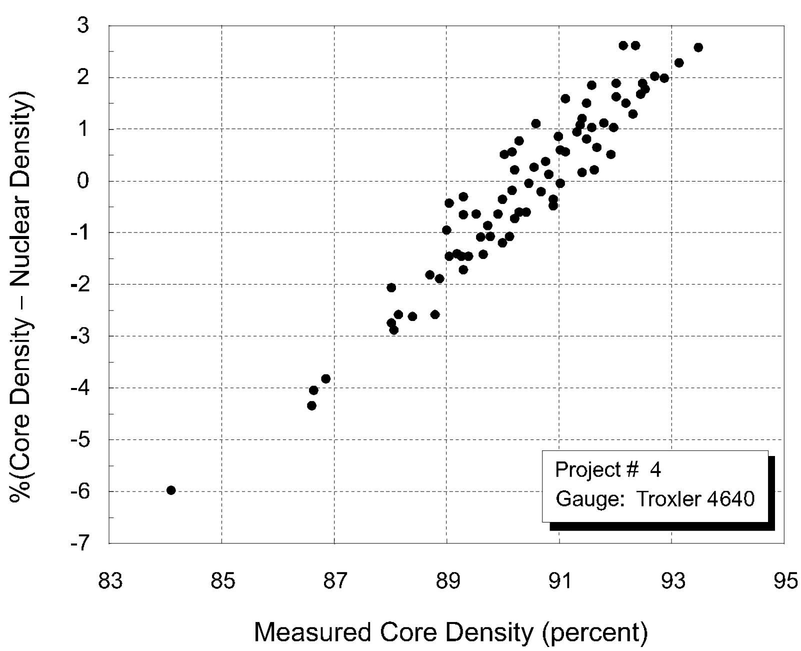


Figure xx (continued). Measured Core Density versus Difference Between Core and Nuclear Density

CHAPTER 7

EVALUATION OF NUCLEAR ASPHALT CONTENT GAUGE

The relative proportions of asphalt cement and aggregate in an HMA must be controlled during production to meet the JMF requirements established by mix design. Asphalt content affects air voids, stability, and thickness of the asphalt film coating the aggregate in the paving mixture. A mixture with low asphalt content is not durable, and one with high asphalt content is not stable. Likewise, aggregate gradation affects almost all the important properties of an HMA, including stiffness, stability, durability, fatigue resistance, skid resistance, workability, and resistance to moisture induced damage. Variability in asphalt content and aggregate gradation can result from a number of factors related to the production process such as inaccurate scales and measuring devices, poor maintenance at the production plant, segregation, etc.

MEASUREMENT OF ASPHALT CONTENT

The composition of HMA mixtures has traditionally been determined using extraction test methods where solvents are applied to a sample of the bituminous mixture to dissolve the asphalt cement from the aggregate. Results of the extraction test provide knowledge of asphalt content, and the remaining aggregate is tested for gradation. In addition to the environmental concerns associated with the use of chlorinated solvents, the test procedure is time consuming and does not permit rapid determination of asphalt content for quality control purposes. These problems have been major factors in the search for alternative methods to determine asphalt content.

Some state DOTs have evaluated and used biodegradable solvents to replace chlorinated solvents. Nevertheless, biodegradable solvents require a time-consuming modified extraction procedure to maintain the accuracy levels provided by the traditional solvents [25]. Proper disposal of biodegradable solvents containing dissolved asphalt cement is also a problem.

An alternative to the extraction test method is the nuclear asphalt content (NAC) gauge which measures asphalt content by noting the presence of hydrogen in a sample of the 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 through the use 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, a correction must be made for the moisture content of the sample. Use of the NAC gauge allows for increasing the frequency of asphalt content determinations for both quality control and acceptance purposes. Nevertheless, the test does not produce any information on aggregate gradation. Cold feed gradation tests can be performed on the aggregate separately to supplement the nuclear gauge results.

Recently, a new method for measuring asphalt content by ignition has been developed by the National Center for Asphalt Technology (NCAT). A test specimen of the HMA mixture is weighed and then placed on a tray inside an ignition oven. The oven heats up to the preset temperature of 538° C (1,000° F), at which point the asphalt cement ignites and burns off. A built-in filter eliminates the smoke at the exhaust. The sample is weighed again, after it cools, to determine the asphalt content. Some models of the ignition oven have a built-in scale with a digital readout to weigh the test specimen continuously during ignition. After the asphalt binder is completely burned and the specimen achieves a constant weight, a printout of the asphalt content is provided. The remaining aggregate is then used for gradation testing.

The ignition oven is an excellent tool for both quality control and acceptance testing. Asphalt content can be determined in approximately 30 minutes, compared to over two hours with solvent extraction methods. The ODOT is evaluating the ignition oven for acceptance testing, and contractors can use it for quality control. Unfortunately, this new test method was not readily available during the sampling and testing phase of this study.

STATISTICAL ANALYSIS OF ASPHALT CONTENT MEASUREMENTS

As discussed in Chapter 3, sample units of the freshly mixed bituminous concrete were obtained from the hauling trucks containing the pre-selected random tonnage according to AASHTO T168-90 [2]. Two sample units, each having a minimum mass of 40 kg (90 lb), were selected from each sublot. The sample units were labeled and transferred to the different laboratories where they were split and tested for asphalt content using the centrifuge extraction method (OHD L-26) and the Troxler 3241-C nuclear gauge.

Summary statistics of the test results are given in Table 7-1. The mean values of asphalt content using the extraction and the nuclear gauge test methods are essentially the same for each project. Nevertheless, the accuracy of either test method was not addressed since the true asphalt content is unknown. Accuracy, the closeness of agreement between an observed value and a true value, requires that the test method be applied to a sample that has been compounded in such a manner that the true value of the property being measured is known. In terms of precision, the data in Table 7-1 suggest that the nuclear gauge has a slightly better precision than that of the extraction method as evidenced by the smaller standard deviation found in three out of the four projects.

Table 7-1. Comparison of Asphalt Content Results Using Solvent Extraction Method and NAC Gauge

Project No.	Mix Type	Count *n*	Extraction Method		NAC Gauge	
			Mean	Std. Deviation [1]	Mean	Std. Deviation [1]
1	F	88	3.75	0.30	3.75	0.35
2	B	98	4.59	0.23	4.65	0.20
3	BH	93	5.05	0.22	4.93	0.21
4	A	92	4.47	0.27	4.53	0.18

(1) Because testing was performed at several laboratories, the standard deviation shown is an estimate of the multilaboratory variability which is usually larger than that of a single laboratory.

A 1990 report "Asphalt Content Determination Manual" published by the FHWA included the results of several studies that compared extraction test data with NAC gauge determinations [27]. Table 7-2 lists some of their findings. The conclusions of these earlier studies indicate that the type of aggregate used in an HMA affects the NAC gauge readings slightly, and that different gradations produce different results. Asphalt sources were also found to cause differences. Therefore, individual calibration for each particular mix is required for accurate determination of asphalt content using the NAC gauge.

Table 7-2. Results of Earlier Studies Comparing Extraction and NAC Gauge Test Methods

Source	Year	Count *n*	Extraction Method		NAC Gauge	
			Mean	Std. Deviation	Mean	Std. Deviation
Arkansas	1987	18	5.61	0.83	5.59	0.79
Missouri	1988	--	4.56	0.55	4.55	0.56
Nevada	1982	--	4.92	0.66	4.83	0.46
Pennsylvania	1989	51	5.64	0.24	5.85	0.12
		12	5.80	0.37	5.54	0.13
		8	4.00	0.55	4.17	0.55
		16	6.46	0.29	6.73	0.17

Regression Analysis

Figure 7-1 presents scatter plots of the asphalt content measurements obtained using the extraction and the NAC gauge test methods. Linear regression analysis was applied to determine the equations of the straight lines which best fit the data. As shown in Table 7-3, the coefficient of correlation ranges from 0.54 to 0.63, and the standard error of the estimate varies from 0.18 to 0.24.

Table 7-3. Regression Equations Relating Extracted and Nuclear Asphalt Content Measurements

Project No.	Regression Equation	R^2	Correlation Coefficient	Std. Error of Y-Estimate	Std. Error of Regression Coeff.
1	$Y = 1664 + 0.559X$	0.40	0.63	0.238	0.073
2	$Y = 1385 + 0.691X$	0.36	0.60	0.183	0.094
3	$Y = 1385 + 0.691X$	0.29	0.54	0.188	0.093
4	$Y = 0.875 + 0.792X$	0.29	0.54	0.232	0.130

Earlier studies of the correlation between asphalt content measurements by extraction and nuclear gauge have produced mixed results; some studies showed strong statistical relationship, while others did not. However, the difference between asphalt content determinations by both methods was not large even in the absence of good correlation. In some studies, the accuracy of the extraction method was suspected for the differences because the procedure used to correct for fines can have a large influence on asphalt content calculation [27].

Analysis of Differences Between Extraction and Nuclear Asphalt Content

Table 7-4 presents summary statistics of the differences between extracted and NAC gauge measurements. The mean difference ranged from –0.068 to 0.094 percent for all four projects.

Table 7-4. Differences Between Extracted and Nuclear Asphalt Content

Project No.	Count n	Minimum Difference	Maximum Difference	Mean Difference $\overline{D}$	Std. Deviation S_D	Std. Error of the Mean, $S_{\overline{D}}$
1	88	–0.58	0.78	0.012	0.283	0.030
2	98	–0.50	0.37	–0.050	0.192	0.019
3	93	–0.48	0.58	0.094	0.208	0.022
4	92	–0.59	0.49	–0.068	0.234	0.024

Statistical analyses similar to those described in Chapter 6 were performed to establish confidence intervals and to test hypotheses concerning the mean differences between extraction and NAC gauge test results. Table 7-5 presents lower and upper confidence limits for the mean difference μ_D between asphalt content measurements by both methods. For example, the table shows that for project 1, there is a 95%

chance that the mean difference between extracted and nuclear asphalt content will not exceed 0.12%. Similar conclusions can be drawn for other confidence levels and other projects.

It should be noted, however, that the range of the individual differences between asphalt content measurements is much wider than that between the mean differences. As shown in Table 7-4, the range of differences between the individual density measurements for project 1 is 1.36% (–0.58% to 0.78%), compared with 0.12% range for the mean difference.

Table 7-5. Confidence Limits and Hypothesis Testing for Average of the Differences Between Extracted and Nuclear Asphalt Content

Project No.	Confidence Level %	Confidence Limits		Hypothesis Testing	
		Lower Limit	Upper Limit	Computed t-value	Conclusion
1	90	–0.038	0.062	0.41	Not Significant
	95	–0.048	0.072	0.41	Not Significant
2	90	–0.082	–0.017	–2.56	Significant
	95	–0.088	–0.011	–2.56	Significant
3	90	0.059	0.130	4.38	Significant
	95	0.051	0.137	4.38	Significant
4	90	–0.109	–0.028	–2.80	Significant
	95	–0.117	–0.020	–2.80	Significant

The Ignition Oven Test Method

Tables 7-6 and 7-7 summarize the results of a recent study performed by NCAT to evaluate the accuracy and precision of the ignition oven test method [7, 25]. The results suggest that the test can accurately measure the asphalt content of HMA mixtures, and that the precision of the method is better than that of solvent extraction methods.

One problem with the ignition oven is that it can slightly change the properties of certain types of aggregates. Although results of the NCAT study indicate that the test did not alter aggregate gradation, it is recommended that round-robin studies be performed to calibrate the test method for local materials [26].

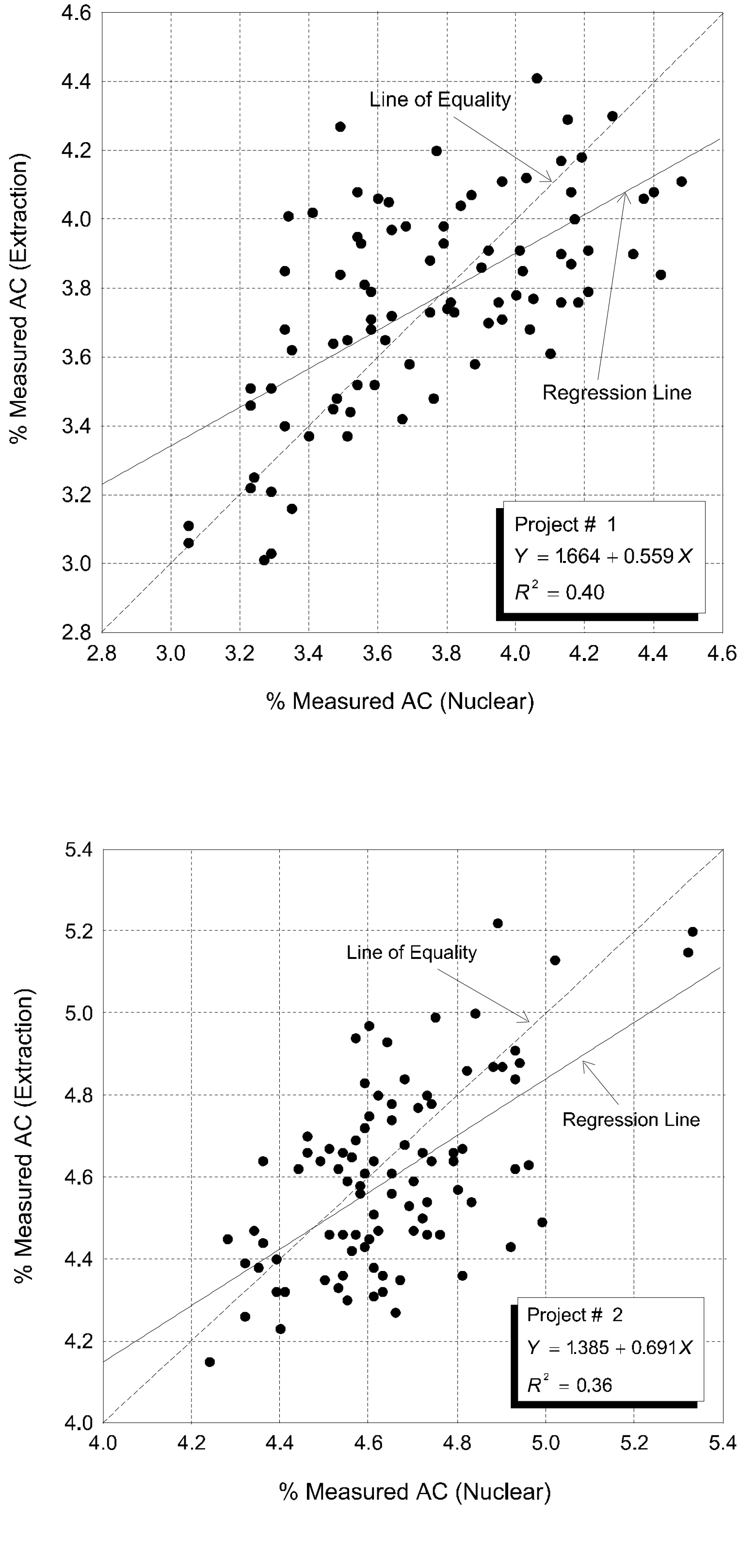
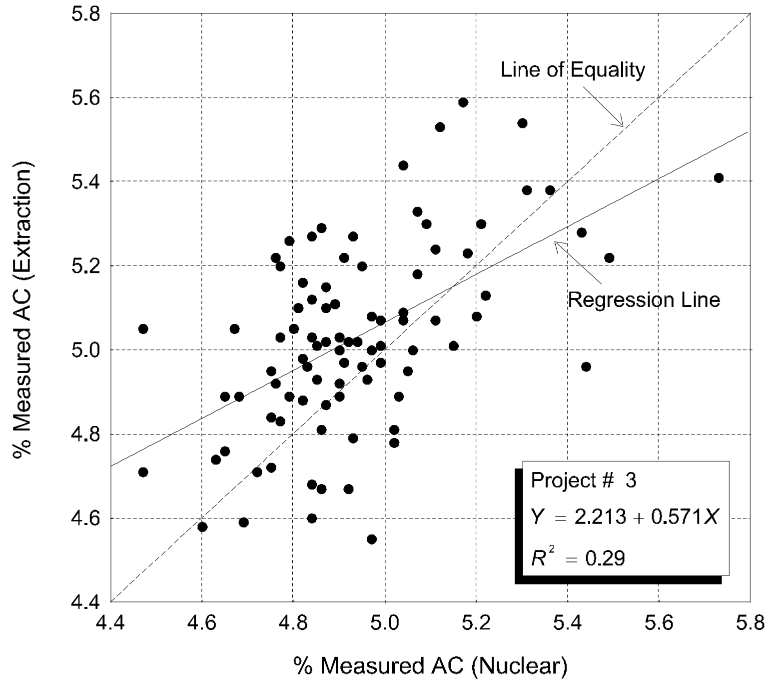


Figure 7-1. Relationship between Extracted and Nuclear Asphalt Content



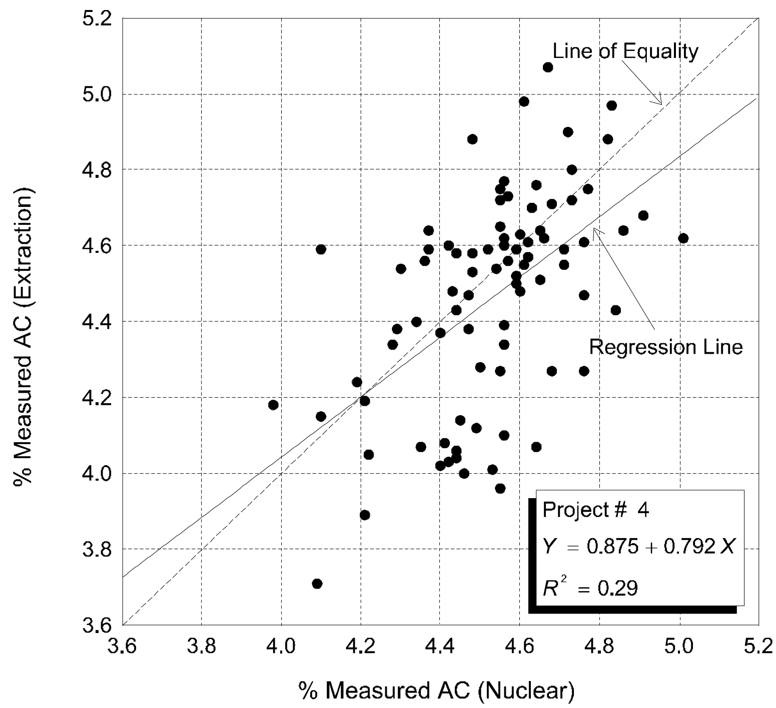


Figure 7-1 (continued). Relationship between Extracted and Nuclear Asphalt Content

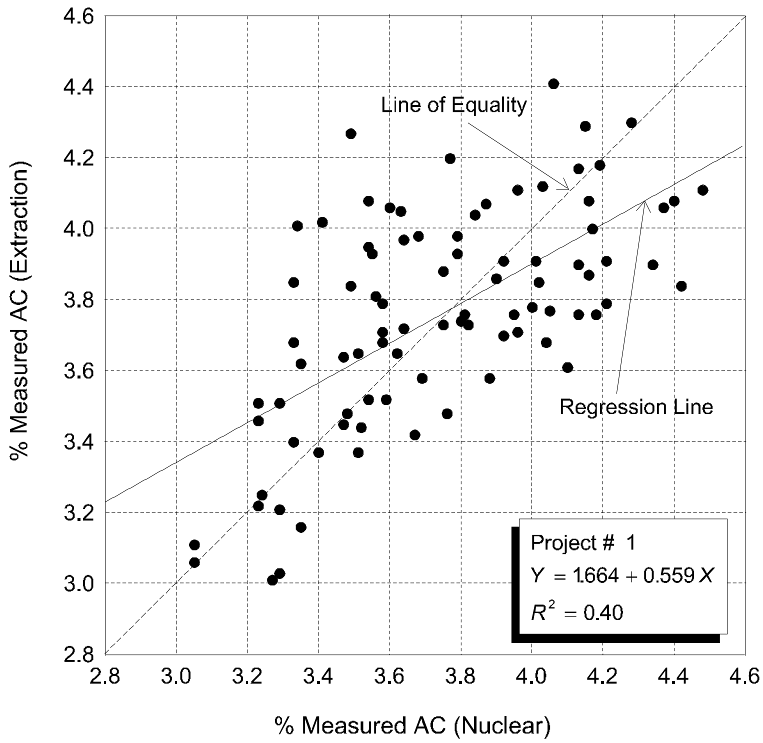
Table 7-6. Accuracy of the Ignition Oven Test Method [1]

Test Property	Aggregate Type			
	Gravel	Granite	Limestone	Traprock
% Asphalt Content				
Actual	6.00	6.00	5.00	5.50
Measured (Ignition Oven)	5.98	5.99	4.97	5.53
% Passing No. 4 Sieve				
Actual	71.60	66.80	61.40	57.00
Measured (Ignition Oven)	71.50	66.60	61.40	56.60
% Passing No. 200 Sieve				
Actual	6.00	7.70	6.70	5.30
Measured (Ignition Oven)	5.60	7.70	7.20	5.10

(1) Each number shown is the average of 48 test results (12 laboratories × 4 replicates). Asphalt content is by weight of the total mix.

Table 7-7. Precision of Asphalt Content Test Methods, percent

Test Method	Standard Deviation		Acceptable Range of Two Test Results	
	Within Lab	Between Labs	Within Lab	Between Labs
Ignition Oven	0.04	0.06	0.11	0.17
Solvent Extraction	0.21	0.22	0.59	0.62



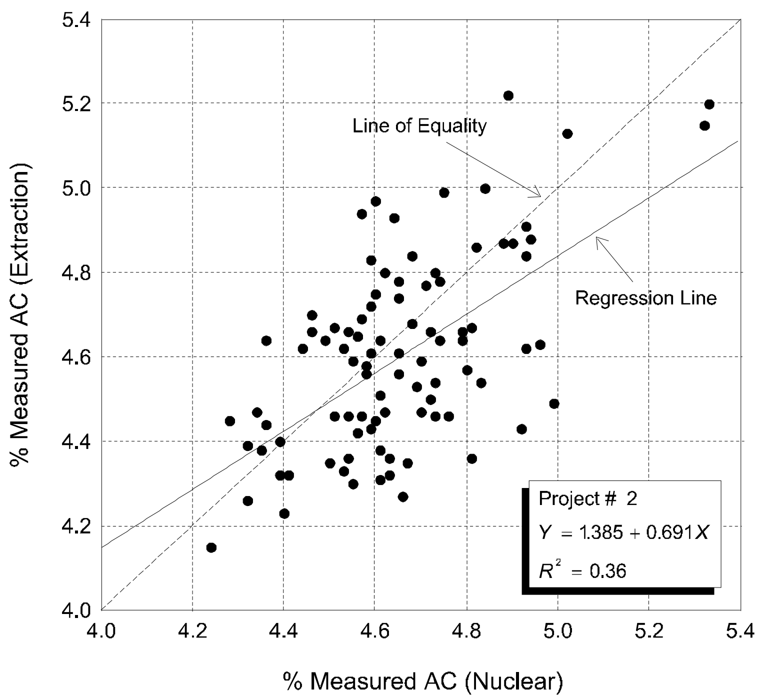
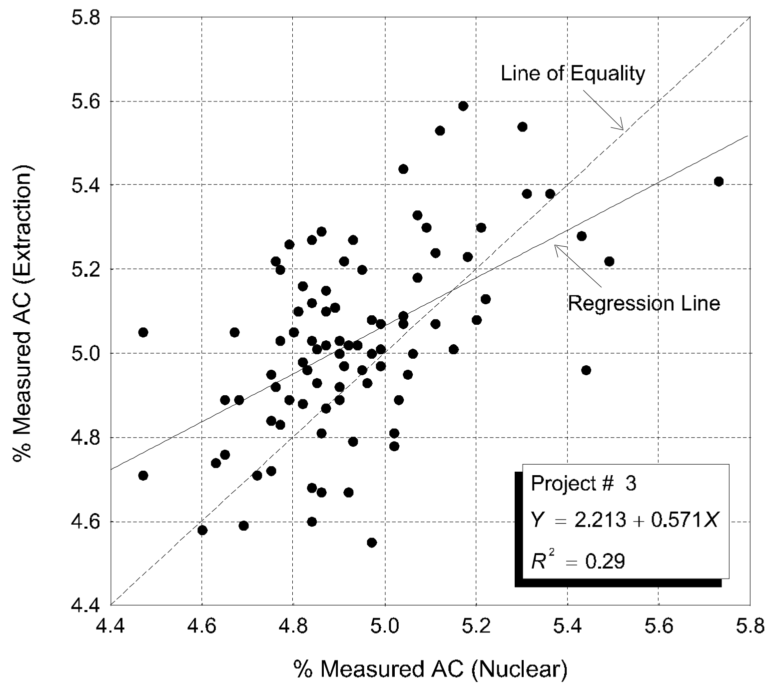


Figure xx. Relationship between Extracted and Nuclear Asphalt Content



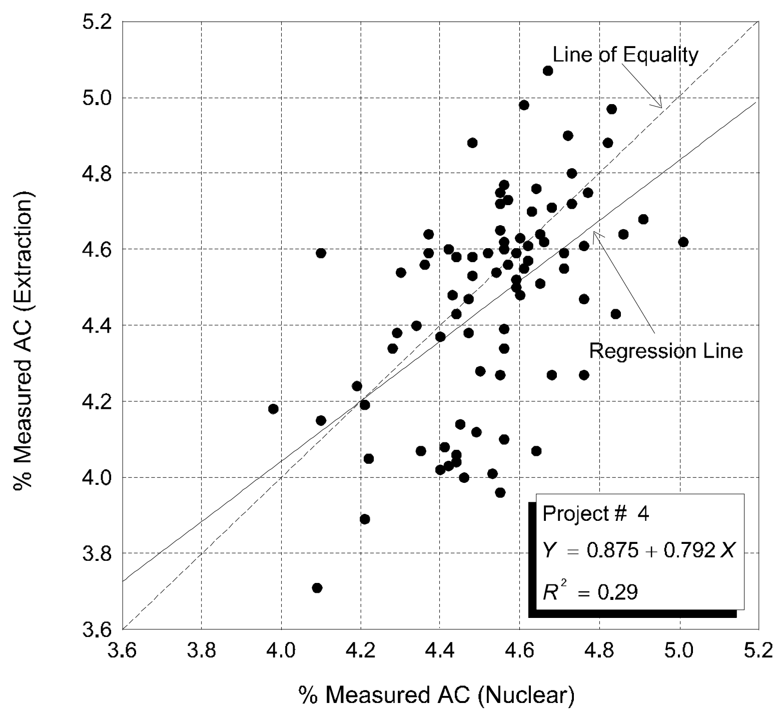
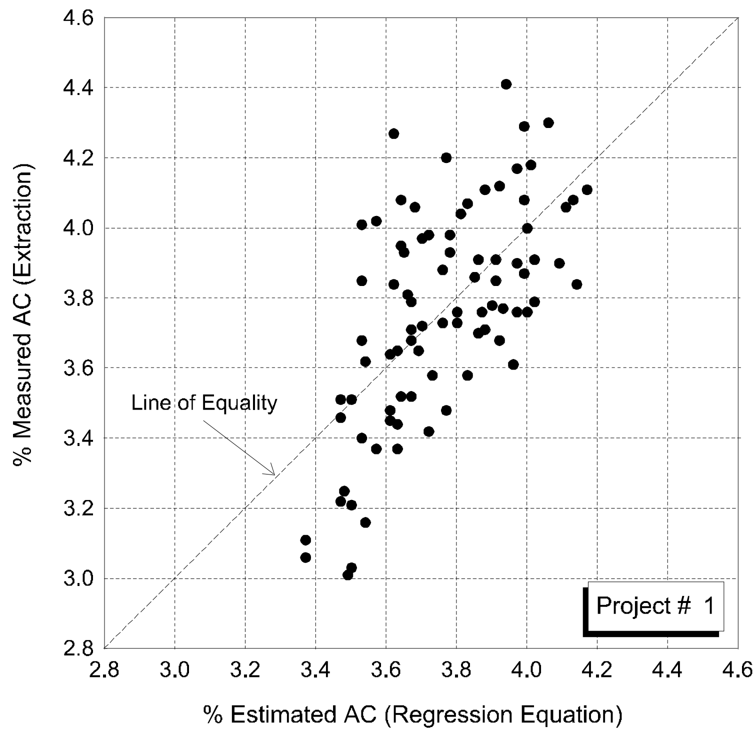


Figure xx (continued). Relationship between Extracted and Nuclear Asphalt Content



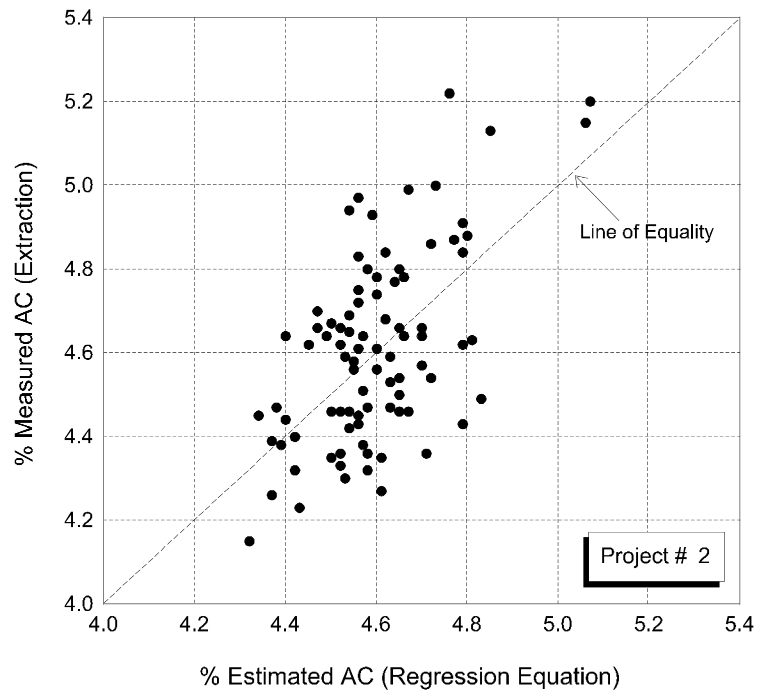
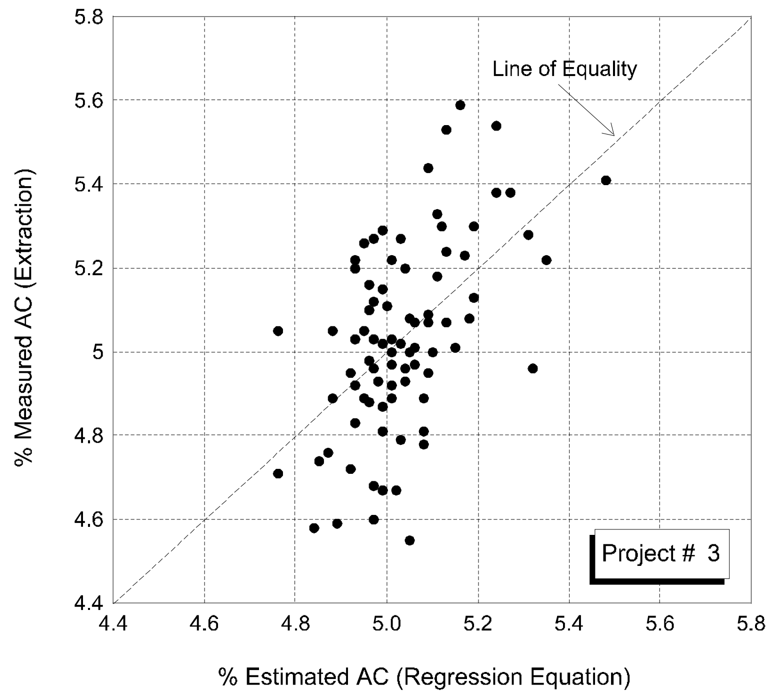


Figure xx. Relationship between Measured and Estimated Asphalt Content



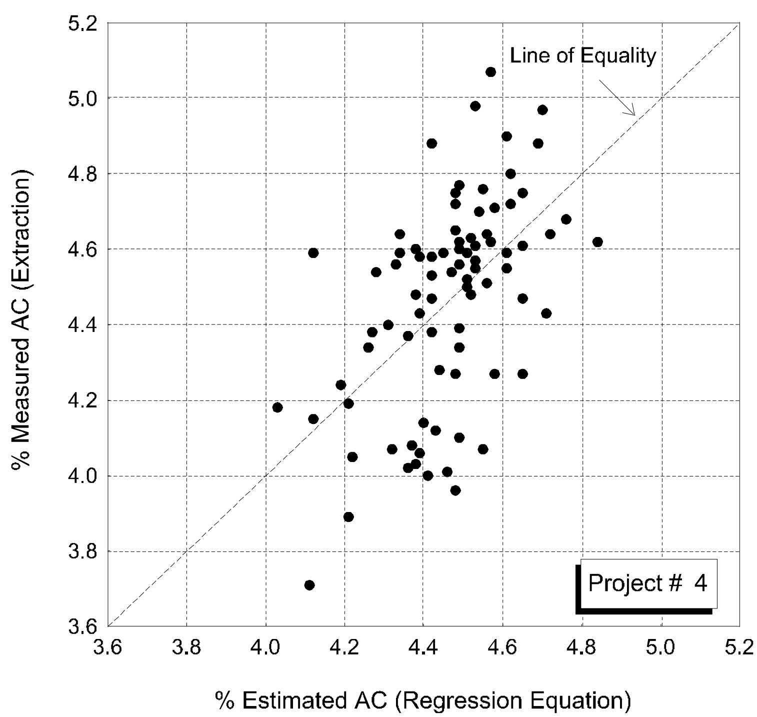
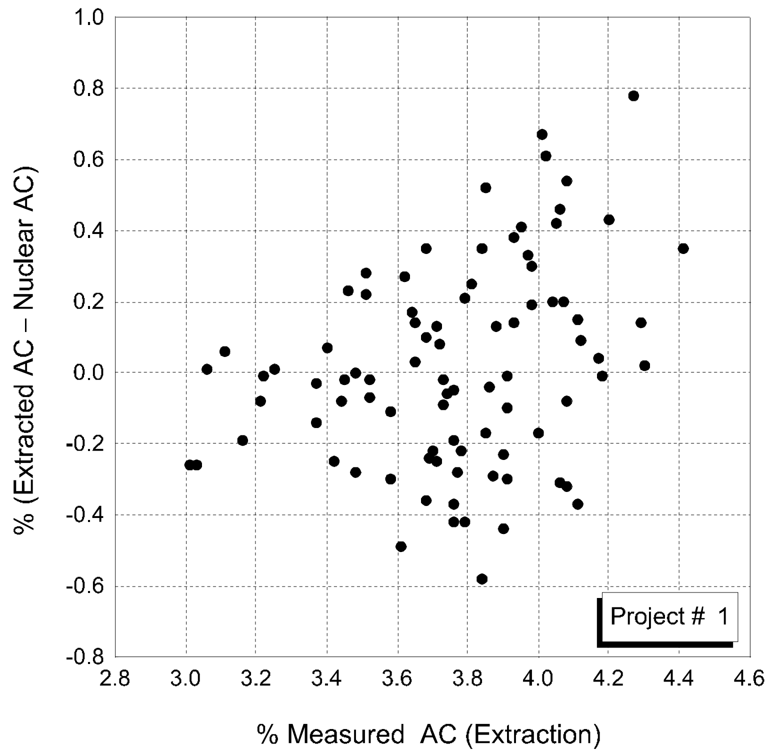


Figure xx (continued). Relationship between Measured and Estimated Asphalt Content



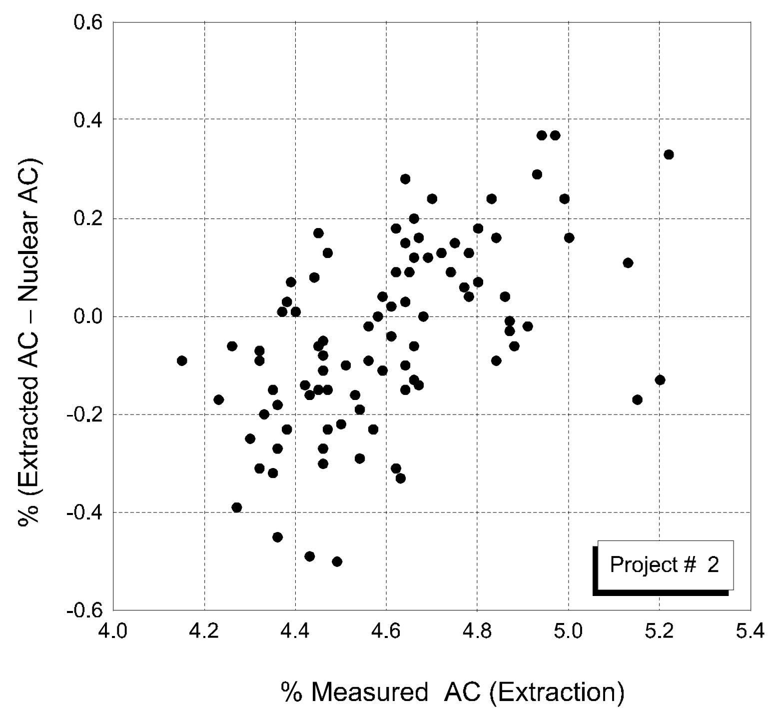
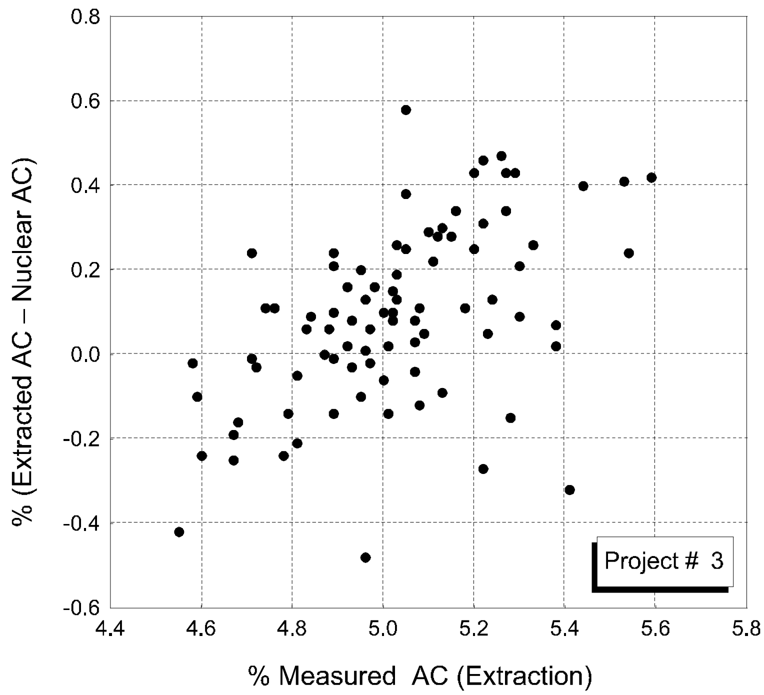


Figure xx. Extracted AC versus Difference between Extracted AC and Nuclear AC



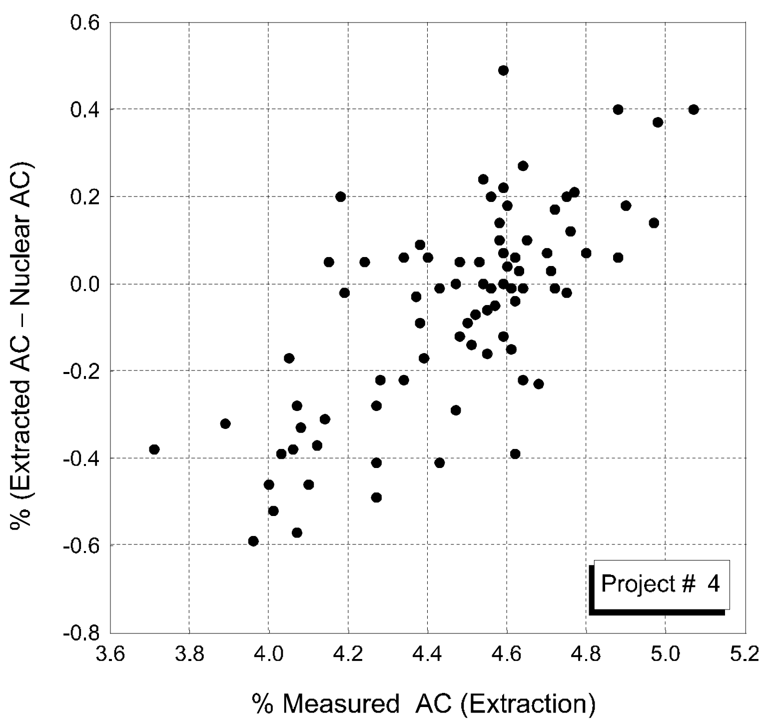


Figure xx (continued). Extracted AC versus Difference between Extracted AC and Nuclear AC

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the findings of the various analyses presented in the previous chapters, the following conclusions have been reached:

Overall Variability

Measures of the overall variability in the quality characteristics for each individual construction project as well as the pooled variation found in all four projects have been determined based on the principles of random sampling and statistical experimental design. In general, the levels of variability in HMA pavement materials and construction in Oklahoma are within the national ranges for the respective quality characteristics. Nevertheless, the variability found in many states is less than that in Oklahoma, which suggests that there is an opportunity for improving the quality of construction products in Oklahoma through the systematic reduction in variation. This can be accomplished only by contractor’s process control which involves collecting production performance data and constructing and maintaining control charts of these data.

Evidence from the four construction projects indicates that the standard deviation of a given quality characteristic is by itself a variable. Therefore, the development of acceptance plans and payment schedules should be based on variability-unknown methods similar to those described in the 1995 AASHTO Quality Assurance Guide Specification [1].

Components of Variability

Estimates of the components of total variation in each quality characteristic due to materials, sampling, and testing have been made using analysis of variance techniques. The contribution of each source of variation is given in terms of the standard deviation of the respective component.

The standard deviation of the materials component is an estimate of the expected variability in a single lot of HMA due to lack of uniformity in the material or construction when the production process is running smoothly. Likewise, the standard deviation of the sampling component is representative of the variation which is introduced during field sampling -- it does not include the variation caused by reducing large portions of the material to test specimens by splitting and quartering which is considered by ODOT to be part of testing. Finally, the standard deviation of the testing component is a measure of the precision of the test method and how sensitive the test method is to changes in the measured property of the material. It should be emphasized that testing was performed by several operators using different testing apparatus in different laboratories. Therefore, the multilaboratory standard deviation of the testing component reported in this study is expected to be greater than the single laboratory standard deviation.

Preliminary estimates of the variability associated with new test methods such as the binder ignition test for asphalt content and those which resulted from the SHRP program indicate a great deal of promise in controlling testing variability [13]. Another positive development is the technician certification program developed by ODOT and AGC to provide uniform training and certification in sampling and testing for ODOT and contractor's personnel. Although the issues of certification and training were not addressed in this research, the program will ensure that meaningful comparisons can be made between the ODOT's and the contractor's test results.

Process Capability and Specifications

An assessment of the capability of each of the four HMA construction/production processes has been made with respect to the requirements of JMF, existing QA specifications, and proposed QA specifications. In terms of the C_p, C_{pk}, and C_{pm} indices, process capability ranges from marginally acceptable to unacceptable by usual standards. Likewise, estimates of the percent within specification limits indicate that, except the aggregate passing large sieves, none of the other quality characteristics met the specification limits 100% of the time in all four projects.

One reason for this inferior performance is that the majority of the quality characteristics were not centered on the specified target. Another reason is that the variability in the quality characteristics was often larger than the window of variation permitted by the specifications. Opportunities for improving process performance can be realized through the use of statistical process control charting.

QA Specification Tolerances

The existing QA specification tolerances for aggregate gradation are somewhat large, whereas the tolerances of the new QA specifications seem to be more focused and adequate for accommodating the overall variation in these quality characteristics. For asphalt content, tolerances of $\pm 0.6\%$ (average of the $\pm 0.7\%$ in the existing QA specifications and $\pm 0.5\%$ in the proposed specifications) seem to be realistic and attainable by a consistent and capable process. For air voids, the $\pm 2.5\%$ tolerances of the existing QA specifications seem to be more reasonable than the $\pm 15\%$ tolerances of the proposed specifications.

Variability in roadway density was considerably higher than what is allowed in both the existing and proposed QA specifications. Although this may be a signal that the specification limits are too restrictive for this quality characteristic, it is more likely that the lack of process control is responsible for the poor level of conformance. More data on roadway density should be gathered and analyzed to verify the specification tolerances for roadway density.

Nuclear Density Gauge

Correlation of individual density measurements by core samples with those obtained by the nuclear gauge ranged from good to fair. The results suggest that an improvement in the prediction of core densities from nuclear gauge measurements can be realized through the use of regression equations. Such equations can be developed based on a reasonable number of core and nuclear density measurements for each project.

Because of its speed and ease of operation, the nuclear gauge is a very useful tool for quality control of pavement density during construction. The relative increase in density following each additional pass of the roller helps determine if the maximum relative density has been obtained.

Nuclear Asphalt Content Gauge

The mean values of asphalt content using the extraction and the nuclear gauge test methods are essentially the same for each of the four construction projects. Nevertheless, the accuracy of either test method was not addressed since the true asphalt content is unknown. In terms of precision, the test results suggest that the NAC gauge has a slightly better precision than the extraction method as evidenced by the smaller standard deviation found in three out of the four projects.

Earlier studies indicate that the type of aggregate used in an HMA affects the NAC gauge readings slightly, and that different gradations produce different results. Asphalt sources were also found to cause differences. Therefore, individual calibration for each particular mix is required to ensure accurate determination of asphalt content using the NAC gauge.

The relatively recent method of determining asphalt content by ignition is an excellent tool for both quality control and acceptance testing. Asphalt content can be measured in approximately 30 minutes, compared to over two hours with solvent extraction methods. Preliminary results of a recent study performed by NCAT suggest that the binder ignition test can accurately measure the asphalt content of HMA mixtures, and that the precision of this method is better than that of solvent extraction methods. Because the ignition oven can slightly change the properties of certain types of aggregates, round-robin studies are warranted to calibrate the test method for local materials.

RECOMMENDATIONS

1. Process control is one of the most important issues which must be stressed in order to realize the full potential of the quality assurance system in Oklahoma. In its present form, process control is often limited to having the contractor's personnel verify the results of acceptance testing performed by ODOT. This practice is flawed because it does not address the causes of defective materials or construction in a timely manner. The focus of process control should be on the identification of both sporadic and chronic faults in the process and formulating improvement actions. This requires the contractor to collect, analyze, and interpret data concerning the process to maintain target and to systematically reduce variability.

2. Fostering the implementation of process control requires increasing awareness within the construction community in Oklahoma of the importance of statistical process control methods and the benefits that can be realized by both contractors and ODOT. This can be ameliorated by providing training and requiring certification on the subject.

3. Research is required to address the following issues:
   - Variability in pavement smoothness and its relationship to process capability and QA specifications tolerances.
   - Variability in the binder ignition test method for asphalt content determination and the effect of the test method on local aggregates.
   - Evaluation of the pay equations in the new QA specifications for HMA pavement construction using acceptance data from several projects.
   - Variability in roadway density measurements by core samples and nuclear gauge.

APPENDIX A

ANALYSIS OF VARIANCE RESULTS

Table A-1. Summary Statistics of Test Results, Project No. 1 (US-412)

Quality Characteristic	Maximum	Minimum	Mean	Variance	Standard Deviation	CV%	Percentiles		
							15th	50th	85th
Cold Feed Aggregate Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	94.80	97.81	1.39	1.18	1.20	96.60	97.75	99.05
3/4"	92.40	79.60	87.14	7.63	2.76	3.17	84.25	87.35	89.70
1/2"	76.40	57.30	67.72	18.85	4.34	6.41	62.45	67.95	72.85
3/8"	65.70	44.70	55.69	19.20	4.38	7.87	51.15	55.45	60.60
No. 4	42.60	24.30	33.98	12.13	3.48	10.25	30.65	33.45	37.85
No. 10	30.70	16.70	23.54	7.77	2.79	11.84	20.90	23.40	26.15
No. 40	19.00	9.40	14.71	3.31	1.82	12.36	13.05	14.45	16.60
No. 80	8.60	4.60	6.81	0.75	0.87	12.74	6.00	6.80	7.90
No. 200	4.67	0.79	2.99	0.57	0.75	25.25	2.09	3.09	3.68
HMA Mixture & Roadway Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	93.90	98.45	2.85	1.69	1.72	96.85	98.60	100.00
3/4"	98.70	79.70	89.55	15.24	3.90	4.36	85.70	89.45	94.30
1/2"	81.30	60.50	71.36	20.16	4.49	6.29	66.40	71.15	76.90
3/8"	68.90	45.40	59.60	21.42	4.63	7.77	55.15	59.75	64.90
No. 4	44.50	27.00	37.70	10.86	3.30	8.74	34.00	37.90	40.95
No. 10	29.50	18.50	25.19	4.50	2.12	8.42	23.20	25.45	27.20
No. 40	18.40	12.00	15.24	1.76	1.33	8.72	13.60	15.40	16.45
No. 80	9.50	5.90	7.67	0.58	0.76	9.91	6.90	7.80	8.45
No. 200	5.47	2.23	3.75	0.35	0.59	15.80	3.19	3.72	4.32
% Asphalt Content									
Extraction	4.41	3.01	3.75	0.09	0.30	8.07	3.45	3.76	4.07
Nuclear Gauge	4.48	3.05	3.75	0.12	0.35	9.31	3.34	3.75	4.15
Rice's SG	2.563	2.457	2.501	0.000	0.019	0.763	2.480	2.500	2.522
LMSG	2.412	2.176	2.368	0.001	0.033	1.402	2.357	2.372	2.389
% Air Voids	14.39	2.48	5.29	2.82	1.68	31.77	4.25	5.02	6.00
% Hveem Stability	63.30	34.00	50.89	28.93	5.38	10.57	45.70	50.40	56.35
% Roadway Density									
Core method	96.30	91.20	94.10	1.09	1.05	1.11	93.10	94.15	95.20
Nuclear gauge	94.97	82.79	90.34	4.92	2.22	2.46	88.21	90.24	92.75

Table A-2. Summary Statistics of Test Results, Project No. 2 (US-70)

Quality Characteristic	Maximum	Minimum	Mean	Variance	Standard Deviation	CV%	Percentiles		
							15th	50th	85th
Cold Feed Aggregate Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
3/4"	100.00	98.40	99.95	0.06	0.25	0.25	100.00	100.00	100.00
1/2"	98.70	94.10	96.92	1.23	1.11	1.14	95.70	97.15	98.00
3/8"	92.10	73.70	83.42	14.04	3.75	4.49	79.40	83.75	87.35
No. 4	70.50	39.80	59.25	23.19	4.82	8.13	54.50	60.05	62.95
No. 10	46.10	17.10	35.52	19.57	4.42	12.45	31.50	35.50	39.85
No. 40	24.20	14.20	19.70	5.45	2.34	11.86	17.25	19.55	22.10
No. 80	14.70	7.40	11.73	1.83	1.35	11.51	10.20	11.85	13.00
No. 200	8.97	2.64	6.96	1.05	1.03	14.73	6.14	6.93	8.09
HMA Mixture & Roadway Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
3/4"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1/2"	99.90	95.80	97.77	0.63	0.79	0.81	96.85	97.80	98.60
3/8"	92.10	81.80	87.51	4.69	2.17	2.47	85.20	87.20	89.70
No. 4	71.30	55.50	62.00	9.74	3.12	5.03	59.00	61.50	65.15
No. 10	42.40	28.20	35.09	9.38	3.06	8.73	31.45	35.40	38.00
No. 40	21.80	12.80	19.24	2.27	1.51	7.83	17.50	19.50	20.60
No. 80	13.60	9.10	11.00	1.25	1.12	10.15	9.80	11.00	12.35
No. 200	7.49	4.20	6.02	0.53	0.73	12.06	5.13	6.10	6.76
% Asphalt Content									
Extraction	5.22	4.15	4.59	0.05	0.23	5.04	4.35	4.57	4.84
Nuclear Gauge	5.33	4.24	4.65	0.04	0.20	4.20	4.46	4.62	4.82
Rice's SG	2.545	2.487	2.525	0.000	0.012	0.481	2.512	2.526	2.536
LMSG	2.421	2.335	2.382	0.000	0.022	0.928	2.353	2.385	2.406
% Air Voids	8.08	2.97	5.64	1.26	1.12	19.89	4.32	5.58	6.78
% Hveem Stability	100.00	40.90	53.01	77.55	8.81	16.61	46.85	51.50	60.35
% Roadway Density									
Core method	90.71	78.99	86.18	5.52	2.35	2.73	83.30	86.44	88.52
Nuclear gauge	91.78	81.49	86.93	4.62	2.15	2.47	84.89	87.17	88.78

Table A-3. Summary Statistics of Test Results, Project No. 3 (US-62)

Quality Characteristic	Maximum	Minimum	Mean	Variance	Standard Deviation	CV%	Percentiles 15th	50th	85th
Cold Feed Aggregate Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
3/4"	100.00	97.70	99.96	0.07	0.27	0.27	100.00	100.00	100.00
1/2"	93.20	64.90	87.30	13.91	3.73	4.27	85.25	87.50	90.85
3/8"	83.40	54.90	73.45	25.19	5.02	6.83	69.40	73.40	78.15
No. 4	64.50	37.50	55.25	27.21	5.22	9.44	50.65	55.30	60.50
No. 10	51.30	18.80	36.82	24.18	4.92	13.35	32.20	36.65	41.70
No. 40	25.50	7.10	19.53	8.59	2.93	15.01	16.75	19.45	22.45
No. 80	13.00	4.90	9.63	1.86	1.36	14.17	8.30	9.60	11.00
No. 200	7.96	3.34	5.27	0.51	0.72	13.62	4.59	5.20	6.03
HMA Mixture & Roadway Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
3/4"	100.00	98.30	99.98	0.03	0.18	0.18	100.00	100.00	100.00
1/2"	93.30	83.10	88.46	5.37	2.32	2.62	85.85	88.60	90.80
3/8"	82.90	69.40	75.59	7.13	2.67	3.53	73.00	75.40	78.25
No. 4	61.90	50.00	56.62	6.22	2.49	4.40	54.10	56.40	59.45
No. 10	42.20	24.80	37.16	6.07	2.46	6.63	35.85	37.20	39.20
No. 40	21.30	17.10	19.62	0.68	0.82	4.19	18.80	19.60	20.40
No. 80	11.00	8.20	9.80	0.29	0.53	5.45	9.35	9.80	10.40
No. 200	5.98	4.44	5.37	0.09	0.30	5.49	5.03	5.40	5.68
% Asphalt Content									
Extraction	5.59	4.55	5.05	0.05	0.22	4.33	4.81	5.03	5.27
Nuclear Gauge	5.73	4.47	4.93	0.05	0.21	4.34	4.75	4.89	5.11
Rice's SG	2.493	2.433	2.463	0.000	0.011	0.465	2.452	2.464	2.472
LMSG	2.394	2.341	2.375	0.000	0.010	0.408	2.365	2.376	2.385
% Air Voids	5.28	1.93	3.55	0.46	0.68	19.05	2.77	3.44	4.30
% Hveem Stability	100.00	37.00	50.98	124.41	11.15	21.88	42.00	48.65	57.40
% Roadway Density									
Core method	92.85	86.64	90.56	3.41	1.85	2.04	87.72	90.90	92.37
Nuclear gauge	93.71	86.80	90.45	3.07	1.75	1.94	88.47	90.30	92.49

Table A-4. Summary Statistics of Test Results, Project No. 4 (US-69)

Quality Characteristic	Maximum	Minimum	Mean	Variance	Standard Deviation	CV%	Percentiles 15th	50th	85th
Cold Feed Aggregate Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	99.80	96.70	98.54	0.44	0.66	0.67	97.70	98.60	99.30
3/4"	91.70	81.90	87.28	4.19	2.05	2.35	84.95	87.20	89.55
1/2"	82.40	68.30	73.50	9.28	3.05	4.14	70.55	73.20	76.25
3/8"	74.10	52.90	63.81	13.79	3.71	5.82	60.10	63.45	67.40
No. 4	61.90	42.50	50.41	14.54	3.81	7.56	46.45	49.70	53.95
No. 10	49.20	30.10	38.71	11.73	3.42	8.84	35.40	38.35	41.95
No. 40	63.20	12.30	16.49	26.69	5.17	31.33	14.00	15.80	17.75
No. 80	11.20	3.50	6.97	0.99	1.00	14.29	6.25	6.85	7.65
No. 200	8.16	0.48	4.14	0.67	0.82	19.77	3.73	4.11	4.57
HMA Mixture & Roadway Samples									
% Passing Sieve									
1 1/2"	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00
1"	100.00	94.40	98.62	2.19	1.48	1.50	96.65	98.70	100.00
3/4"	96.20	80.80	88.33	14.00	3.74	4.24	83.20	88.50	91.70
1/2"	84.50	66.70	76.95	14.52	3.81	4.95	72.95	76.95	81.00
3/8"	77.60	59.00	67.38	15.57	3.95	5.86	62.40	67.55	70.70
No. 4	64.10	46.50	54.04	11.06	3.33	6.15	50.25	54.10	56.90
No. 10	48.80	35.40	41.62	6.94	2.63	6.33	38.80	41.75	43.75
No. 40	21.70	10.20	17.05	2.52	1.59	9.31	15.40	17.00	18.40
No. 80	15.00	2.90	7.57	1.34	1.16	15.30	6.90	7.40	8.15
No. 200	6.77	1.23	4.43	0.41	0.64	14.42	4.00	4.37	4.82
% Asphalt Content									
Extraction	5.07	3.71	4.47	0.08	0.27	6.14	4.07	4.54	4.72
Nuclear Gauge	5.01	3.98	4.53	0.03	0.18	4.05	4.35	4.55	4.69
Rice's SG	2.399	2.301	2.363	0.000	0.014	0.610	2.353	2.365	2.376
LMSG	2.232	2.163	2.208	0.000	0.013	0.607	2.194	2.210	2.222
% Air Voids	8.59	3.40	6.54	0.74	0.86	13.16	5.86	6.39	7.40
% Hveem Stability	100.00	42.70	58.13	337.70	18.38	31.61	46.05	51.55	80.25
% Roadway Density									
Core method	93.47	86.60	90.51	2.01	1.42	1.57	89.03	90.63	91.94
Nuclear gauge	91.41	89.48	90.57	0.23	0.48	0.53	90.04	90.66	91.02

Table A-5. Pooled Variance and Pooled Standard Deviation, Four Projects

Quality Characteristic	Project # 1		Project # 2		Project # 3		Project # 4		Pooled Estimate	
	s	n	s	n	s	n	s	n	s^2	s
Cold Feed Aggregate Samples										
% Passing Sieve:										
1-1/2"	0.00	92	0.00	100	0.00	92	0.00	100	0.00	0.00
1"	1.18	92	0.00	100	0.00	92	0.66	100	0.45	0.67
3/4"	2.76	92	0.25	100	0.27	92	2.05	100	2.95	1.72
1/2"	4.34	92	1.11	100	3.73	92	3.05	100	10.59	3.25
3/8"	4.38	92	3.75	100	5.02	92	3.71	100	17.88	4.23
No. 4	3.48	92	4.82	100	5.22	92	3.81	100	19.26	4.39
No. 10	2.79	92	4.42	100	4.92	92	3.42	100	15.80	3.97
No. 40	1.82	92	2.34	100	2.93	92	5.17	100	11.24	3.35
No. 80	0.87	92	1.35	100	1.36	92	1.00	100	1.36	1.17
No. 200	0.75	92	1.03	100	0.72	92	0.82	100	0.71	0.84
HMA Mixture & Roadway Samples										
% Passing Sieve:										
1-1/2"	0.00	92	0.00	100	0.00	88	0.00	88	0.00	0.00
1"	1.69	92	0.00	100	0.00	88	1.48	92	1.25	1.12
3/4"	3.90	92	0.00	100	0.18	88	3.74	60	6.58	2.57
1/2"	4.49	92	0.79	100	2.32	88	3.81	92	10.02	3.16
3/8"	4.63	92	2.17	100	2.67	88	3.95	60	11.78	3.43
No. 4	3.30	92	3.12	100	2.49	88	3.33	92	9.52	3.09
No. 10	2.12	92	3.06	100	2.46	88	2.63	92	6.77	2.60
No. 40	1.33	92	1.51	100	0.82	88	1.59	92	1.83	1.35
No. 80	0.76	92	1.12	100	0.53	88	1.16	92	0.88	0.94
No. 200	0.59	92	0.73	100	0.30	88	0.64	92	0.35	0.59
% Asphalt Content										
Extraction Method	0.30	92	0.23	100	0.22	84	0.27	92	0.07	0.26
Nuclear Gauge	0.35	88	0.20	96	0.21	92	0.18	100	0.06	0.24
Rice's SG	0.02	92	0.01	100	0.01	88	0.01	88	0.00	0.01
LMSG	0.03	88	0.02	100	0.01	88	0.01	100	0.00	0.02
% Air Voids	1.68	88	1.12	100	0.68	88	0.86	88	1.32	1.15
% Hveem Stability	5.38	68	8.81	100	11.15	64	18.38	52	123.87	11.13
% Roadway Density										
Core Method	1.05	100	2.35	100	1.85	20	1.42	84	2.96	1.72
Nuclear Gauge	2.22	100	2.15	100	1.75	100	0.48	100	3.21	1.79

Table A-6. Analysis of Variance Results, Project No. 1 (US-412)

Quality Characteristic	Overall Std. Dev.	Std. Dev. Of Components			Hypothesis 1 [1]		Hypothesis 2 [2]	
		Materials	Sampling	Testing	F-ratio	Conclusion [3]	F-ratio	Conclusion [3]
Cold Feed Aggregate Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	1.18	0.56	0.03	1.04	2.17	Significant	1.00	Not Significant
3/4"	2.76	1.26	0.65	2.37	1.98	Not Significant	1.15	Not Significant
1/2"	4.34	2.14	0.00	3.78	3.13	Significant	0.60	Not Significant
3/8"	4.38	1.89	0.00	3.95	3.02	Significant	0.45	Significant [4]
No. 4	3.48	1.21	0.00	3.26	2.24	Significant	0.45	Significant [4]
No. 10	2.79	0.82	0.00	2.66	1.78	Not Significant	0.48	Significant [4]
No. 40	1.82	0.63	0.00	1.71	1.87	Not Significant	0.62	Not Significant
No. 80	0.87	0.50	0.00	0.71	3.10	Significant	0.95	Not Significant
No. 200	0.75	0.57	0.32	0.38	4.67	Significant	2.48	Significant
Average all sieves	2.68	1.15	0.23	2.41				
HMA Mixture & Roadway Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	1.69	0.42	0.00	1.63	1.30	Not Significant	0.89	Not Significant
3/4"	3.90	1.60	0.00	3.56	2.07	Significant	0.75	Not Significant
1/2"	4.49	1.07	2.14	3.80	1.19	Not Significant	1.63	Not Significant
3/8"	4.63	1.73	2.19	3.69	1.52	Not Significant	1.70	Not Significant
No. 4	3.30	1.63	1.87	2.17	1.91	Not Significant	2.48	Significant
No. 10	2.12	1.36	0.97	1.30	3.07	Significant	2.13	Significant
No. 40	1.33	0.97	0.55	0.72	4.41	Significant	2.16	Significant
No. 80	0.76	0.51	0.42	0.38	3.14	Significant	3.42	Significant
No. 200	0.59	0.43	0.33	0.24	3.63	Significant	4.73	Significant
Average all sieves	2.79	1.13	1.20	2.25				
% Asphalt Content	0.30	0.19	0.13	0.19	3.10	Significant	1.93	Significant
Extraction	0.35	0.29	0.14	0.13	6.62	Significant	3.24	Significant
Nuclear Gauge								
	0.02	0.01	0.01	0.01	2.06	Significant	6.42	Significant
Rice's SG	0.03	0.02	0.02	0.01	3.29	Significant	14.98	Significant
LMSG								
	1.68	1.23	1.01	0.53	3.59	Significant	8.19	Significant
% Air Voids								
	5.38	4.45	2.21	2.05	6.68	Significant	3.33	Significant
% Hveem Stability								
% Roadway Density	1.05	0.51	0.79	0.46	1.70	Not Significant	6.81	Significant
Core method	2.22	1.47	1.31	1.02	2.92	Significant	4.30	Significant
Nuclear gauge								

1) H_0: $\sigma_M^2 = 0$ vs. H_1: $\sigma_M^2 > 0$

2) H_0: $\sigma_S^2 = 0$ vs. H_1: $\sigma_S^2 > 0$

3) Level of significance = 5%

4) F' is significant

Table A-7. Analysis of Variance Results, Project No. 2 (US-70)

Quality Characteristic	Overall Std. Dev.	Std. Dev. Of Components			Hypothesis 1 [1]		Hypothesis 2 [2]	
		Materials	Sampling	Testing	F-ratio	Conclusion [3]	F-ratio	Conclusion [3]
Cold Feed Aggregate Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
3/4"	0.25	0.00	0.10	0.23	0.92	Not Significant	1.38	Not Significant
1/2"	1.11	0.46	0.60	0.81	1.63	Not Significant	2.09	Significant
3/8"	3.75	1.81	2.64	1.95	1.74	Not Significant	4.64	Significant
No. 4	4.82	0.69	3.69	3.02	1.05	Not Significant	4.00	Significant
No. 10	4.42	0.69	3.47	2.66	1.06	Not Significant	4.39	Significant
No. 40	2.34	0.96	1.46	1.55	1.55	Not Significant	2.78	Significant
No. 80	1.35	0.00	1.13	0.74	0.97	Not Significant	5.63	Significant
No. 200	1.03	0.22	0.89	0.47	1.11	Not Significant	8.24	Significant
Average all sieves	2.58	0.74	1.93	1.55				
HMA Mixture & Roadway Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
3/4"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1/2"	0.79	0.29	0.00	0.74	1.74	Not Significant	0.83	Not Significant
3/8"	2.17	0.75	1.29	1.57	1.38	Not Significant	2.35	Significant
No. 4	3.12	1.72	1.89	1.79	2.13	Significant	3.23	Significant
No. 10	3.06	2.24	1.32	1.62	4.28	Significant	2.33	Significant
No. 40	1.51	0.99	0.87	0.73	2.88	Significant	3.85	Significant
No. 80	1.12	0.89	0.51	0.44	5.45	Significant	3.76	Significant
No. 200	0.73	0.57	0.28	0.36	5.52	Significant	2.14	Significant
Average all sieves	1.69	1.03	0.90	0.98				
% Asphalt Content	0.23	0.00	0.19	0.13	0.99	Not Significant	5.34	Significant
Extraction	0.20	0.07	0.16	0.09	1.30	Not Significant	7.37	Significant
Nuclear Gauge								
	0.01	0.01	0.01	0.01	2.35	Significant	3.93	Significant
Rice's SG	0.02	0.02	0.01	0.01	5.41	Significant	6.40	Significant
LMSG								
	1.12	0.83	0.66	0.37	3.77	Significant	7.47	Significant
% Air Voids								
	8.81	4.69	7.12	2.19	1.83	Not Significant	22.12	Significant
% Hveem Stability								
% Roadway Density	2.35	1.35	1.61	1.06	2.16	Significant	5.58	Significant
Core method	2.15	1.00	1.72	0.81	1.61	Not Significant	10.13	Significant
Nuclear gauge								

1) $H_0: \sigma_M^2 = 0$ vs. $H_1: \sigma_M^2 > 0$

2) $H_0: \sigma_S^2 = 0$ vs. $H_1: \sigma_S^2 > 0$

3) Level of significance = 5%

4) F' is significant

Table A-8. Analysis of Variance Results, Project No. 3 (US-62)

Quality Characteristic	Overall Std. Dev.	Std. Dev. Of Components			Hypothesis 1 (1)		Hypothesis 2 (2)	
		Materials	Sampling	Testing	F-ratio	Conclusion (3)	F-ratio	Conclusion (3)
Cold Feed Aggregate Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
3/4"	0.27	0.00	0.00	0.27	0.99	Not Significant	1.00	Not Significant
1/2"	3.73	1.44	1.52	3.09	1.59	Not Significant	1.48	Not Significant
3/8"	5.02	1.00	1.99	4.50	1.14	Not Significant	1.39	Not Significant
No. 4	5.22	1.89	2.34	4.26	1.49	Not Significant	1.60	Not Significant
No. 10	4.92	2.30	1.87	3.92	1.95	Not Significant	1.46	Not Significant
No. 40	2.93	1.32	1.25	2.30	1.83	Not Significant	1.59	Not Significant
No. 80	1.36	0.60	0.62	1.06	1.76	Not Significant	1.69	Not Significant
No. 200	0.72	0.31	0.35	0.55	1.71	Not Significant	1.81	Significant
Average all sieves	3.19	1.19	1.32	2.65				
HMA Mixture & Roadway Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
3/4"	0.18	0.02	0.01	0.18	1.05	Not Significant	1.00	Not Significant
1/2"	2.32	0.00	1.22	1.97	0.59	Not Significant	1.77	Not Significant
3/8"	2.67	0.64	1.51	2.11	1.19	Not Significant	2.02	Significant
No. 4	2.49	0.98	0.94	2.09	1.62	Not Significant	1.40	Not Significant
No. 10	2.46	0.90	0.19	2.28	1.62	Not Significant	1.01	Not Significant
No. 40	0.82	0.33	0.58	0.49	1.50	Not Significant	3.79	Significant
No. 80	0.53	0.29	0.27	0.35	2.24	Significant	2.23	Significant
No. 200	0.30	0.17	0.16	0.20	2.27	Significant	2.25	Significant
Average all sieves	1.61	0.49	0.72	1.35				
% Asphalt Content	0.22	0.10	0.13	0.16	1.63	Not Significant	2.39	Significant
Extraction	0.21	0.11	0.15	0.10	1.90	Not Significant	5.87	Significant
Nuclear Gauge								
	0.01	0.01	0.00	0.01	4.84	Significant	1.90	Significant
Rice's SG	0.01	0.01	0.01	0.01	2.96	Significant	3.52	Significant
LMSG								
	0.68	0.52	0.29	0.33	4.85	Significant	2.54	Significant
% Air Voids								
	11.15	7.97	0.00	7.80	22.18	Significant	0.20	Significant (4)
% Hveem Stability								
% Roadway Density	1.85	0.00	1.64	0.86	0.50	Not Significant	8.31	Significant
Core method	1.75	1.15	1.29	0.30	2.55	Not Significant	38.61	Significant
Nuclear gauge								

1) $H_0: \sigma_M^2 = 0$ vs. $H_1: \sigma_M^2 > 0$

2) $H_0: \sigma_S^2 = 0$ vs. $H_1: \sigma_S^2 > 0$

3) Level of significance = 5%

4) F' is significant

Table A-9. Analysis of Variance Results, Project No. 4 (US-69)

Quality Characteristic	Overall Std. Dev.	Std. Dev. Of Components			Hypothesis 1 [1]		Hypothesis 2 [2]	
		Materials	Sampling	Testing	F-ratio	Conclusion [3]	F-ratio	Conclusion [3]
Cold Feed Aggregate Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	0.66	0.09	0.32	0.57	1.06	Not Significant	1.64	Not Significant
3/4"	2.05	0.83	0.00	1.87	1.94	Not Significant	0.93	Not Significant
1/2"	3.05	1.76	0.00	2.49	6.32	Significant	0.37	Not Significant
3/8"	3.71	2.18	0.00	3.00	4.89	Significant	0.54	Not Significant
No. 4	3.81	2.37	0.00	2.98	7.77	Significant	0.37	Not Significant
No. 10	3.42	2.24	0.00	2.59	5.54	Significant	0.66	Not Significant
No. 40	5.17	1.09	0.00	5.05	1.19	Not Significant	0.99	Not Significant
No. 80	1.00	0.53	0.47	0.71	2.16	Significant	1.90	Significant
No. 200	0.82	0.35	0.52	0.53	1.60	Not Significant	2.95	Significant
Average all sieves	2.87	1.44	0.24	2.47				
HMA Mixture & Roadway Samples								
% Passing Sieve								
1 1/2"	0.00	0.00	0.00	0.00	0.00	Not Significant	0.00	Not Significant
1"	1.48	0.00	0.78	1.26	0.95	Not Significant	1.76	Not Significant
3/4"	3.74	1.97	1.75	2.65	2.18	Not Significant	1.88	Not Significant
1/2"	3.81	1.37	1.29	3.31	1.53	Not Significant	1.30	Not Significant
3/8"	3.95	0.62	2.33	3.13	1.07	Not Significant	2.11	Significant
No. 4	3.33	1.00	1.51	2.79	1.32	Not Significant	1.58	Not Significant
No. 10	2.63	1.08	1.11	2.13	1.66	Not Significant	1.54	Not Significant
No. 40	1.59	1.03	0.48	1.11	3.51	Significant	1.37	Not Significant
No. 80	1.16	0.50	0.00	1.04	2.43	Significant	0.65	Not Significant
No. 200	0.64	0.25	0.00	0.59	1.95	Not Significant	0.74	Not Significant
Average all sieves	2.62	0.98	1.20	2.11				
% Asphalt Content	0.27	0.19	0.13	0.14	3.82	Significant	2.52	Significant
Extraction	0.18	0.13	0.08	0.10	4.24	Significant	2.30	Significant
Nuclear Gauge								
	0.01	0.01	0.00	0.01	4.16	Significant	2.38	Significant
Rice's SG	0.01	0.01	0.00	0.01	3.24	Significant	2.33	Significant
LMSG								
	0.86	0.65	0.36	0.43	4.80	Significant	2.39	Significant
% Air Voids								
	18.38	18.30	0.78	1.49	388.88	Significant	1.55	Not Significant
% Hveem Stability								
% Roadway Density	1.42	0.00	1.32	0.53	0.61	Not Significant	13.41	Significant
Core method	0.48	0.15	0.46	0.00	1.21	Not Significant	0.00	Not Significant
Nuclear gauge								

1) $H_0: \sigma_M^2 = 0$ vs. $H_1: \sigma_M^2 > 0$

2) $H_0: \sigma_S^2 = 0$ vs. $H_1: \sigma_S^2 > 0$

3) Level of significance = 5%

4) F' is significant

APPENDIX B

PROCESS CAPABILITY & SPECIFICATIONS

Table B-1. Natural Process Tolerances, Project No. 1 (US-412)

Quality Characteristic	$\bar{X}$	S	$\bar{X} \pm 2S$ Limits	$\bar{X} \pm 2S$ Percent	$\bar{X} \pm 3S$ Limits	$\bar{X} \pm 3S$ Percent
Cold Feed Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	97.81	1.18	95.45 - 100.00	95.65	94.27 - 100.00	100.00
3/4"	87.14	2.76	81.62 - 92.66	96.74	78.86 - 95.42	100.00
1/2"	67.72	4.34	59.04 - 76.40	98.91	54.70 - 80.74	100.00
No. 4	33.98	3.48	27.02 - 40.94	96.74	23.54 - 44.42	100.00
No. 10	23.54	2.79	17.96 - 29.12	92.39	15.17 - 31.91	100.00
No. 40	14.71	1.82	11.07 - 18.35	93.48	9.25 - 20.17	100.00
No. 80	6.81	0.87	5.07 - 8.55	96.74	4.20 - 9.42	100.00
No. 200	2.99	0.75	1.49 - 4.49	95.65	0.74 - 5.24	100.00
HMA Mixture Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	98.45	1.69	95.07 - 100.00	94.57	93.38 - 100.00	100.00
3/4"	89.55	3.90	81.75 - 97.35	96.74	77.85 - 100.00	100.00
1/2"	71.36	4.49	62.38 - 80.34	96.74	57.89 - 84.83	100.00
No. 4	37.70	3.30	31.10 - 44.30	95.65	27.80 - 47.60	98.91
No. 10	25.19	2.12	20.95 - 29.43	94.57	18.83 - 31.55	98.91
No. 40	15.24	1.33	12.58 - 17.90	93.48	11.25 - 19.23	100.00
No. 80	7.67	0.76	6.15 - 9.19	96.74	5.39 - 9.95	100.00
No. 200	3.75	0.59	2.57 - 4.93	93.48	1.98 - 5.52	100.00
% Asphalt Content						
Extraction	3.75	0.30	3.15 - 4.35	94.57	2.85 - 4.65	100.00
Nuclear Gauge	3.75	0.35	3.05 - 4.45	96.59	2.70 - 4.80	100.00
Rice's SG	2.501	0.019	2.46 - 2.54	93.48	2.44 - 2.56	98.91
Lab Molded SG	2.368	0.033	2.30 - 2.43	97.73	2.27 - 2.47	97.73
% Air Voids	5.29	1.68	1.93 - 8.65	95.45	0.25 - 10.33	97.73
% Hveem Stability	50.89	5.38	40.13 - 61.65	94.12	34.75 - 67.03	98.53
% Roadway Density						
Core Method	94.10	1.05	92.00 - 96.20	92.00	90.95 - 97.25	100.00
Nuclear Gauge	90.34	2.22	85.90 - 94.78	97.00	83.68 - 97.00	99.00

Table B-1 (continued). Natural Process Tolerances, Project No. 2 (US-70)

Quality Characteristic	$\bar{X}$	S	$\bar{X} \pm 2S$ Limits	$\bar{X} \pm 2S$ Percent	$\bar{X} \pm 3S$ Limits	$\bar{X} \pm 3S$ Percent
Cold Feed Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
3/4"	99.95	0.25	99.45 - 100.00	96.00	99.20 - 100.00	97.00
1/2"	96.92	1.11	94.70 - 99.14	96.00	93.59 - 100.00	100.00
3/8"	83.42	3.75	75.92 - 90.92	94.00	72.17 - 94.67	100.00
No. 4	59.25	4.82	49.61 - 68.89	94.00	44.79 - 73.71	98.00
No. 10	35.52	4.42	26.68 - 44.36	96.00	22.26 - 48.78	99.00
No. 40	19.70	2.34	15.02 - 24.38	97.00	12.68 - 26.72	100.00
No. 80	11.73	1.35	9.03 - 14.43	97.00	7.68 - 15.78	99.00
No. 200	6.96	1.03	4.90 - 9.02	98.00	3.87 - 10.05	98.00
HMA Mixture Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
3/4"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1/2"	97.77	0.79	96.19 - 99.35	97.00	95.40 - 100.00	100.00
3/8"	87.51	2.17	83.17 - 91.85	96.00	81.00 - 94.02	100.00
No. 4	62.00	3.12	55.76 - 68.24	94.00	52.64 - 71.36	100.00
No. 10	35.09	3.06	28.97 - 41.21	97.00	25.91 - 44.27	100.00
No. 40	19.24	1.51	16.22 - 22.26	99.00	14.71 - 23.77	99.00
No. 80	11.00	1.12	8.76 - 13.24	98.00	7.64 - 14.36	100.00
No. 200	6.02	0.73	4.56 - 7.48	98.00	3.83 - 8.21	100.00
% Asphalt Content						
Extraction	4.59	0.23	4.13 - 5.05	96.00	3.90 - 5.28	100.00
Nuclear Gauge	4.65	0.20	4.25 - 5.05	96.88	4.05 - 5.25	97.92
Rice's SG	2.525	0.012	2.50 - 2.55	96.00	2.49 - 2.56	99.00
Lab Molded SG	2.382	0.022	2.34 - 2.43	99.00	2.32 - 2.45	100.00
% Air Voids	5.64	1.12	3.40 - 7.88	97.00	2.28 - 9.00	100.00
% Hveem Stability	53.01	8.81	35.39 - 70.63	98.00	26.58 - 79.44	98.00
% Roadway Density						
Core Method	86.18	2.35	81.48 - 90.88	98.00	79.13 - 93.23	99.00
Nuclear Gauge	86.93	2.15	82.63 - 91.23	93.00	80.48 - 93.38	100.00

Table B-1 (continued). Natural Process Tolerances, Project No. 3 (US-62)

Quality Characteristic	$\bar{X}$	S	$\bar{X} \pm 2S$ Limits	$\bar{X} \pm 2S$ Percent	$\bar{X} \pm 3S$ Limits	$\bar{X} \pm 3S$ Percent
Cold Feed Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
3/4"	99.96	0.27	99.42 - 100.00	96.74	99.15 - 100.00	97.83
1/2"	87.30	3.73	79.84 - 94.76	96.74	76.11 - 98.49	98.91
3/8"	73.45	5.02	63.41 - 83.49	95.65	58.39 - 88.51	97.83
No. 4	55.25	5.22	44.81 - 65.69	96.74	39.59 - 70.91	98.91
No. 10	36.82	4.92	26.98 - 46.66	95.65	22.06 - 51.58	98.91
No. 40	19.53	2.93	13.67 - 25.39	95.65	10.74 - 28.32	98.91
No. 80	9.63	1.36	6.91 - 12.35	95.65	5.55 - 13.71	98.91
No. 200	5.27	0.72	3.83 - 6.71	95.65	3.11 - 7.43	98.91
HMA Mixture Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
3/4"	99.98	0.18	99.62 - 100.00	98.86	99.44 - 100.00	98.86
1/2"	88.46	2.32	83.82 - 93.10	95.45	81.50 - 95.42	100.00
3/8"	75.59	2.67	70.25 - 80.93	94.32	67.58 - 83.60	100.00
No. 4	56.62	2.49	51.64 - 61.60	96.59	49.15 - 64.09	100.00
No. 10	37.16	2.46	32.24 - 42.08	95.45	29.78 - 44.54	97.73
No. 40	19.62	0.82	17.98 - 21.26	93.18	17.16 - 22.08	98.86
No. 80	9.80	0.53	8.74 - 10.86	95.45	8.21 - 11.39	100.00
No. 200	5.37	0.30	4.77 - 5.97	96.59	4.47 - 6.27	98.86
% Asphalt Content						
Extraction	5.05	0.22	4.13 - 5.05	94.05	4.39 - 5.71	100.00
Nuclear Gauge	4.93	0.21	4.25 - 5.05	92.39	4.30 - 5.56	98.91
Rice's SG	2.463	0.011	4.44 - 2.48	94.32	2.43 - 2.50	100.00
Lab Molded SG	2.375	0.010	2.35 - 2.40	98.86	2.34 - 2.41	98.86
% Air Voids	3.55	0.68	3.40 - 7.88	96.59	1.51 - 5.59	100.00
% Hveem Stability	50.98	11.15	35.39 - 70.63	95.31	17.53 - 84.43	96.88
% Roadway Density						
Core Method	90.56	1.85	81.48 - 90.88	95.00	85.01 - 96.11	100.00
Nuclear Gauge	90.45	1.75	82.63 - 91.23	98.00	85.20 - 95.70	100.00

Table B-1 (continued). Natural Process Tolerances, Project No. 4 (US-69)

Quality Characteristic	$\overline{X}$	S	$\overline{X} \pm 2S$ Limits	$\overline{X} \pm 2S$ Percent	$\overline{X} \pm 3S$ Limits	$\overline{X} \pm 3S$ Percent
Cold Feed Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	98.54	0.66	97.22 - 99.86	98.00	96.56 - 100.00	100.00
3/4"	87.28	2.05	83.18 - 91.38	97.00	81.13 - 93.43	100.00
1/2"	73.50	3.05	67.40 - 79.60	95.00	64.35 - 82.65	100.00
3/8"	63.81	3.71	56.39 - 71.23	95.00	52.68 - 74.94	100.00
No. 4	50.41	3.81	42.79 - 58.03	94.00	38.98 - 61.84	99.00
No. 10	38.71	3.42	31.87 - 45.55	95.00	28.45 - 48.97	99.00
No. 40	16.49	5.17	6.15 - 26.83	99.00	0.98 - 32.00	99.00
No. 80	6.97	1.00	4.97 - 8.97	94.00	3.97 - 9.97	97.00
No. 200	4.14	0.82	2.50 - 5.78	95.00	1.68 - 6.60	97.00
HMA Mixture Analysis						
% Passing Sieve						
1 1/2"	100.00	0.00	100.00 - 100.00	100.00	100.00 - 100.00	100.00
1"	98.62	1.48	95.66 - 100.00	95.65	94.18 - 100.00	100.00
3/4"	88.33	3.74	80.85 - 95.81	96.67	77.11 - 99.55	100.00
1/2"	76.95	3.81	69.33 - 84.57	96.74	65.52 - 88.38	100.00
3/8"	67.38	3.95	59.48 - 75.28	93.33	55.53 - 79.23	100.00
No. 4	54.04	3.33	47.38 - 60.70	94.57	44.05 - 64.03	98.91
No. 10	41.62	2.63	36.36 - 46.88	94.57	33.73 - 49.51	100.00
No. 40	17.05	1.59	13.87 - 20.23	97.83	12.28 - 21.82	98.91
No. 80	7.57	1.16	5.25 - 9.89	95.65	4.09 - 11.05	97.83
No. 200	4.43	0.64	3.15 - 5.71	95.65	2.51 - 6.35	96.74
% Asphalt Content						
Extraction	4.47	0.27	3.93 - 5.01	96.74	3.66 - 5.28	100.00
Nuclear Gauge	4.53	0.18	4.17 - 4.89	94.00	3.99 - 5.07	100.00
Rice's SG	2.363	0.014	2.34 - 2.39	94.32	2.32 - 2.41	97.73
Lab Molded SG	2.208	0.013	2.18 - 2.23	96.00	2.17 - 2.25	99.00
% Air Voids	6.54	0.86	4.82 - 8.26	93.18	3.96 - 9.12	98.86
% Hveem Stability	58.13	18.38	21.37 - 94.89	84.62	2.99 - 100.00	100.00
% Roadway Density						
Core Method	90.51	1.42	87.67 - 93.35	95.24	86.25 - 94.77	100.00
Nuclear Gauge	90.57	0.48	89.61 - 91.53	92.00	89.13 - 92.01	100.00

Table B-2. Process Capability with respect to JMF Tolerances

Quality Characteristic	JMF			Cold Feed Analysis			HMA Mixture Analysis		
	Tolerances	LSL	USL	C_P	C_{PK}	C_{PM}	C_P	C_{PK}	C_{PM}
Project No. 1, US-412									
% Passing Sieve									
1 1/2"	100.0 ± 0.0	100.0	100.0	VL	VL	VL	VL	VL	VL
1"	98.0 ± 7.0	91.0	100.0	1.27	0.62	1.26	0.89	0.31	0.86
3/4"	87.0 ± 7.0	80.0	94.0	0.84	0.83	0.84	0.60	0.38	0.50
1/2"	70.0 ± 7.0	63.0	77.0	0.54	0.36	0.48	0.52	0.42	0.50
No. 4	34.0 ± 7.0	27.0	41.0	0.67	0.67	0.67	0.71	0.33	0.47
No. 10	25.0 ± 4.0	21.0	29.0	0.48	0.30	0.42	0.63	0.60	0.63
No. 40	16.0 ± 4.0	12.0	20.0	0.73	0.50	0.60	1.00	0.81	0.87
No. 80	8.0 ± 4.0	4.0	12.0	1.54	1.08	0.90	1.75	1.61	1.61
No. 200	4.0 ± 2.0	2.0	6.0	0.88	0.44	0.53	1.13	0.98	1.04
% Asphalt Content									
Extraction	4.1 ± 0.4	3.7	4.5				0.44	0.06	0.29
Nuclear Gauge	4.1 ± 0.4	3.7	4.5				0.38	0.05	0.27
% Air Voids	5.0 ± 1.0	4.0	6.0				0.20	0.14	0.20
% Hveem Stability	40 Min.	40.0	100.0				1.86	0.67	NA
% Roadway Density									
Core Method	94.0 ± 2.0	92.0	96.0				0.64	0.61	0.63
Nuclear Gauge	94.0 ± 2.0	92.0	96.0				0.30	0.00	0.16
Project No. 2, US-70									
% Passing Sieve									
1 1/2"	100.0 ± 0.0	100.0	100.0	VL	VL	VL	VL	VL	VL
1"	100.0 ± 0.0	100.0	100.0	VL	VL	VL	VL	VL	VL
3/4"	100.0 ± 0.0	100.0	100.0	0.00	0.00	0.00	VL	VL	VL
1/2"	99.0 ± 7.0	92.0	100.0	1.20	0.93	0.56	1.69	0.94	0.91
3/8"	86.0 ± 7.0	79.0	93.0	0.62	0.39	0.51	1.08	0.84	0.88
No. 4	63.0 ± 7.0	56.0	70.0	0.48	0.22	0.38	0.75	0.64	0.71
No. 10	37.0 ± 4.0	33.0	41.0	0.30	0.19	0.29	0.44	0.23	0.37
No. 40	22.0 ± 4.0	18.0	26.0	0.57	0.24	0.41	0.89	0.27	0.42
No. 80	10.0 ± 4.0	6.0	14.0	0.99	0.56	0.60	1.19	0.90	0.89
No. 200	4.8 ± 2.0	2.8	6.8	0.65	0.00	0.28	0.92	0.36	0.47
% Asphalt Content									
Extraction	4.7 ± 0.4	4.3	5.1				0.58	0.41	0.52
Nuclear Gauge	4.7 ± 0.4	4.3	5.1				0.68	0.60	0.66
% Air Voids	4.0 ± 1.0	3.0	5.0				0.30	0.00	0.17
% Hveem Stability	40 Min.	40.0	100.0				1.14	0.49	NA
% Roadway Density									
Core Method	94.0 ± 2.0	92.0	96.0				0.28	0.00	0.08
Nuclear Gauge	94.0 ± 2.0	92.0	96.0				0.31	0.00	0.09

VL: Very large value -- standard deviation = 0

NA: Not applicable -- no specified target

Table B-2 (continued). Process Capability with respect to JMF Tolerances

Quality Characteristic	JMF			Cold Feed Analysis			HMA Mixture Analysis		
	Tolerances	LSL	USL	C_P	C_{PK}	C_{PM}	C_P	C_{PK}	C_{PM}
Project No. 3, US-62									
% Passing Sieve									
1 1/2"	100.0 ± 0.0	100.0	100.0	VL	VL	VL	VL	VL	VL
1"	100.0 ± 0.0	100.0	100.0	VL	VL	VL	VL	VL	VL
3/4"	100.0 ± 0.0	100.0	100.0	0.00	0.00	0.00	0.00	0.00	0.00
1/2"	89.0 ± 7.0	82.0	96.0	0.63	0.47	0.57	1.01	0.93	0.98
3/8"	71.0 ± 7.0	64.0	78.0	0.46	0.30	0.42	0.87	0.30	0.44
No. 4	54.0 ± 7.0	47.0	61.0	0.45	0.37	0.43	0.94	0.59	0.64
No. 10	35.0 ± 4.0	31.0	39.0	0.27	0.15	0.25	0.54	0.25	0.41
No. 40	18.0 ± 4.0	14.0	22.0	0.45	0.28	0.40	1.62	0.96	0.73
No. 80	8.0 ± 4.0	4.0	12.0	0.98	0.58	0.62	2.50	1.38	0.71
No. 200	4.3 ± 2.0	2.3	6.3	0.93	0.48	0.55	2.26	1.05	0.60
% Asphalt Content									
Extraction	4.7 ± 0.4	4.3	5.1				0.61	0.08	0.32
Nuclear Gauge	4.7 ± 0.4	4.3	5.1				0.62	0.26	0.42
% Air Voids	5.0 ± 1.0	4.0	6.0				0.49	0.00	0.21
% Hveem Stability	40 Min.	40.0	100.0				0.90	0.33	NA
% Roadway Density									
Core Method	94.0 ± 2.0	92.0	96.0				0.36	0.00	0.17
Nuclear Gauge	94.0 ± 2.0	92.0	96.0				0.38	0.00	0.17
Project No. 4, US-69									
% Passing Sieve									
1 1/2"	100.0 ± 0.0	100.0	100.0	VL	VL	VL	VL	VL	VL
1"	98.0 ± 7.0	91.0	100.0	2.27	0.73	1.75	1.01	0.31	0.93
1/2"	72.0 ± 7.0	65.0	79.0	0.77	0.60	0.69	0.61	0.18	0.37
No. 4	52.0 ± 7.0	45.0	59.0	0.61	0.47	0.56	0.70	0.50	0.60
No. 10	38.0 ± 4.0	34.0	42.0	0.39	0.32	0.38	0.51	0.05	0.30
No. 40	14.0 ± 4.0	10.0	18.0	0.26	0.10	0.23	0.84	0.20	0.39
No. 80	7.0 ± 4.0	3.0	11.0	1.34	1.33	1.34	1.15	0.99	1.03
No. 200	3.8 ± 2.0	1.8	5.8	0.81	0.68	0.75	1.04	0.71	0.74
% Asphalt Content									
Extraction	4.7 ± 0.4	4.4	5.2				0.49	0.08	0.31
Nuclear Gauge	4.7 ± 0.4	4.4	5.2				0.73	0.23	0.40
% Air Voids	4.0 ± 1.0	4.0	6.0				0.39	0.00	0.19
% Hveem Stability	40 Min.	40.0	100.0				0.54	0.33	NA
% Roadway Density									
Core Method		92.0	98.0				0.71	0.00	0.26
Nuclear Gauge		92.0	98.0				2.10	0.00	0.29

VL: Very large value -- standard deviation = 0

NA: Not applicable -- no specified target

Table B-3. Process Capability with respect to Existing QA Specifications Tolerances

Quality Characteristic	Existing QA Specification			Cold Feed Analysis			HMA Mixture Analysis		
	Tolerances	LSL	USL	C_P	C_{PK}	C_{PM}	C_P	C_{PK}	C_{PM}
Project No. 1, US-412									
% Passing Sieve									
1 1/2"	100.0 ± 8.0	92.0	100.0	VL	VL	VL	VL	VL	VL
1"	98.0 ± 8.0	90.0	100.0	1.42	0.62	1.40	0.99	0.31	0.95
3/4"	87.0 ± 8.0	79.0	95.0	0.97	0.95	0.96	0.68	0.47	0.57
1/2"	70.0 ± 8.0	62.0	78.0	0.61	0.44	0.54	0.59	0.49	0.57
No. 4	34.0 ± 8.0	26.0	42.0	0.77	0.76	0.77	0.81	0.43	0.54
No. 10	25.0 ± 6.5	18.5	31.5	0.78	0.60	0.69	1.02	0.99	1.02
No. 40	16.0 ± 6.5	9.5	22.5	1.19	0.96	0.97	1.63	1.44	1.41
No. 80	8.0 ± 6.5	1.5	14.5	2.50	2.04	1.47	2.85	2.71	2.62
No. 200	4.0 ± 3.0	1.0	7.0	1.33	0.88	0.79	1.69	1.55	1.55
% Asphalt Content									
Extraction	4.1 ± 0.7	3.4	4.8				0.77	0.39	0.51
Nuclear Gauge	4.1 ± 0.7	3.4	4.8				0.67	0.33	0.47
% Air Voids	5.0 ± 2.5	2.5	7.5				0.50	0.44	0.49
% Hveem Stability		38.0	100.0				1.92	0.80	NA
% Roadway Density									
Core Method		92.0	98.0				0.96	0.67	0.95
Nuclear Gauge		92.0	98.0				0.45	0.00	0.23
Project No. 2, US-70									
% Passing Sieve									
1 1/2"	100.0 ± 8.0	92.0	100.0	VL	VL	VL	VL	VL	VL
1"	100.0 ± 8.0	92.0	100.0	VL	VL	VL	VL	VL	VL
3/4"	100.0 ± 8.0	92.0	100.0	5.41	0.07	5.29	VL	VL	VL
1/2"	99.0 ± 8.0	91.0	100.0	1.35	0.93	0.63	1.90	0.94	1.02
3/8"	86.0 ± 8.0	78.0	94.0	0.71	0.48	0.59	1.23	1.00	1.01
No. 4	63.0 ± 8.0	55.0	71.0	0.55	0.29	0.44	0.85	0.75	0.81
No. 10	37.0 ± 6.5	30.5	43.5	0.49	0.38	0.46	0.71	0.50	0.60
No. 40	22.0 ± 6.5	15.5	28.5	0.93	0.60	0.66	1.44	0.83	0.69
No. 80	10.0 ± 6.5	3.5	16.5	1.60	1.18	0.98	1.94	1.64	1.44
No. 200	4.8 ± 3.0	1.8	7.8	0.97	0.27	0.42	1.38	0.82	0.70
% Asphalt Content									
Extraction	4.7 ± 0.7	4.0	5.4				1.01	0.85	0.91
Nuclear Gauge	4.7 ± 0.7	4.0	5.4				1.20	1.11	1.16
% Air Voids	4.0 ± 2.5	1.5	6.5				0.74	0.26	0.42
% Hveem Stability		38.0	100.0				1.17	0.57	NA
% Roadway Density									
Core Method		92.0	98.0				0.43	0.00	0.12
Nuclear Gauge		92.0	98.0				0.47	0.00	0.13

VL: Very large value -- standard deviation = 0

NA: Not applicable -- no specified target

Table B-3 (continued). Process Capability with respect to Existing QA Specifications Tolerances

Quality Characteristic	Existing QA Specification			Cold Feed Analysis			HMA Mixture Analysis		
	Tolerances	LSL	USL	C_P	C_{PK}	C_{PM}	C_P	C_{PK}	C_{PM}
Project No. 3, US-62									
% Passing Sieve									
1 1/2"	100.0 ± 8.0	92.0	100.0	VL	VL	VL	VL	VL	VL
1"	100.0 ± 8.0	92.0	100.0	VL	VL	VL	VL	VL	VL
3/4"	100.0 ± 8.0	92.0	100.0	4.99	0.05	4.93	7.31	0.04	7.27
1/2"	89.0 ± 8.0	81.0	97.0	0.71	0.56	0.65	1.15	1.07	1.12
3/8"	71.0 ± 8.0	63.0	79.0	0.53	0.37	0.48	1.00	0.43	0.50
No. 4	54.0 ± 8.0	46.0	62.0	0.51	0.43	0.50	1.07	0.72	0.74
No. 10	35.0 ± 6.5	28.5	41.5	0.44	0.32	0.41	0.88	0.59	0.66
No. 40	18.0 ± 6.5	11.5	24.5	0.74	0.56	0.65	2.64	1.98	1.19
No. 80	8.0 ± 6.5	1.5	14.5	1.59	1.19	1.01	4.06	2.94	1.15
No. 200	4.3 ± 3.0	1.3	7.3	1.39	0.95	0.83	3.39	2.18	0.90
% Asphalt Content									
Extraction	4.7 ± 0.7	4.0	5.4				1.07	0.54	0.57
Nuclear Gauge	4.7 ± 0.7	4.0	5.4				1.09	0.73	0.74
% Air Voids	5.0 ± 2.5	2.5	7.5				1.23	0.52	0.52
% Hveem Stability		38.0	100.0				0.93	0.39	NA
% Roadway Density									
Core Method		92.0	98.0				0.54	0.00	0.25
Nuclear Gauge		92.0	98.0				0.57	0.00	0.25
Project No. 4, US-69									
% Passing Sieve									
1 1/2"	100.0 ± 8.0	92.0	100.0	VL	VL	VL	VL	VL	VL
1"	98.0 ± 8.0	90.0	100.0	2.52	0.73	1.94	1.13	0.31	1.04
1/2"	72.0 ± 8.0	64.0	80.0	0.88	0.71	0.79	0.70	0.27	0.43
No. 4	52.0 ± 8.0	44.0	60.0	0.70	0.56	0.64	0.80	0.60	0.68
No. 10	38.0 ± 6.5	31.5	44.5	0.63	0.56	0.62	0.82	0.36	0.48
No. 40	14.0 ± 6.5	7.5	20.5	0.42	0.26	0.38	1.37	0.73	0.63
No. 80	7.0 ± 6.5	0.5	13.5	2.18	2.17	2.17	1.87	1.71	1.68
No. 200	3.8 ± 3.0	0.8	6.8	1.22	1.08	1.13	1.56	1.23	1.11
% Asphalt Content									
Extraction	4.8 ± 0.7	4.1	5.5				0.85	0.45	0.54
Nuclear Gauge	4.8 ± 0.7	4.1	5.5				1.27	0.77	0.70
% Air Voids	5.0 ± 2.5	2.5	7.5				0.97	0.37	0.47
% Hveem Stability		38.0	100.0				0.56	0.37	NA
% Roadway Density									
Core Method		92.0	98.0				0.71	0.00	0.26
Nuclear Gauge		92.0	98.0				2.10	0.00	0.29

VL: Very large value -- standard deviation = 0

NA: Not applicable -- no specified target

Table B-4. Process Capability with respect to Proposed QA Specification Tolerances

Quality Characteristic	Proposed QA Specification			Cold Feed Analysis			HMA Mixture Analysis		
	Tolerances	LSL	USL	C_P	C_{PK}	C_{PM}	C_P	C_{PK}	C_{PM}
Project No. 1, US-412									
% Passing Sieve									
1 1/2"	100.0 ± 6.0	94.0	100.0	VL	VL	VL	VL	VL	VL
1"	98.0 ± 6.0	92.0	100.0	1.13	0.62	1.12	0.79	0.31	0.76
3/4"	87.0 ± 6.0	81.0	93.0	0.72	0.71	0.72	0.51	0.29	0.43
1/2"	70.0 ± 6.0	64.0	76.0	0.46	0.29	0.41	0.45	0.34	0.43
No. 4	34.0 ± 6.0	28.0	40.0	0.57	0.57	0.57	0.61	0.23	0.40
No. 10	25.0 ± 4.5	20.5	29.5	0.54	0.36	0.48	0.71	0.68	0.70
No. 40	16.0 ± 4.5	11.5	20.5	0.82	0.59	0.67	1.13	0.94	0.98
No. 80	8.0 ± 4.5	3.5	12.5	1.73	1.27	1.02	1.97	1.83	1.81
No. 200	4.0 ± 2.0	2.0	6.0	0.88	0.44	0.53	1.13	0.98	1.04
% Asphalt Content									
Extraction	4.1 ± 0.5	3.6	4.6				0.55	0.17	0.36
Nuclear Gauge	4.1 ± 0.5	3.6	4.6				0.48	0.14	0.34
% Air Voids	5.0 ± 1.5	3.5	6.5				0.30	0.24	0.29
% Roadway Density									
Core Method		92.0	98.0				0.96	0.67	0.95
Nuclear Gauge		92.0	98.0				0.45	0.00	0.23
Project No. 2, US-70									
% Passing Sieve									
1 1/2"	100.0 ± 6.0	94.0	100.0	VL	VL	VL	VL	VL	VL
1"	100.0 ± 6.0	94.0	100.0	VL	VL	VL	VL	VL	VL
3/4"	100.0 ± 6.0	94.0	100.0	4.06	0.07	3.96	VL	VL	VL
1/2"	99.0 ± 6.0	93.0	100.0	1.05	0.93	0.49	1.47	0.94	0.80
3/8"	86.0 ± 6.0	80.0	92.0	0.53	0.30	0.44	0.92	0.69	0.76
No. 4	63.0 ± 6.0	57.0	69.0	0.42	0.16	0.33	0.64	0.53	0.61
No. 10	37.0 ± 4.5	32.5	41.5	0.34	0.23	0.32	0.49	0.28	0.41
No. 40	22.0 ± 4.5	17.5	26.5	0.64	0.31	0.46	1.00	0.38	0.48
No. 80	10.0 ± 4.5	5.5	14.5	1.11	0.68	0.68	1.34	1.05	1.00
No. 200	4.8 ± 2.0	2.8	6.8	0.65	0.00	0.28	0.92	0.36	0.47
% Asphalt Content									
Extraction	4.7 ± 0.5	4.2	5.2				0.72	0.56	0.65
Nuclear Gauge	4.7 ± 0.5	4.2	5.2				0.85	0.77	0.83
% Air Voids	4.0 ± 1.5	2.5	5.5				0.45	0.00	0.25
% Roadway Density									
Core Method		92.0	98.0				0.43	0.00	0.12
Nuclear Gauge		92.0	98.0				0.47	0.00	0.13

VL: Very large value -- standard deviation = 0

Table B-4 (continued). Process Capability with respect to Proposed QA Specification Tolerances

Quality Characteristic	Proposed QA Specification			Cold Feed Analysis			HMA Mixture Analysis		
	Tolerances	LSL	USL	C_P	C_{PK}	C_{PM}	C_P	C_{PK}	C_{PM}
Project No. 3, US-62									
% Passing Sieve									
1 1/2"	100.0 ± 6.0	94.0	100.0	VL	VL	VL	VL	VL	VL
1"	100.0 ± 6.0	94.0	100.0	VL	VL	VL	VL	VL	VL
3/4"	100.0 ± 6.0	94.0	100.0	3.74	0.05	3.69	5.48	0.04	5.45
1/2"	89.0 ± 6.0	83.0	95.0	0.54	0.38	0.49	0.86	0.79	0.84
3/8"	71.0 ± 6.0	65.0	77.0	0.40	0.24	0.36	0.75	0.18	0.37
No. 4	54.0 ± 6.0	48.0	60.0	0.38	0.30	0.37	0.80	0.45	0.55
No. 10	35.0 ± 4.5	30.5	39.5	0.31	0.18	0.29	0.61	0.32	0.46
No. 40	18.0 ± 4.5	13.5	22.5	0.51	0.34	0.45	1.83	1.17	0.82
No. 80	8.0 ± 4.5	3.5	12.5	1.10	0.70	0.70	2.81	1.69	0.80
No. 200	4.3 ± 2.0	2.3	6.3	0.93	0.48	0.55	2.26	1.05	0.60
% Asphalt Content									
Extraction	4.7 ± 0.5	4.2	5.2				0.76	0.23	0.40
Nuclear Gauge	4.7 ± 0.5	4.2	5.2				0.78	0.42	0.53
% Air Voids	5.0 ± 1.5	3.5	6.5				0.74	0.03	0.31
% Roadway Density									
Core Method		92.0	98.0				0.54	0.00	0.25
Nuclear Gauge		92.0	98.0				0.57	0.00	0.25
Project No. 4, US-69									
% Passing Sieve									
1 1/2"	100.0 ± 6.0	94.0	100.0	VL	VL	VL	VL	VL	VL
1"	98.0 ± 6.0	92.0	100.0	2.02	0.73	1.55	0.90	0.31	0.83
1/2"	72.0 ± 6.0	66.0	78.0	0.66	0.49	0.59	0.52	0.09	0.32
No. 4	52.0 ± 6.0	46.0	58.0	0.52	0.39	0.48	0.60	0.40	0.51
No. 10	38.0 ± 4.5	33.5	42.5	0.44	0.37	0.43	0.57	0.11	0.33
No. 40	14.0 ± 4.5	9.5	18.5	0.29	0.13	0.26	0.95	0.31	0.43
No. 80	7.0 ± 4.5	2.5	11.5	1.51	1.50	1.51	1.30	1.13	1.16
No. 200	3.8 ± 2.0	1.8	5.8	0.81	0.68	0.75	1.04	0.71	0.74
% Asphalt Content									
Extraction	4.8 ± 0.5	4.3	5.3				0.61	0.20	0.38
Nuclear Gauge	4.8 ± 0.5	4.3	5.3				0.91	0.41	0.50
% Air Voids	5.0 ± 1.5	3.5	6.5				0.58	0.00	0.28
% Roadway Density									
Core Method		92.0	98.0				0.71	0.00	0.26
Nuclear Gauge		92.0	98.0				2.10	0.00	0.29

VL: Very large value -- standard deviation = 0

Table B-5. Percent within JMF Tolerances

Quality Characteristic	JMF			% within JMF Tolerances	
	Tolerances	LSL	USL	Cold Feed Analysis	HMA Mixture Analysis
Project No. 1, US-412					
% Passing Sieve					
1 1/2"	100.0 ± 0.0	100.0	100.0	100.00	100.00
1"	98.0 ± 7.0	91.0	100.0	100.00	100.00
3/4"	87.0 ± 7.0	80.0	94.0	98.91	82.61
1/2"	70.0 ± 7.0	63.0	77.0	82.61	84.78
No. 4	34.0 ± 7.0	27.0	41.0	96.74	85.87
No. 10	25.0 ± 4.0	21.0	29.0	79.35	94.57
No. 40	16.0 ± 4.0	12.0	20.0	97.83	100.00
No. 80	8.0 ± 4.0	4.0	12.0	100.00	100.00
No. 200	4.0 ± 2.0	2.0	6.0	89.13	100.00
% Asphalt Content					
Extraction	4.1 ± 0.4	3.7	4.5		60.87
Nuclear Gauge	4.1 ± 0.4	3.7	4.5		51.14
% Air Voids	5.0 ± 1.0	4.0	6.0		76.14
% Hveem Stability	40 Minimum	40.0	100.0		97.06
% Roadway Density					
Core Method	94.0 ± 2.0	92.0	96.0		92.00
Nuclear Gauge	94.0 ± 2.0	92.0	96.0		25.00
Project No. 2, US-70					
% Passing Sieve					
1 1/2"	100.0 ± 0.0	100.0	100.0	100.00	100.00
1"	100.0 ± 0.0	100.0	100.0	100.00	100.00
3/4"	100.0 ± 0.0	100.0	100.0	94.00	100.00
1/2"	99.0 ± 7.0	92.0	100.0	100.00	100.00
3/8"	86.0 ± 7.0	79.0	93.0	87.00	100.00
No. 4	63.0 ± 7.0	56.0	70.0	78.00	96.00
No. 10	37.0 ± 4.0	33.0	41.0	66.00	67.00
No. 40	22.0 ± 4.0	18.0	26.0	80.00	75.00
No. 80	10.0 ± 4.0	6.0	14.0	97.00	100.00
No. 200	4.8 ± 2.0	2.8	6.8	44.00	86.00
% Asphalt Content					
Extraction	4.7 ± 0.4	4.3	5.1		89.00
Nuclear Gauge	4.7 ± 0.4	4.3	5.1		95.83
% Air Voids	4.0 ± 1.0	3.0	5.0		26.00
% Hveem Stability	40 Minimum	40.0	100.0		100.00
% Roadway Density					
Core Method	94.0 ± 2.0	92.0	96.0		0.00
Nuclear Gauge	94.0 ± 2.0	92.0	96.0		0.00

Table B-5 (continued). Percent within JMF Tolerances

Quality Characteristic	JMF			% within JMF Tolerances	
	Tolerances	LSL	USL	Cold Feed Analysis	HMA Mixture Analysis
		Project No. 3, US-62			
% Passing Sieve					
1 1/2"	100.0 ± 0.0	100.0	100.0	100.00	100.00
1"	100.0 ± 0.0	100.0	100.0	100.00	100.00
3/4"	100.0 ± 0.0	100.0	100.0	96.74	98.86
1/2"	89.0 ± 7.0	82.0	96.0	95.65	100.00
3/8"	71.0 ± 7.0	64.0	78.0	79.35	81.82
No. 4	54.0 ± 7.0	47.0	61.0	81.52	98.86
No. 10	35.0 ± 4.0	31.0	39.0	59.78	79.55
No. 40	18.0 ± 4.0	14.0	22.0	75.00	100.00
No. 80	8.0 ± 4.0	4.0	12.0	97.83	100.00
No. 200	4.3 ± 2.0	2.3	6.3	93.48	100.00
% Asphalt Content					
Extraction	4.7 ± 0.4	4.3	5.1		64.29
Nuclear Gauge	4.7 ± 0.4	4.3	5.1		82.61
% Air Voids	5.0 ± 1.0	4.0	6.0		29.55
% Hveem Stability	40 Minimum	40.0	100.0		95.31
% Roadway Density					
Core Method	94.0 ± 2.0	92.0	96.0		25.00
Nuclear Gauge	94.0 ± 2.0	92.0	96.0		27.00
		Project No. 4, US-69			
% Passing Sieve					
1 1/2"	100.0 ± 0.0	100.0	100.0	100.00	100.00
1"	98.0 ± 7.0	91.0	100.0	100.00	100.00
1/2"	72.0 ± 7.0	65.0	79.0	93.00	72.83
No. 4	52.0 ± 7.0	45.0	59.0	91.00	94.57
No. 10	38.0 ± 4.0	34.0	42.0	82.00	56.52
No. 40	14.0 ± 4.0	10.0	18.0	87.00	78.26
No. 80	7.0 ± 4.0	3.0	11.0	99.00	97.83
No. 200	3.8 ± 2.0	1.8	5.8	95.00	95.65
% Asphalt Content					
Extraction	4.8 ± 0.4	4.4	5.2		66.30
Nuclear Gauge	4.8 ± 0.4	4.4	5.2		81.00
% Air Voids	5.0 ± 1.0	4.0	6.0		26.14
% Hveem Stability	40 Minimum	40.0	100.0		100.00
% Roadway Density					
Core Method	94.0 (–2), (+4)	92.0	98.0		14.29
Nuclear Gauge	94.0 (–2), (+4)	92.0	98.0		00.00

Table B-6. Percent within Existing QA Specification Tolerances

Quality Characteristic	Existing QA Specification			% within QA Spec. Tolerances	
	Tolerances	LSL	USL	Cold Feed Analysis	HMA Mixture Analysis
			Project No. 1, US-412		
% Passing Sieve					
1 1/2"	100.0 ± 8.0	92.0	100.0	100.00	100.00
1"	98.0 ± 8.0	90.0	100.0	100.00	100.00
3/4"	87.0 ± 8.0	79.0	95.0	100.00	94.57
1/2"	70.0 ± 8.0	62.0	78.0	89.13	88.04
No. 4	34.0 ± 8.0	26.0	42.0	96.74	95.65
No. 10	25.0 ± 6.5	18.5	31.5	97.83	100.00
No. 40	16.0 ± 6.5	9.5	22.5	98.91	100.00
No. 80	8.0 ± 6.5	1.5	14.5	100.00	100.00
No. 200	4.0 ± 3.0	1.0	7.0	98.91	100.00
% Asphalt Content					
Extraction	4.1 ± 0.7	3.4	4.8		89.13
Nuclear Gauge	4.1 ± 0.7	3.4	4.8		81.82
% Air Voids	5.0 ± 2.5	2.5	7.5		93.18
% Hveem Stability	38 Minimum	38.0	100.0		98.53
% Roadway Density					
Core Method	94.0 (–2), (+4)	92.0	98.0		94.00
Nuclear Gauge	94.0 (–2), (+4)	92.0	98.0		25.00
			Project No. 2, US-70		
% Passing Sieve					
1 1/2"	100.0 ± 8.0	92.0	100.0	100.00	100.00
1"	100.0 ± 8.0	92.0	100.0	100.00	100.00
3/4"	100.0 ± 8.0	92.0	100.0	100.00	100.00
1/2"	99.0 ± 8.0	91.0	100.0	100.00	100.00
3/8"	86.0 ± 8.0	78.0	94.0	92.00	100.00
No. 4	63.0 ± 8.0	55.0	71.0	84.00	99.00
No. 10	37.0 ± 6.5	30.5	43.5	87.00	92.00
No. 40	22.0 ± 6.5	15.5	28.5	96.00	99.00
No. 80	10.0 ± 6.5	3.5	16.5	100.00	100.00
No. 200	4.8 ± 3.0	1.8	7.8	78.00	100.00
% Asphalt Content					
Extraction	4.7 ± 0.7	4.0	5.4		100.00
Nuclear Gauge	4.7 ± 0.7	4.0	5.4		100.00
% Air Voids	4.0 ± 2.5	1.5	6.5		80.00
% Hveem Stability	38 Minimum	38.0	100.0		100.00
% Roadway Density					
Core Method	94.0 (–2) - (+4)	92.0	98.0		0.00
Nuclear Gauge	94.0 (–2) - (+4)	92.0	98.0		0.00

Table B-6 (continued). Percent within Existing QA Specification Tolerances

Quality Characteristic	Existing QA Specification			% within QA Spec. Tolerances	
	Tolerances	LSL	USL	Cold Feed Analysis	HMA Mixture Analysis
		Project No. 3, US-62			
% Passing Sieve					
1 1/2"	100.0 ± 8.0	92.0	100.0	100.00	100.00
1"	100.0 ± 8.0	92.0	100.0	100.00	100.00
3/4"	100.0 ± 8.0	92.0	100.0	100.00	100.00
1/2"	89.0 ± 8.0	81.0	97.0	96.74	100.00
3/8"	71.0 ± 8.0	63.0	79.0	85.87	89.77
No. 4	54.0 ± 8.0	46.0	62.0	85.87	100.00
No. 10	35.0 ± 6.5	28.5	41.5	80.43	95.45
No. 40	18.0 ± 6.5	11.5	24.5	94.57	100.00
No. 80	8.0 ± 6.5	1.5	14.5	100.00	100.00
No. 200	4.3 ± 3.0	1.3	7.3	98.91	100.00
% Asphalt Content					
Extraction	4.7 ± 0.7	4.0	5.4		94.05
Nuclear Gauge	4.7 ± 0.7	4.0	5.4		95.65
% Air Voids	5.0 ± 2.5	2.5	7.5		95.45
% Hveem Stability	38 Minimum	38.0	100.0		96.88
% Roadway Density					
Core Method	94.0 (–2) - (+4)	92.0	98.0		25.00
Nuclear Gauge	94.0 (–2) - (+4)	92.0	98.0		27.00
		Project No. 4, US-69			
% Passing Sieve					
1 1/2"	100.0 ± 8.0	92.0	100.0	100.00	100.00
1"	98.0 ± 8.0	90.0	100.0	100.00	100.00
1/2"	72.0 ± 8.0	64.0	80.0	96.00	81.52
No. 4	52.0 ± 8.0	44.0	60.0	95.00	94.57
No. 10	38.0 ± 6.5	31.5	44.5	93.00	88.04
No. 40	14.0 ± 6.5	7.5	20.5	95.00	98.91
No. 80	7.0 ± 6.5	0.5	13.5	100.00	98.91
No. 200	3.8 ± 3.0	0.8	6.8	97.00	100.00
% Asphalt Content					
Extraction	4.8 ± 0.7	4.1	5.5		84.78
Nuclear Gauge	4.8 ± 0.7	4.1	5.5		98.00
% Air Voids	5.0 ± 2.5	2.5	7.5		86.36
% Hveem Stability	38 Minimum	38.0	100.0		100.00
% Roadway Density					
Core Method	94.0 (–2) - (+4)	92.0	98.0		14.29
Nuclear Gauge	94.0 (–2) - (+4)	92.0	98.0		0.00

Table B-7. Percent within Proposed QA Specification Tolerances

Quality Characteristic	Proposed QA Specification			% within QA Spec. Tolerances	
	Tolerances	LSL	USL	Cold Feed Analysis	HMA Mixture Analysis
Project No. 1, US-412					
% Passing Sieve					
1 1/2"	100.0 ± 6.0	94.0	100.0	100.00	100.00
1"	98.0 ± 6.0	92.0	100.0	100.00	100.00
3/4"	87.0 ± 6.0	81.0	93.0	98.91	76.09
1/2"	70.0 ± 6.0	64.0	76.0	76.09	80.43
No. 4	34.0 ± 6.0	28.0	40.0	91.30	70.65
No. 10	25.0 ± 4.5	20.5	29.5	88.04	95.65
No. 40	16.0 ± 4.5	11.5	20.5	97.83	100.00
No. 80	8.0 ± 4.5	3.5	12.5	100.00	100.00
No. 200	4.0 ± 2.0	2.0	6.0	89.13	100.00
% Asphalt Content					
Extraction	4.1 ± 0.5	3.6	4.6		72.83
Nuclear Gauge	4.1 ± 0.5	3.6	4.6		60.23
% Air Voids	5.0 ± 1.5	3.5	6.5		84.09
% Roadway Density					
Core Method	94.0 (–2), (+4)	92.0	98.0		94.00
Nuclear Gauge	94.0 (–2), (+4)	92.0	98.0		25.00
Project No. 2, US-70					
% Passing Sieve					
1 1/2"	100.0 ± 6.0	94.0	100.0	100.00	100.00
1"	100.0 ± 6.0	94.0	100.0	100.00	100.00
3/4"	100.0 ± 6.0	94.0	100.0	100.00	100.00
1/2"	99.0 ± 6.0	93.0	100.0	100.00	100.00
3/8"	86.0 ± 6.0	80.0	92.0	84.00	98.00
No. 4	63.0 ± 6.0	57.0	69.0	69.00	92.00
No. 10	37.0 ± 4.5	32.5	41.5	73.00	75.00
No. 40	22.0 ± 4.5	17.5	26.5	84.00	87.00
No. 80	10.0 ± 4.5	5.5	14.5	99.00	100.00
No. 200	4.8 ± 2.0	2.8	6.8	44.00	86.00
% Asphalt Content					
Extraction	4.7 ± 0.5	4.2	5.2		98.00
Nuclear Gauge	4.7 ± 0.5	4.2	5.2		98.00
% Air Voids	4.0 ± 1.5	2.5	5.5		47.00
% Roadway Density					
Core Method	94.0 (–2) - (+4)	92.0	98.0		0.00
Nuclear Gauge	94.0 (–2) - (+4)	92.0	98.0		0.00

Table B-7 (continued). Percent within Proposed QA Specification Tolerances

Quality Characteristic	Proposed QA Specification			% within QA Spec. Tolerances	
	Tolerances	LSL	USL	Cold Feed Analysis	HMA Mixture Analysis
Project No. 3, US-62					
% Passing Sieve					
1 1/2"	100.0 ± 6.0	94.0	100.0	100.00	100.00
1"	100.0 ± 6.0	94.0	100.0	100.00	100.00
3/4"	100.0 ± 6.0	94.0	100.0	100.00	100.00
1/2"	89.0 ± 6.0	83.0	95.0	93.48	100.00
3/8"	71.0 ± 6.0	65.0	77.0	68.48	73.86
No. 4	54.0 ± 6.0	48.0	60.0	72.83	93.18
No. 10	35.0 ± 4.5	30.5	39.5	64.13	86.36
No. 40	18.0 ± 4.5	13.5	22.5	82.61	100.00
No. 80	8.0 ± 4.5	3.5	12.5	98.91	100.00
No. 200	4.3 ± 2.0	2.3	6.3	93.48	100.00
% Asphalt Content					
Extraction	4.7 ± 0.5	4.2	5.2		76.19
Nuclear Gauge	4.7 ± 0.5	4.2	5.2		90.22
% Air Voids	5.0 ± 1.5	3.5	6.5		47.73
% Roadway Density					
Core Method	94.0 (–2) - (+4)	92.0	98.0		25.00
Nuclear Gauge	94.0 (–2) - (+4)	92.0	98.0		27.00
Project No. 4, US-69					
% Passing Sieve					
1 1/2"	100.0 ± 6.0	94.0	100.0	100.00	100.00
1"	98.0 ± 6.0	92.0	100.0	100.00	100.00
1/2"	72.0 ± 6.0	66.0	78.0	89.00	63.04
No. 4	52.0 ± 6.0	46.0	58.0	87.00	92.39
No. 10	38.0 ± 4.5	33.5	42.5	83.00	70.65
No. 40	14.0 ± 4.5	9.5	18.5	89.00	86.96
No. 80	7.0 ± 4.5	2.5	11.5	100.00	98.91
No. 200	3.8 ± 2.0	1.8	5.8	95.00	95.65
% Asphalt Content					
Extraction	4.8 ± 0.5	4.3	5.3		72.83
Nuclear Gauge	4.8 ± 0.5	4.3	5.3		90.00
% Air Voids	5.0 ± 1.5	3.5	6.5		53.41
% Roadway Density					
Core Method	94.0 (–2) - (+4)	92.0	98.0		14.29
Nuclear Gauge	94.0 (–2) - (+4)	92.0	98.0		0.00

Table B-8. Conformity Indices

Quality Characteristic	Project 1	Project 2	Project 3	Project 4
Cold Feed Analysis				
% Passing Sieve				
1 1/2"	0.00	0.00	0.00	0.00
1"	1.19	0.00	0.00	0.85
3/4"	2.75	0.25	0.27	N/A
1/2"	4.88	2.35	4.08	3.38
3/8"	N/A	4.53	5.56	N/A
No. 4	3.46	6.09	5.34	4.11
No. 10	3.14	4.64	5.22	3.48
No. 40	2.22	3.27	3.29	5.71
No. 80	1.47	2.19	2.12	0.99
No. 200	1.26	2.39	1.20	0.88
HMA Mixture Analysis				
% Passing Sieve				
1 1/2"	0.00	0.00	0.00	0.00
1"	1.74	0.00	0.00	1.60
3/4"	4.64	0.00	0.18	N/A
1/2"	4.67	1.46	2.37	6.23
3/8"	N/A	2.63	5.30	N/A
No. 4	4.95	3.26	3.61	3.89
No. 10	2.12	3.60	3.27	4.47
No. 40	1.53	3.14	1.82	3.43
No. 80	0.82	1.49	1.87	1.28
No. 200	0.64	1.41	1.11	0.90
% Asphalt Content				
Extraction	0.46	0.26	0.41	0.43
Nuclear Gauge	0.49	0.20	0.31	0.33
% Air Voids	1.69	1.98	1.60	1.77
% Hveem Stability	N/A	N/A	N/A	N/A
% Roadway Density				
Core Method	1.05	8.16	3.88	3.77
Nuclear Gauge	4.27	7.39	3.96	3.46

Table B-9. Tolerances that Include Approximately 85% of Process Output

Quality Characteristic	JMF Target	Cold Feed Analysis		HMA Mixture Analysis	
		Tolerances	Percent	Tolerances	Percent
Project No. 1, US-412					
% Passing Sieve					
1 1/2"	100.0	± 0.0	100.00	± 0.0	100.00
1"	98.0	± 2.0	92.39	± 2.0	90.22
3/4"	87.0	± 4.0	84.78	± 7.0	82.61
1/2"	70.0	± 8.0	89.13	± 8.0	88.04
No. 4	34.0	± 5.0	82.61	± 7.0	85.87
No. 10	25.0	± 5.0	89.13	± 3.0	86.96
No. 40	16.0	± 3.0	88.04	± 2.0	81.52
No. 80	8.0	± 2.0	86.96	± 1.5	94.57
No. 200	4.0	± 2.0	89.13	± 1.0	86.96
% Asphalt Content					
Extraction	4.1			± 0.7	89.13
Nuclear Gauge	4.1			± 0.8	88.64
% Air Voids	5.0			± 2.0	89.77
% Hveem Stability	40 Min.			– 0.0	97.06
% Roadway Density					
Core Method	94.0			± 2.0	92.00
Nuclear Gauge	94.0			(–6) - (+2)	88.00
Project No. 2, US-70					
% Passing Sieve					
1 1/2"	100.0	± 0.0	100.00	± 0.0	100.00
1"	100.0	± 0.0	100.00	± 0.0	100.00
3/4"	100.0	± 0.0	100.00	± 0.0	100.00
1/2"	99.0	± 4.0	94.00	± 2.0	84.00
3/8"	86.0	± 6.0	84.00	± 4.0	87.00
No. 4	63.0	± 8.0	84.00	± 5.0	87.00
No. 10	37.0	± 6.0	85.00	± 5.0	82.00
No. 40	22.0	± 5.0	88.00	± 5.0	95.00
No. 80	10.0	± 3.0	85.00	± 3.0	95.00
No. 200	4.8	± 3.5	94.00	± 2.0	86.00
% Asphalt Content					
Extraction	4.7			± 0.4	89.00
Nuclear Gauge	4.7			± 0.3	87.50
% Air Voids	4.0			± 3.0	90.00
% Hveem Stability	40 Min.			– 0.0	100.00
% Roadway Density					
Core Method	94.0			(–10) - (+4)	83.00
Nuclear Gauge	94.0			(–9) - (+4)	85.00

Table B-9 (continued). Tolerances that Include Approximately 85% of Process Output

Quality Characteristic	JMF Target	Cold Feed Analysis		HMA Mixture Analysis	
		Tolerances	Percent	Tolerances	Percent
Project No. 3, US-62					
% Passing Sieve					
1 1/2"	100.0	± 0.0	100.00	± 0.0	100.00
1"	100.0	± 0.0	100.00	± 0.0	100.00
3/4"	100.0	± 0.0	96.74	± 0.0	98.86
1/2"	89.0	± 4.0	86.96	± 4.0	92.05
3/8"	71.0	± 8.0	85.87	± 8.0	89.77
No. 4	54.0	± 8.0	85.87	± 6.0	93.18
No. 10	35.0	± 8.0	89.13	± 5.0	92.05
No. 40	18.0	± 5.0	86.96	± 3.0	94.32
No. 80	8.0	± 3.0	84.78	± 3.0	100.00
No. 200	4.3	± 2.0	93.48	± 2.0	100.00
% Asphalt Content					
Extraction	4.7			± 0.6	90.48
Nuclear Gauge	4.7			± 0.4	82.61
% Air Voids	5.0			± 2.5	95.45
% Hveem Stability	40 Min.			− 0.0	95.31
% Roadway Density					
Core Method	94.0			(–6) - (+6)	90.00
Nuclear Gauge	94.0			(–6) - (+6)	94.00
Project No. 4, US-69					
% Passing Sieve					
1 1/2"	100.0	± 0.0	100.00	± 0.0	100.00
1"	98.0	± 2.0	100.00	± 2.0	94.57
1/2"	72.0	± 5.0	86.00	± 9.0	84.78
No. 4	52.0	± 6.0	87.00	± 5.0	86.96
No. 10	38.0	± 5.0	86.00	± 6.0	85.87
No. 40	14.0	± 4.0	87.00	± 5.0	91.30
No. 80	7.0	± 1.0	85.00	± 1.0	81.52
No. 200	3.8	± 1.0	89.00	± 1.0	81.52
% Asphalt Content					
Extraction	4.8			± 0.7	84.78
Nuclear Gauge	4.8			± 0.5	90.00
% Air Voids	5.0			± 2.5	86.36
% Hveem Stability	40 Min.			− 0.0	100.00
% Roadway Density					
Core Method	94.0			(–5) - (+4)	86.90
Nuclear Gauge	94.0			(–4) - (+4)	86.00

Table B-10. Tolerances Based on Pooled Estimates of Natural Process Variability

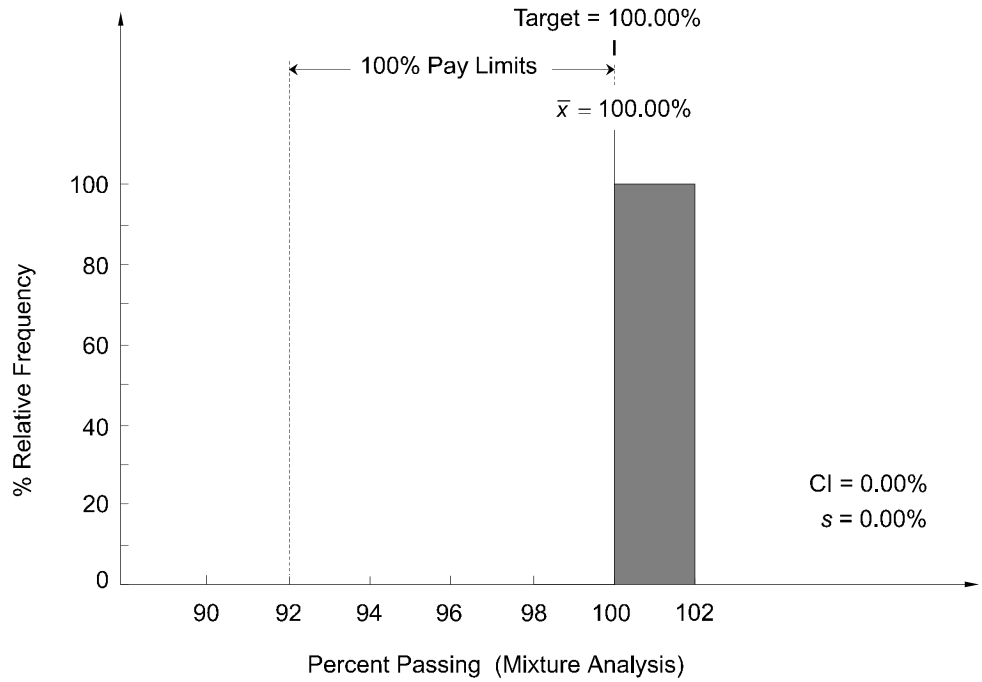
Quality Characteristic	Cold Feed Analysis		HMA Mixture Analysis	
	Pooled *S*	Tolerances	Pooled *S*	Tolerances
% Passing Sieve				
1 1/2"	0.00	± 0.0	0.00	± 0.0
1"	0.67	± 2.0	1.12	± 3.0
3/4"	1.72	± 0.0	2.57	± 7.5
1/2"	3.25	± 5.0	3.16	± 9.5
3/8"	4.23	± 13.0	3.43	± 10.0
No. 4	4.39	± 13.0	3.09	± 9.0
No. 10	3.97	± 12.0	2.60	± 8.0
No. 40	3.35	± 10.0	1.35	± 4.0
No. 80	1.17	± 3.5	0.94	± 3.0
No. 200	0.84	± 2.5	0.59	± 2.0
% Asphalt Content				
Extraction			0.26	± 0.8
Nuclear Gauge			0.24	± 0.7
% Air Voids			1.32	± 4.0
% Roadway Density				
Core Method			2.96	± 9.0
Nuclear Gauge			3.21	± 10.0

Table B-11. Existing and Proposed QA Specifications Tolerances

Quality Characteristic	Existing QA Specifications	Proposed QA Specifications
% Passing Sieve		
1 1/2"	Target ± 8.0%	Target ± 6.0%
1"	Target ± 8.0%	Target ± 6.0%
3/4"	Target ± 8.0%	Target ± 6.0%
1/2"	Target ± 8.0%	Target ± 6.0%
3/8"	Target ± 8.0%	Target ± 6.0%
No. 4	Target ± 8.0%	Target ± 6.0%
No. 10	Target ± 6.5%	Target ± 4.5%
No. 40	Target ± 6.5%	Target ± 4.5%
No. 80	Target ± 6.5%	Target ± 4.5%
No. 200	Target ± 3.0%	Target ± 2.0%
% Asphalt Content		
Extraction	Target ± 0.7%	Target ± 0.5%
Nuclear Gauge	Target ± 0.7%	Target ± 0.5%
% Air Voids	Target ± 2.5%	Target ± 1.5%
% Roadway Density		
Core Method	92% - 98%	92% - 98%
Nuclear Gauge	92% - 98%	92% - 98%

APPENDIX C

DISTRIBUTIONS OF QUALITY CHARACTERISTICS PROJECT 1, US-412



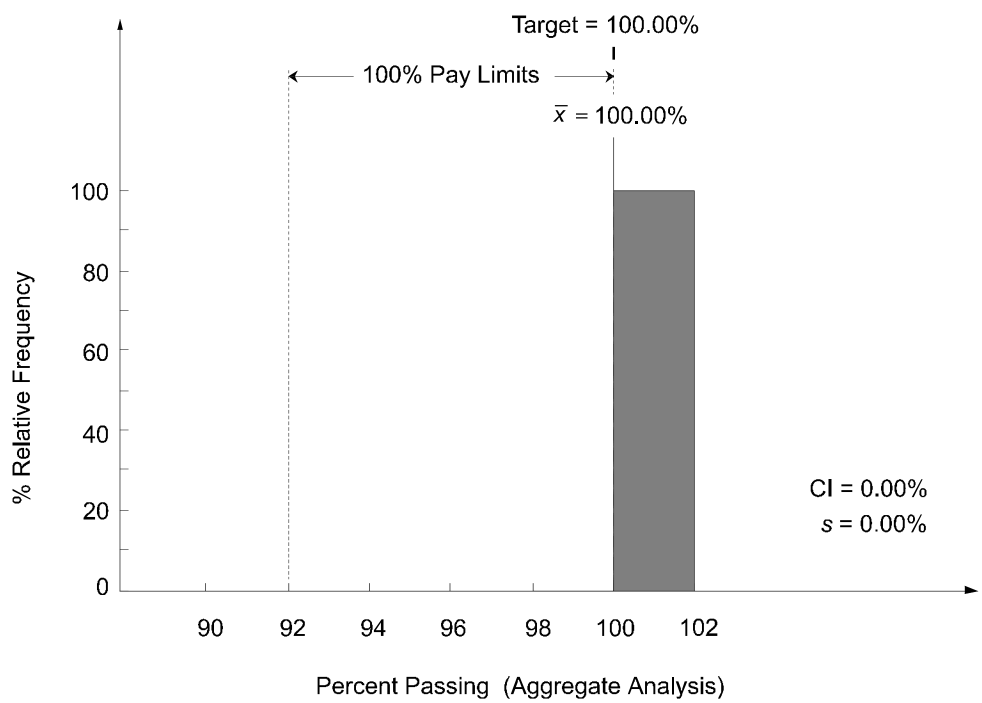
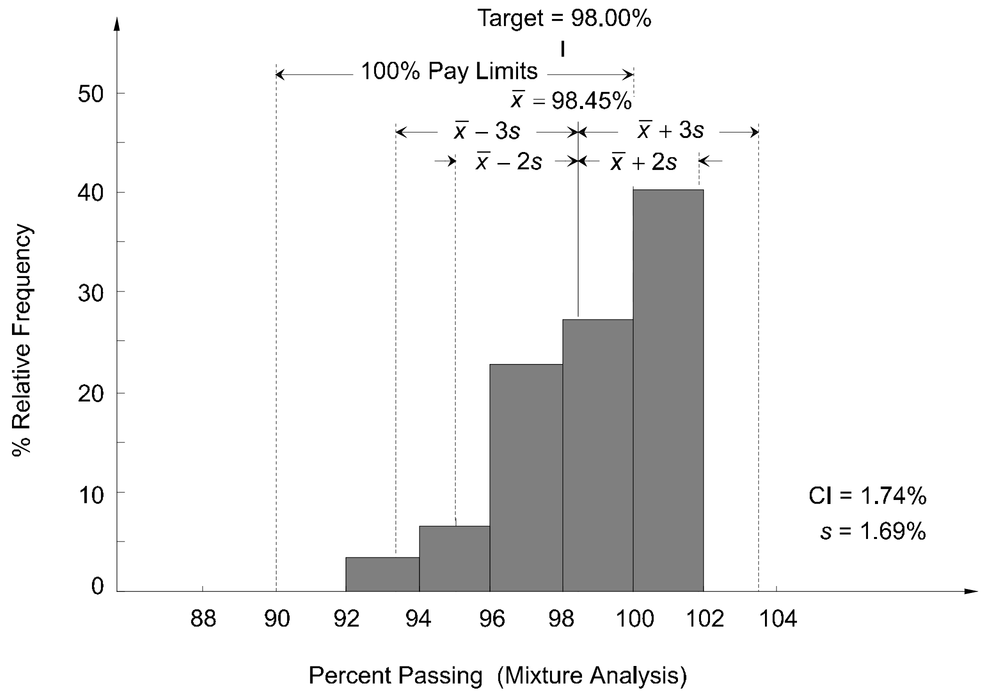


Figure C-1. Percent Passing Sieve 1½ ″



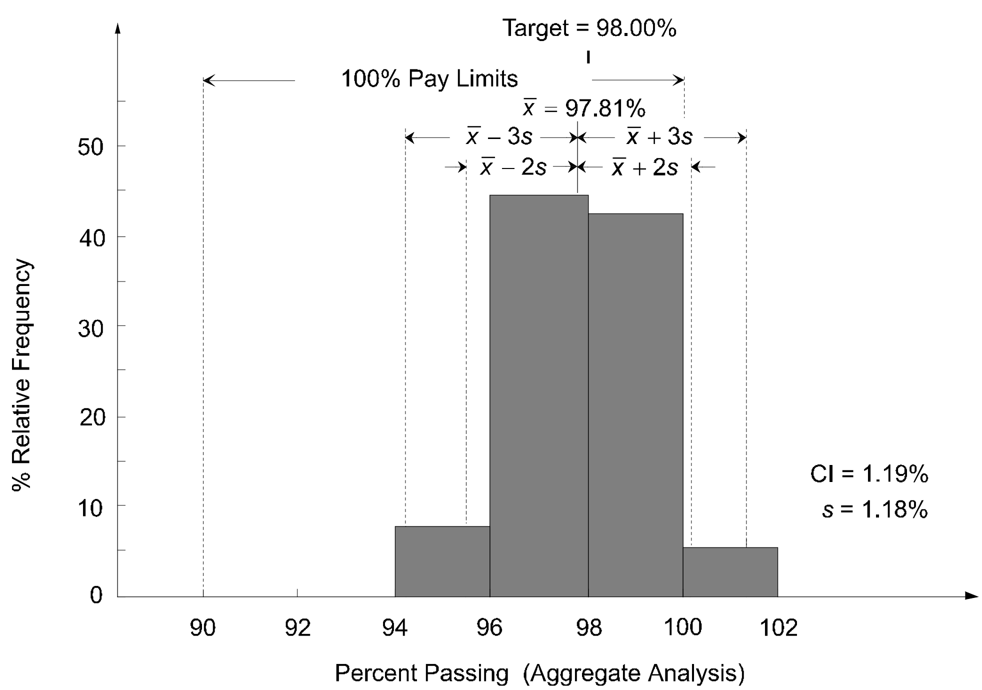
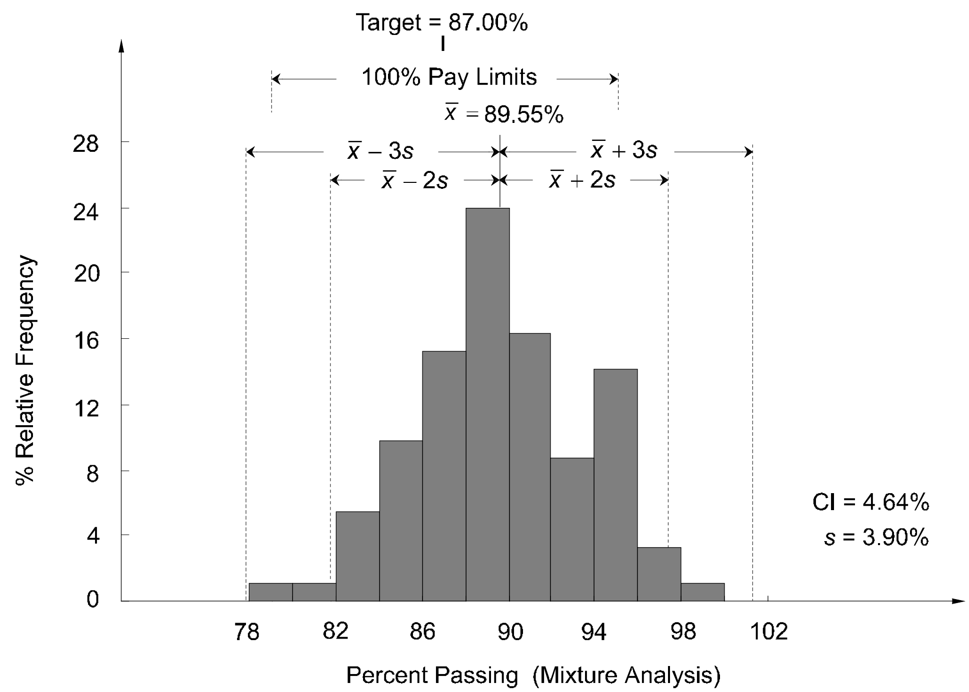


Figure C-2. Percent Passing Sieve 1″



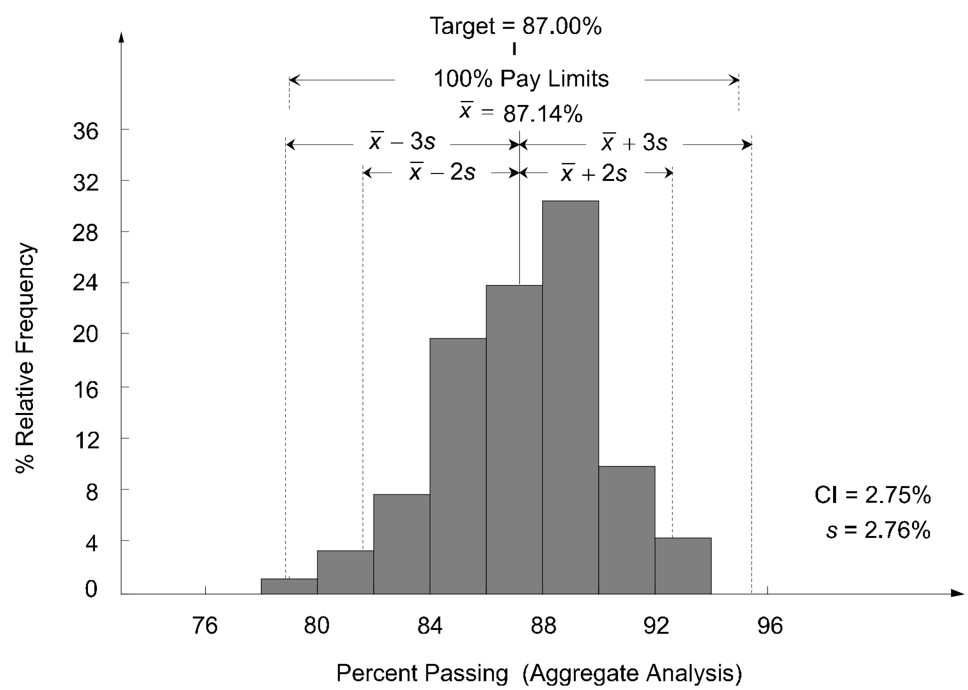
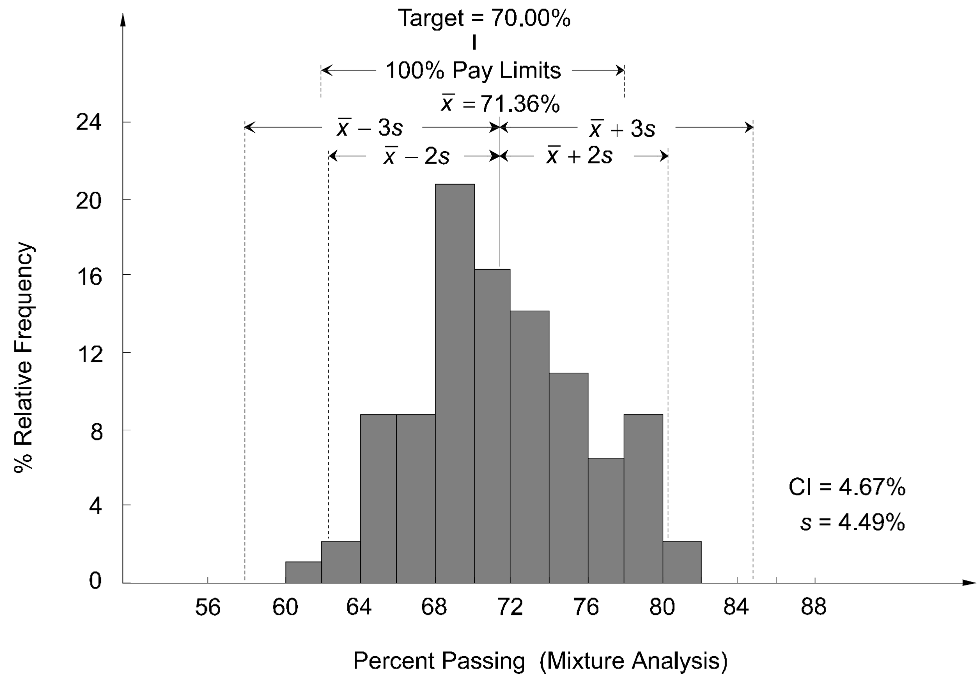


Figure C-3. Percent Passing Sieve ¾″



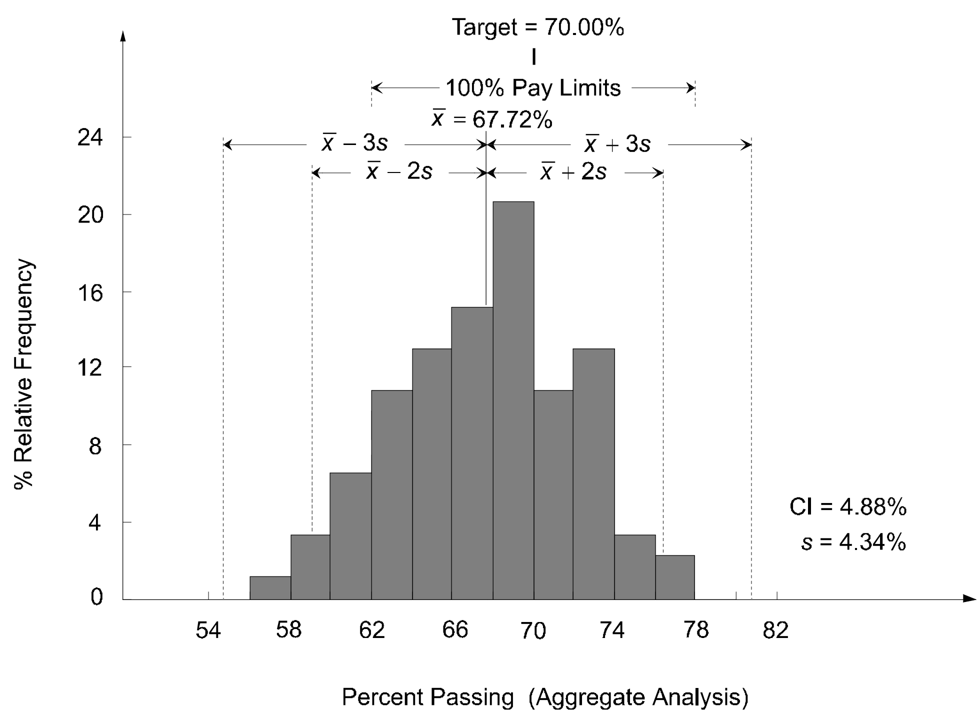
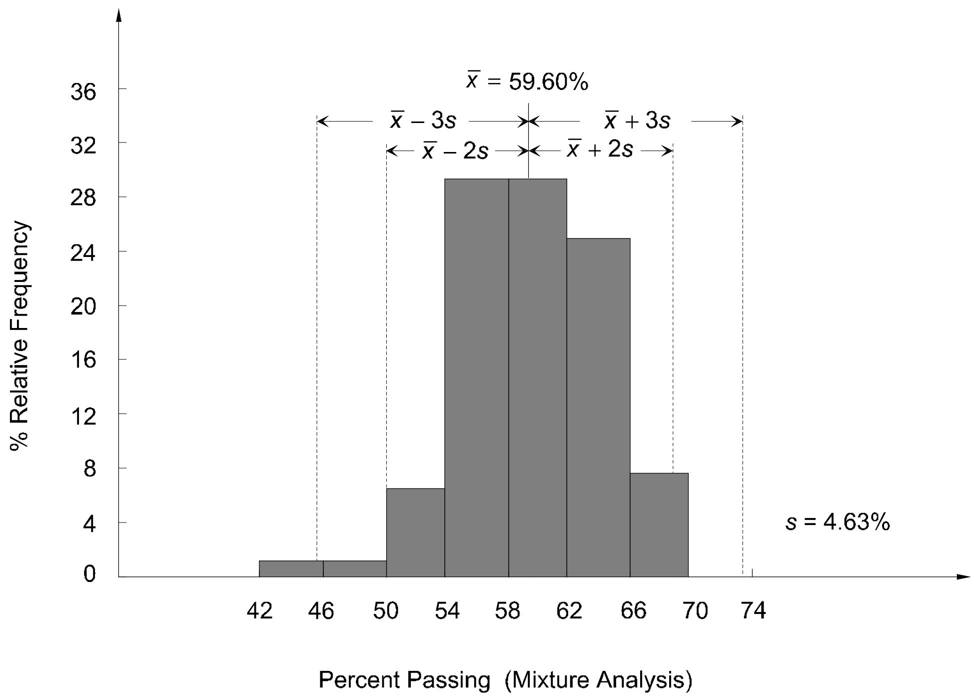


Figure C-4. Percent Passing Sieve ½″



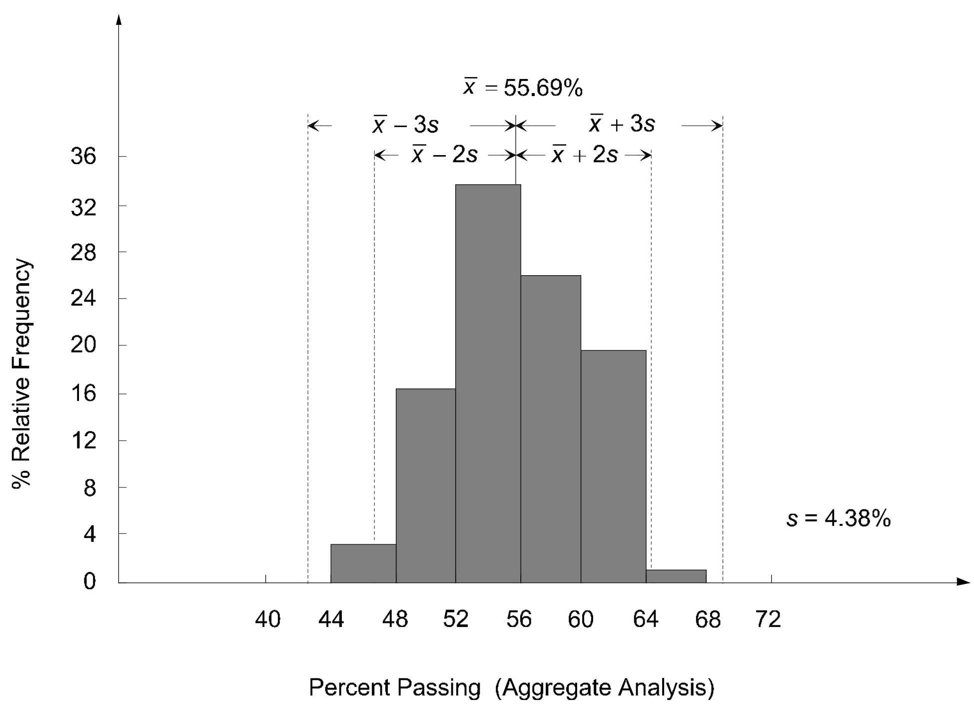
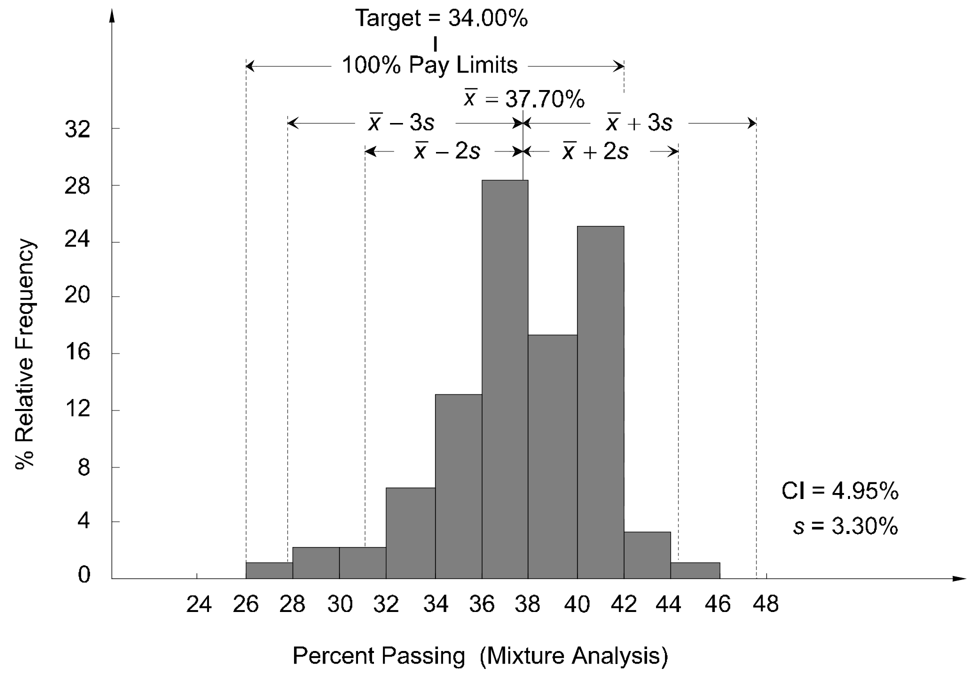


Figure C-5. Percent Passing Sieve 3/8″



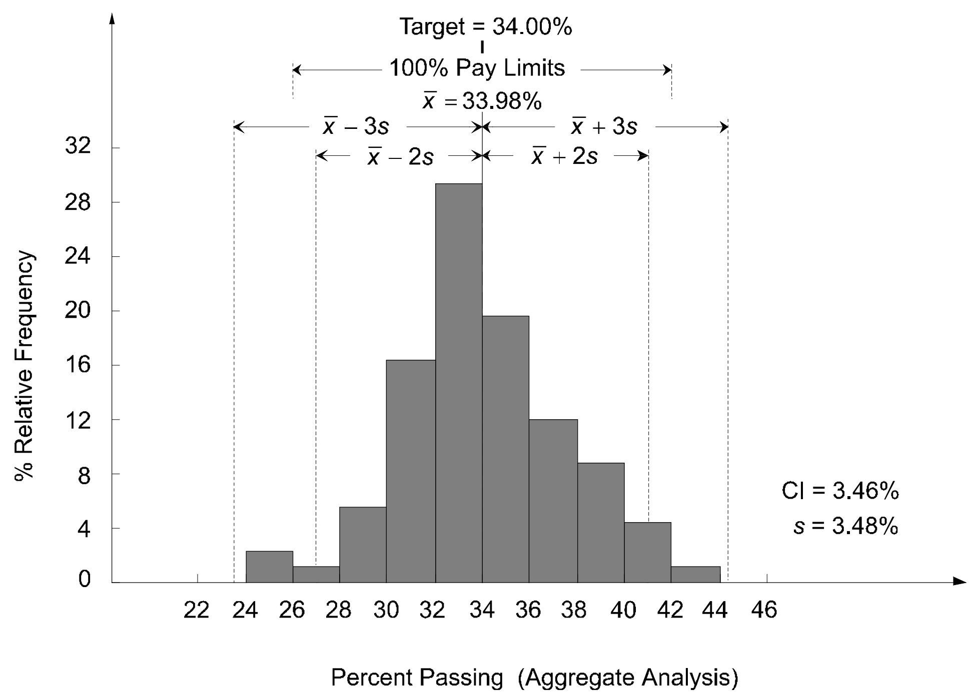
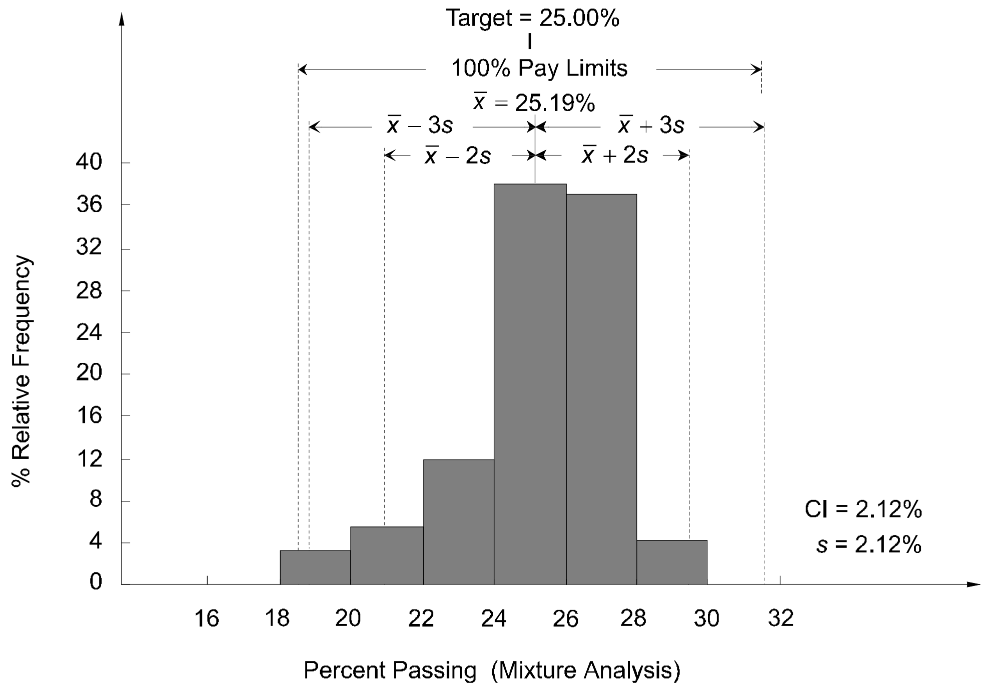


Figure C-6. Percent Passing Sieve No. 4



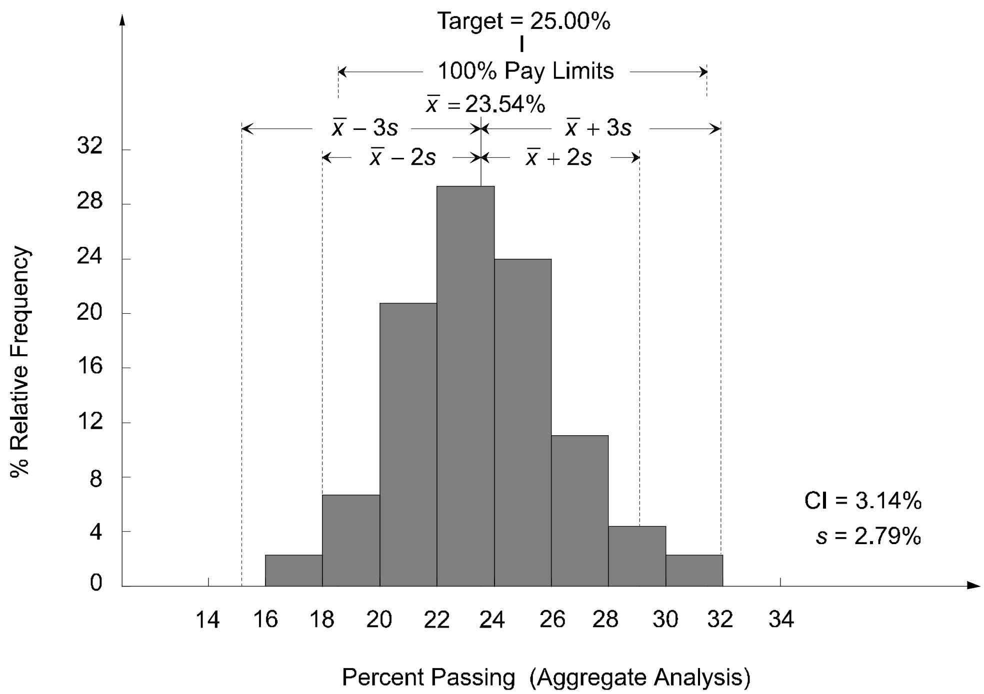
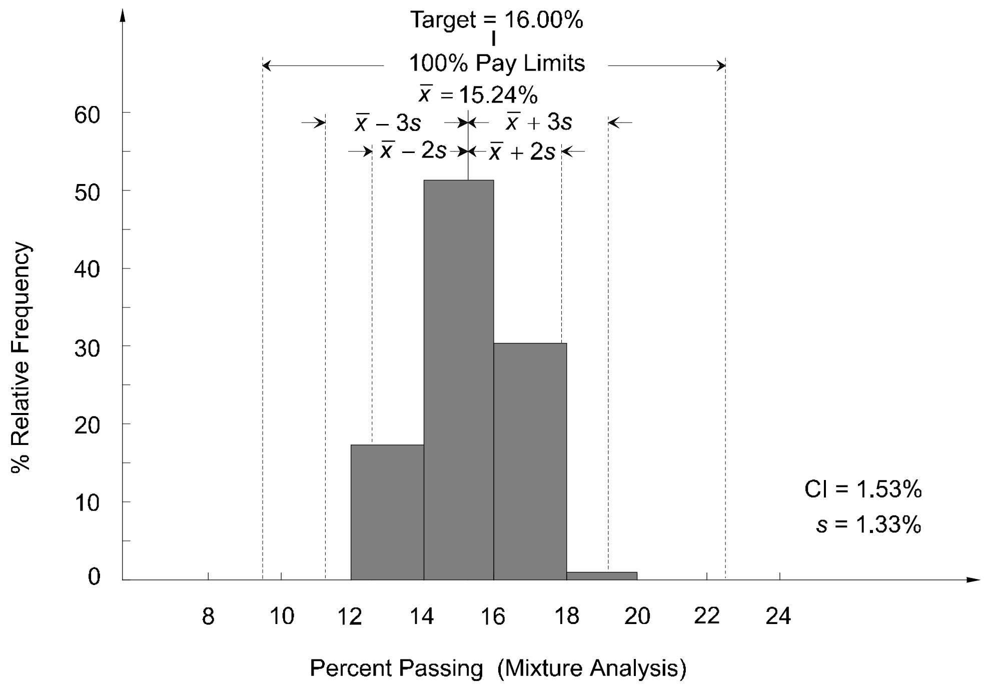


Figure C-7. Percent Passing Sieve No. 10



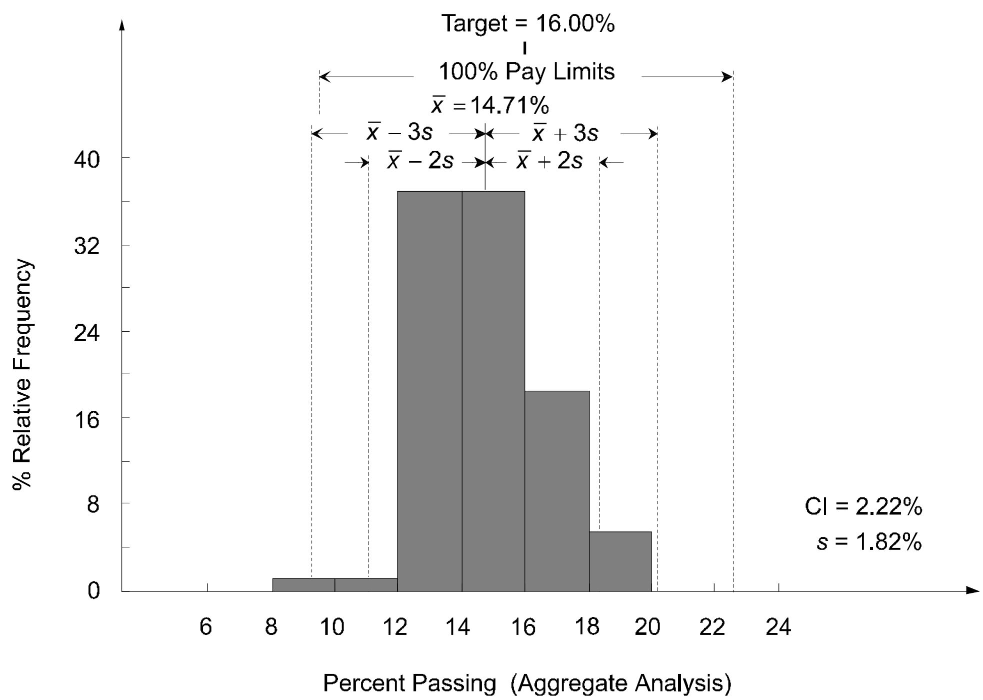
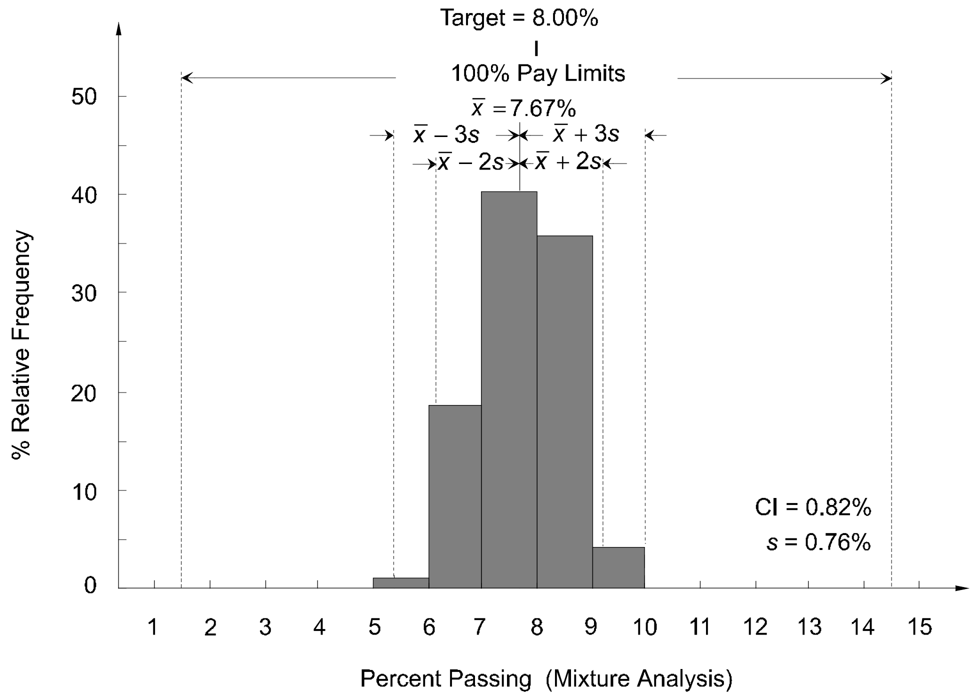


Figure C-8. Percent Passing Sieve No. 40



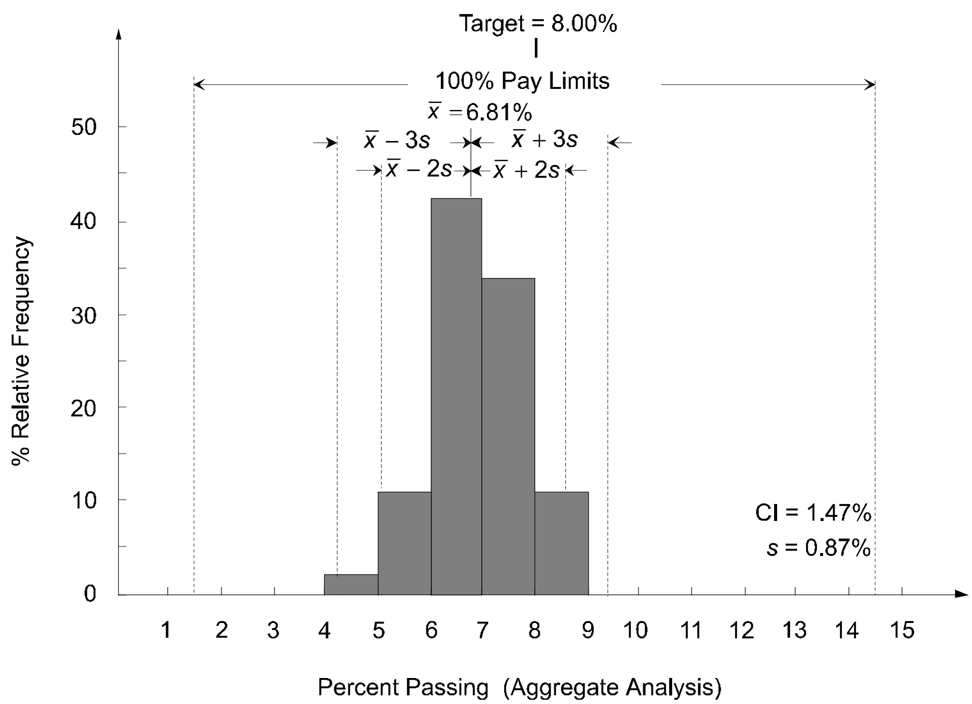
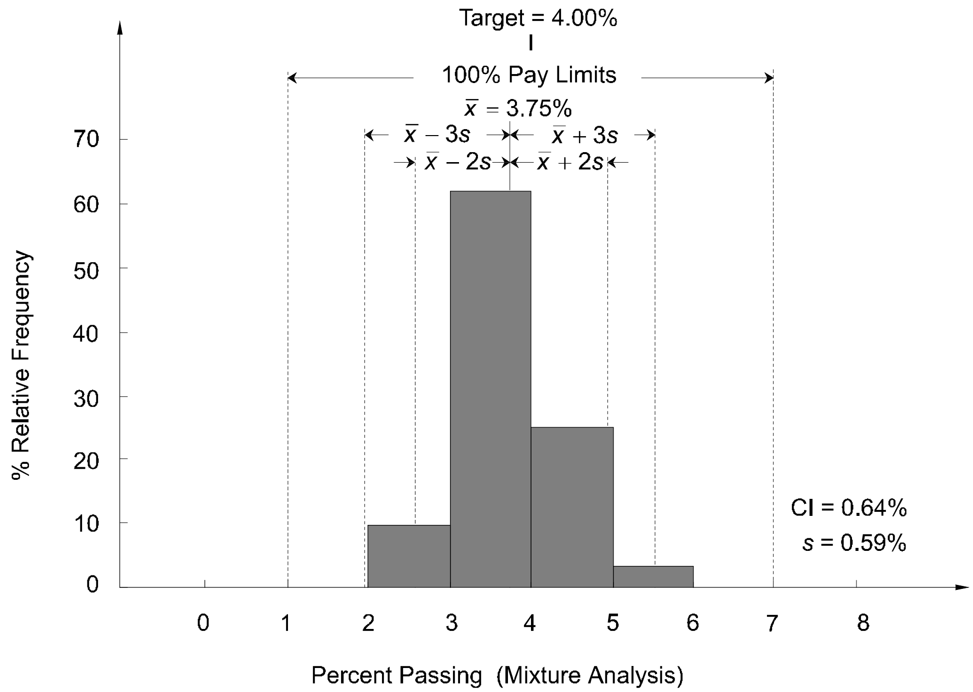


Figure C-9. Percent Passing Sieve No. 80



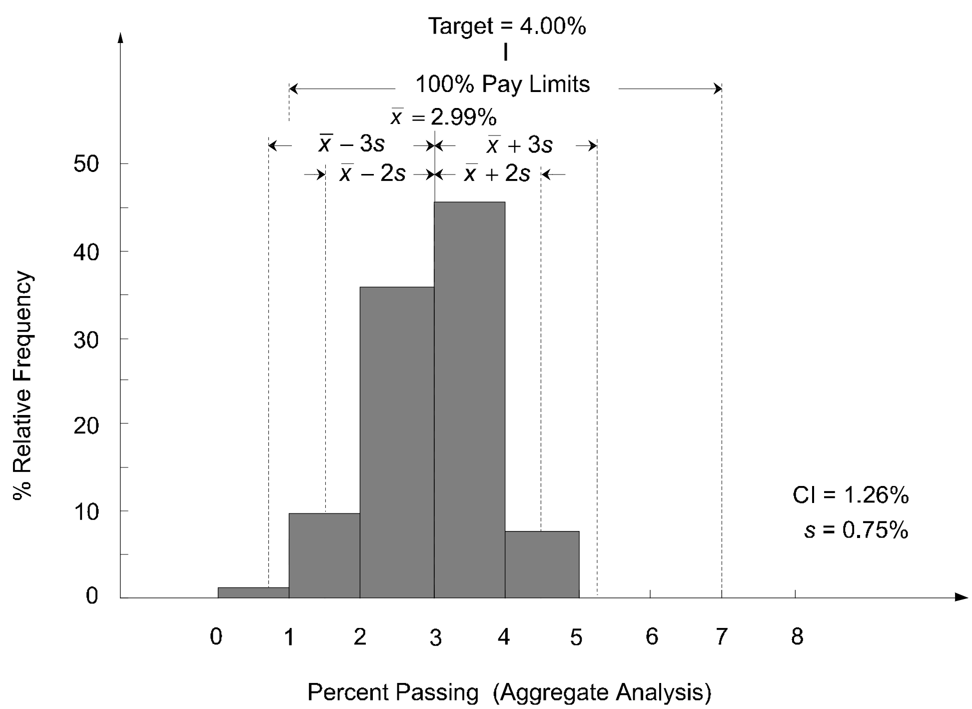
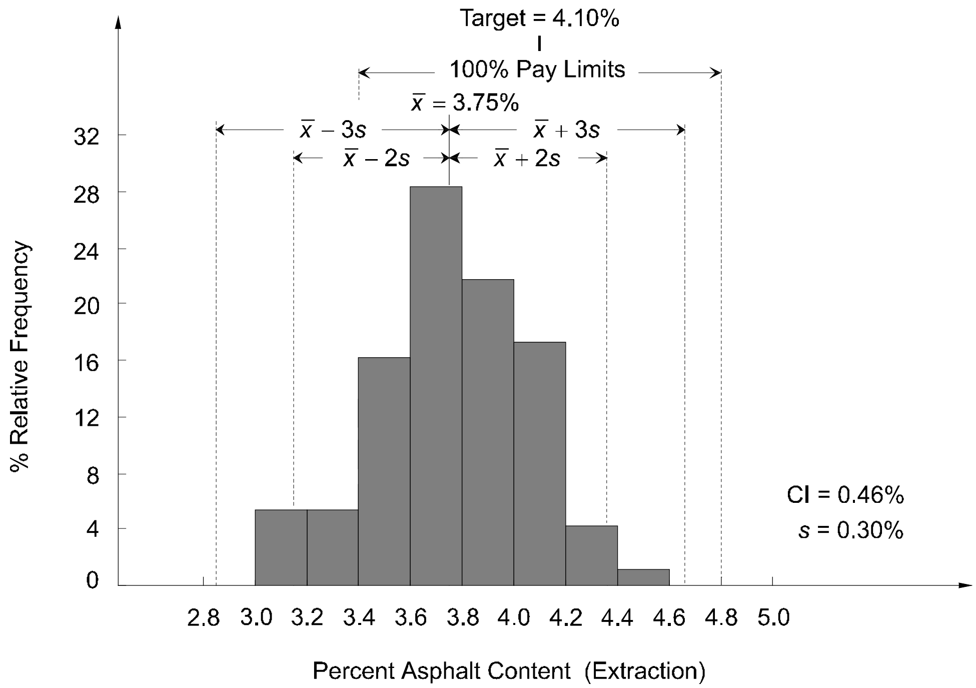


Figure C-10. Percent Passing Sieve No. 200



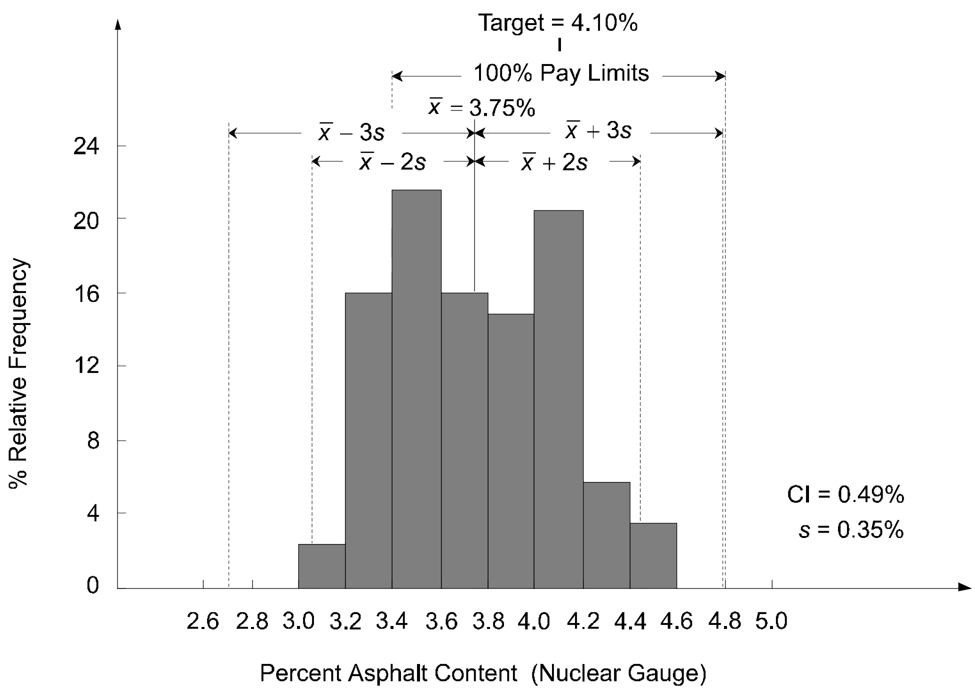
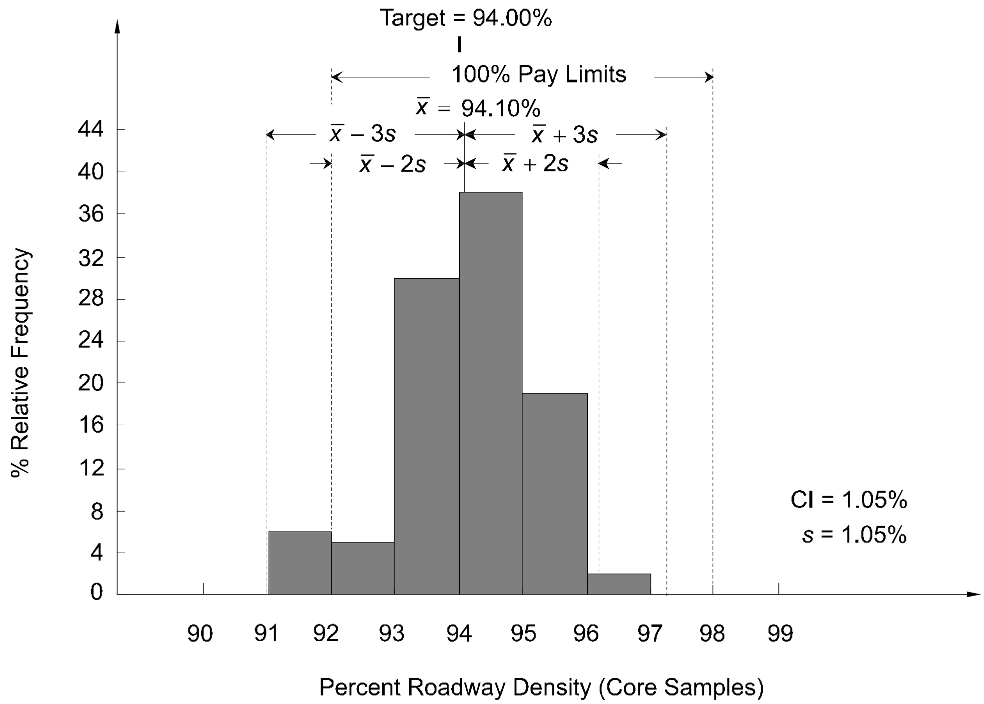


Figure C-11. Percent Asphalt Content



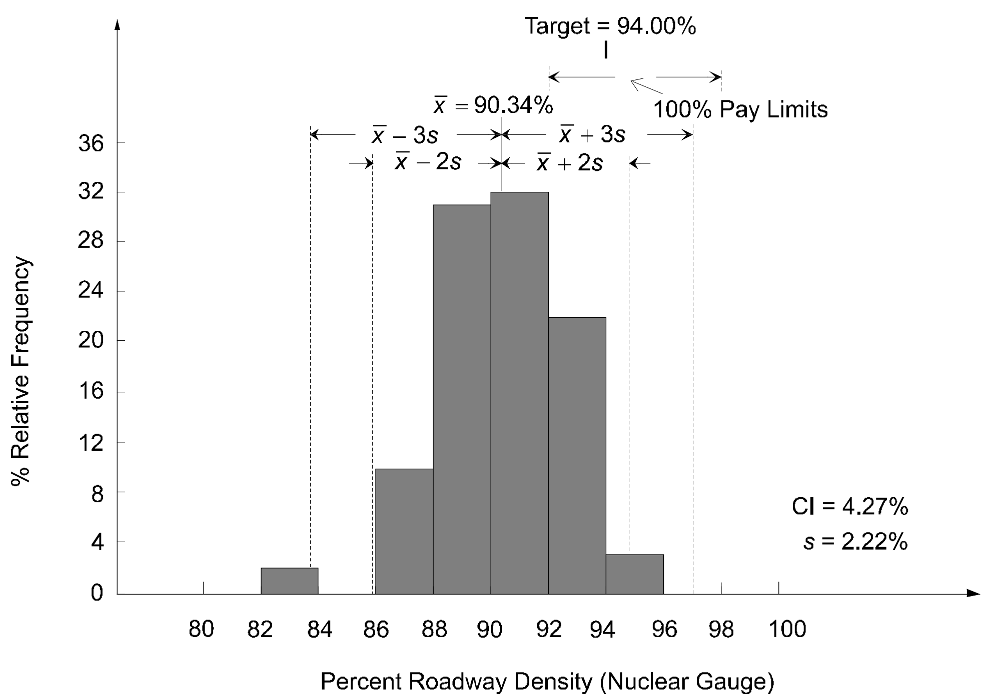


Figure C-12. Percent Roadway Density

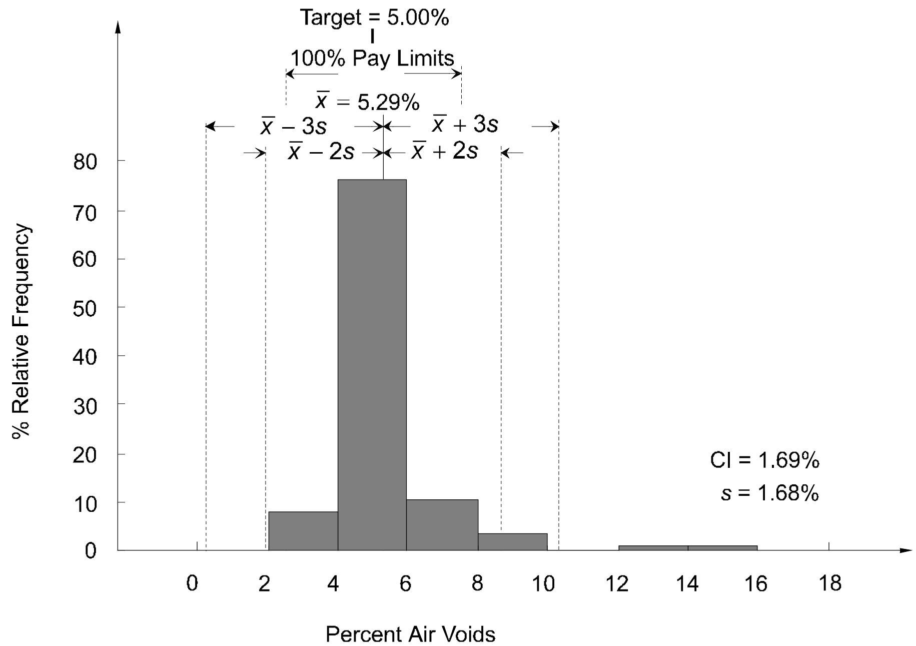


Figure C-13. Percent Air Voids

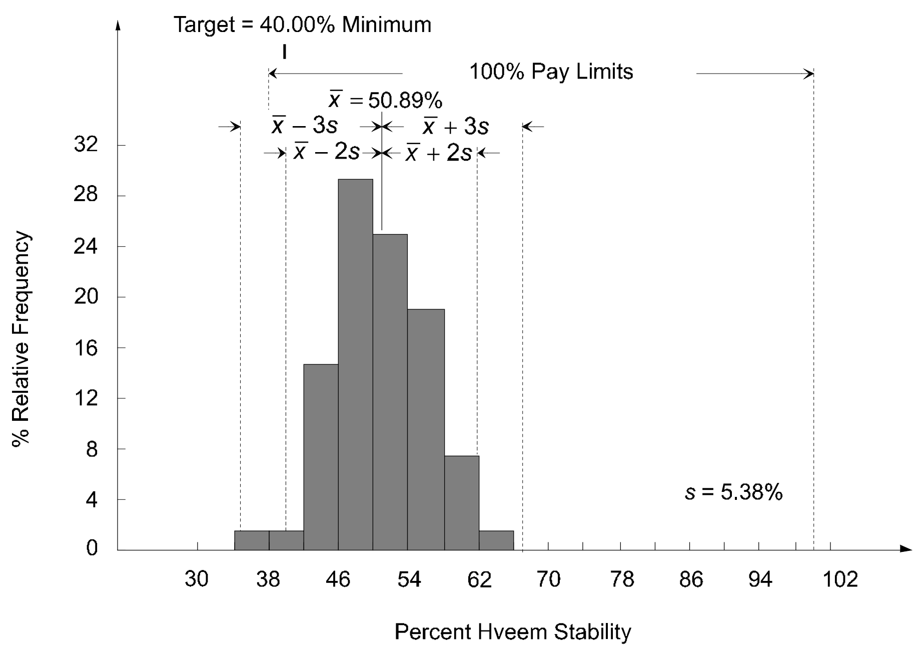
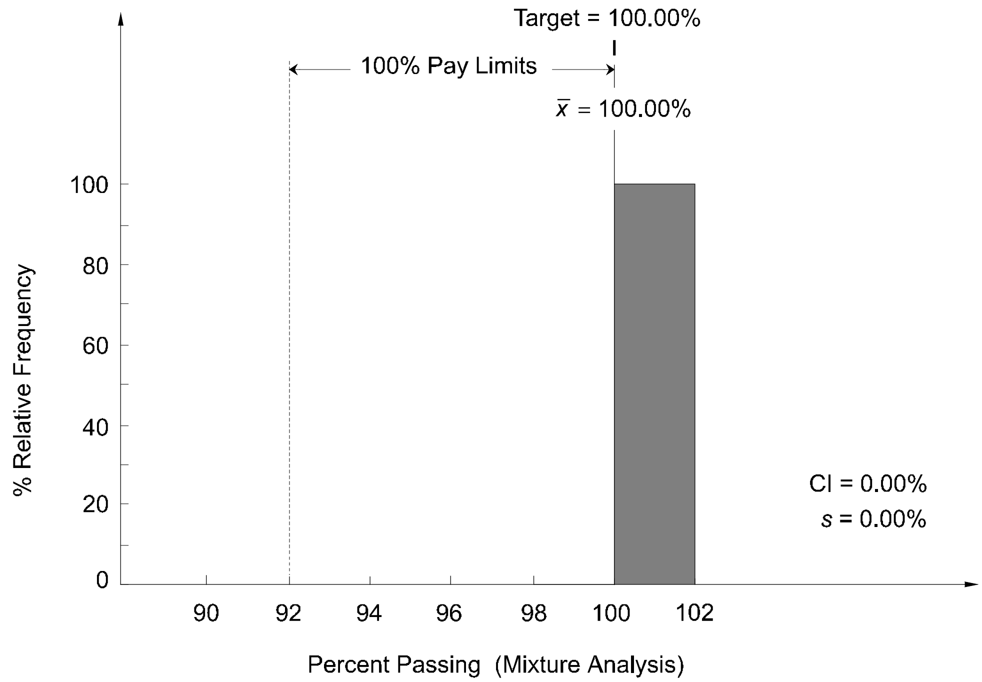


Figure C-14. Percent Hveem Stability

APPENDIX D

DISTRIBUTIONS OF QUALITY CHARACTERISTICS PROJECT 2, US-70



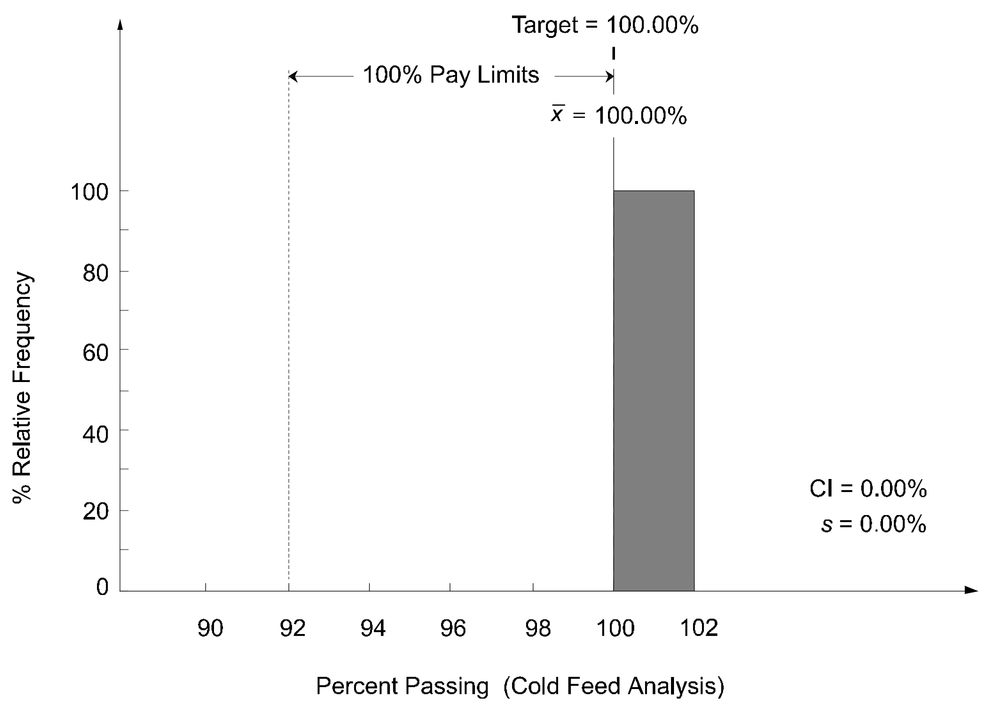
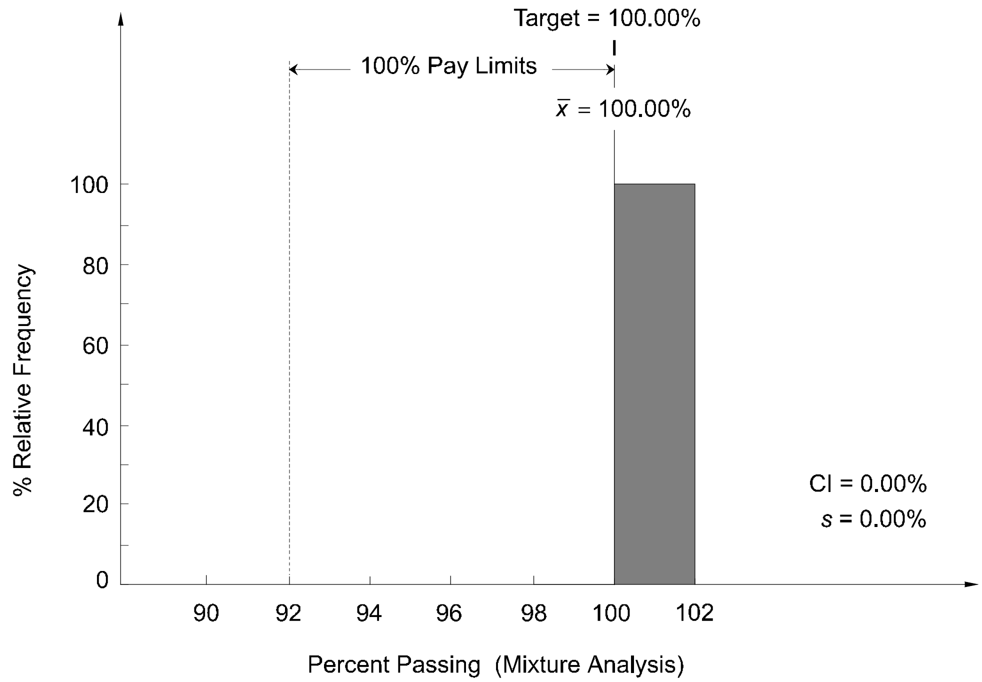


Figure D-1. Percent Passing Sieve 1½″



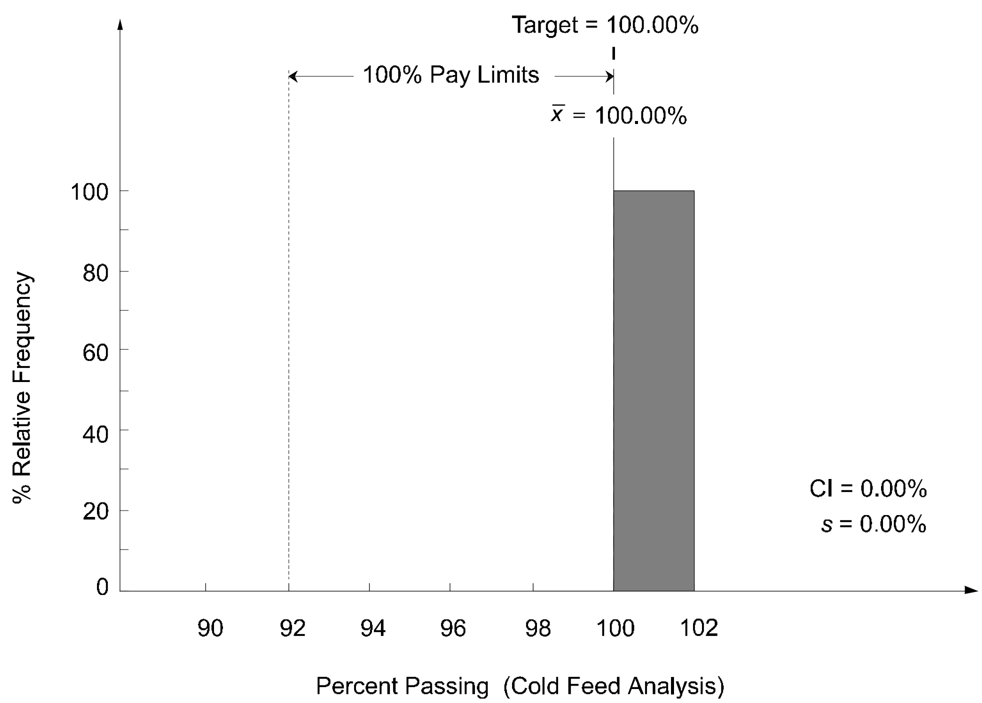


Figure D-2. Percent Passing Sieve 1″

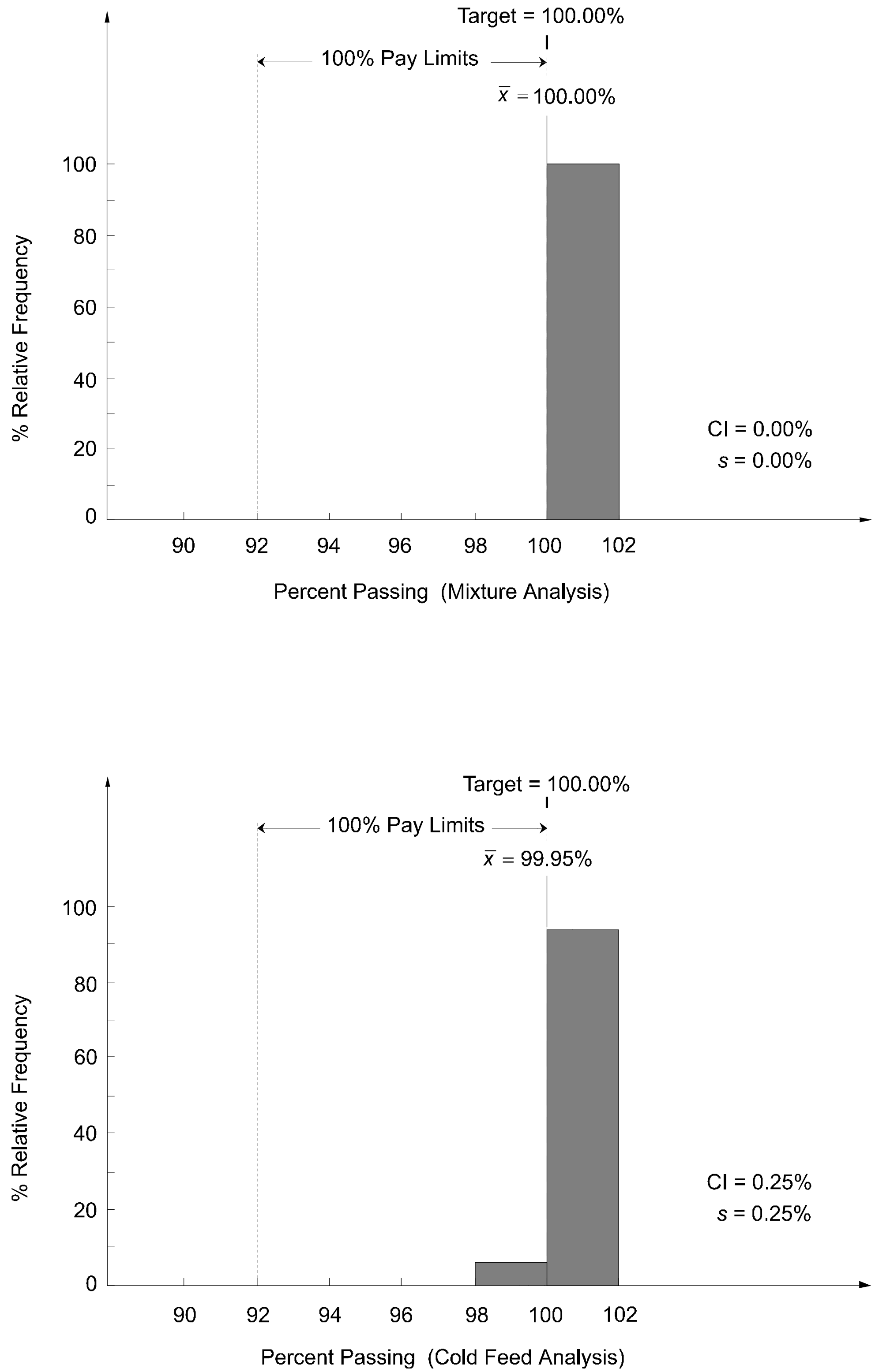
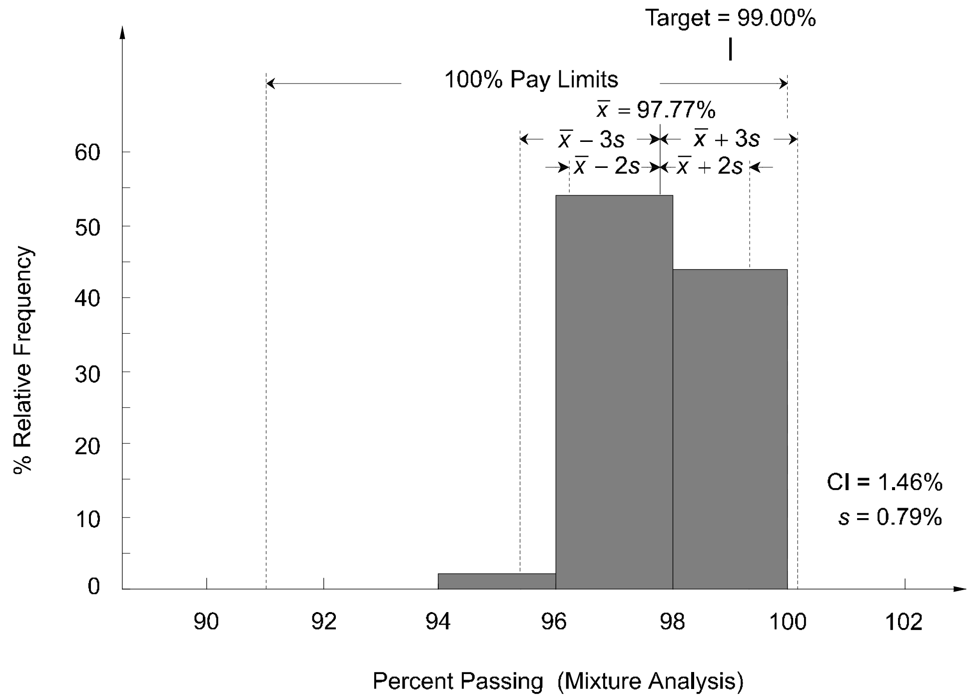


Figure D-3. Percent Passing Sieve ¾″



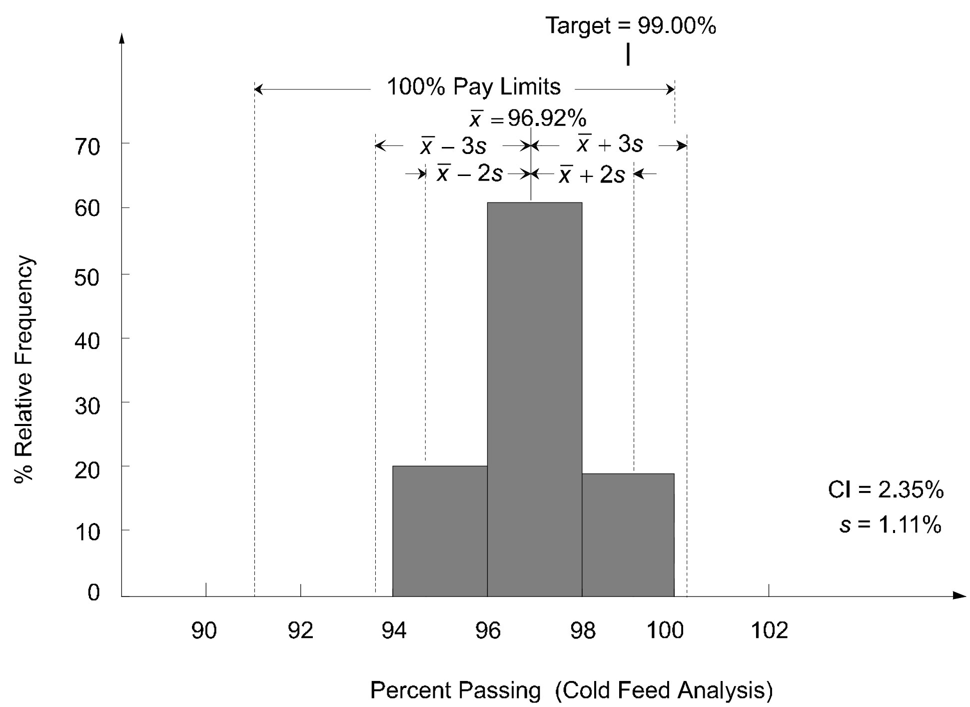
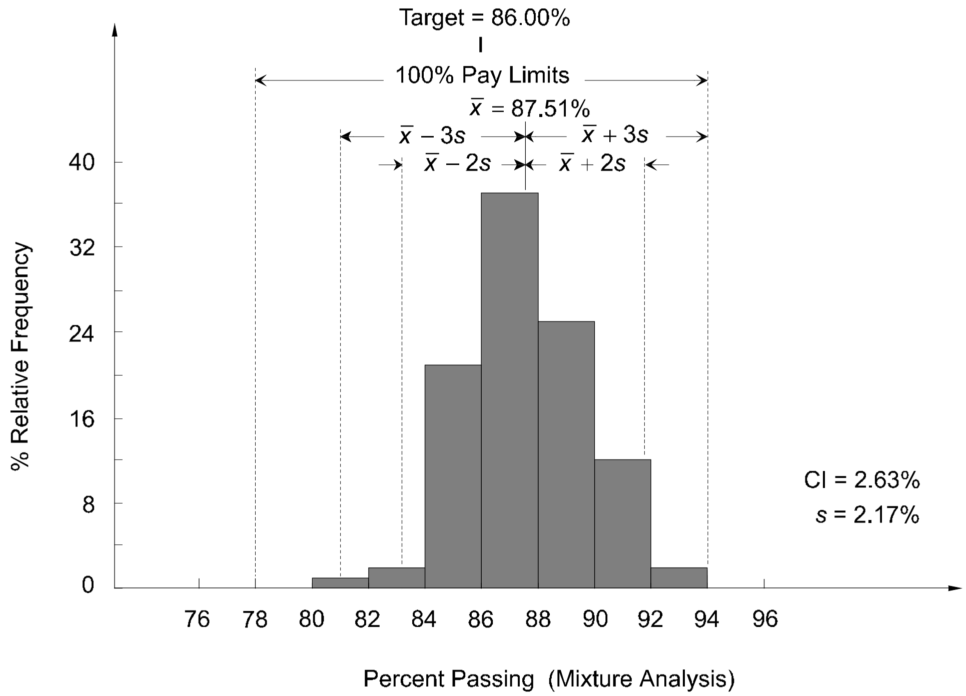


Figure D-4. Percent Passing Sieve ½″



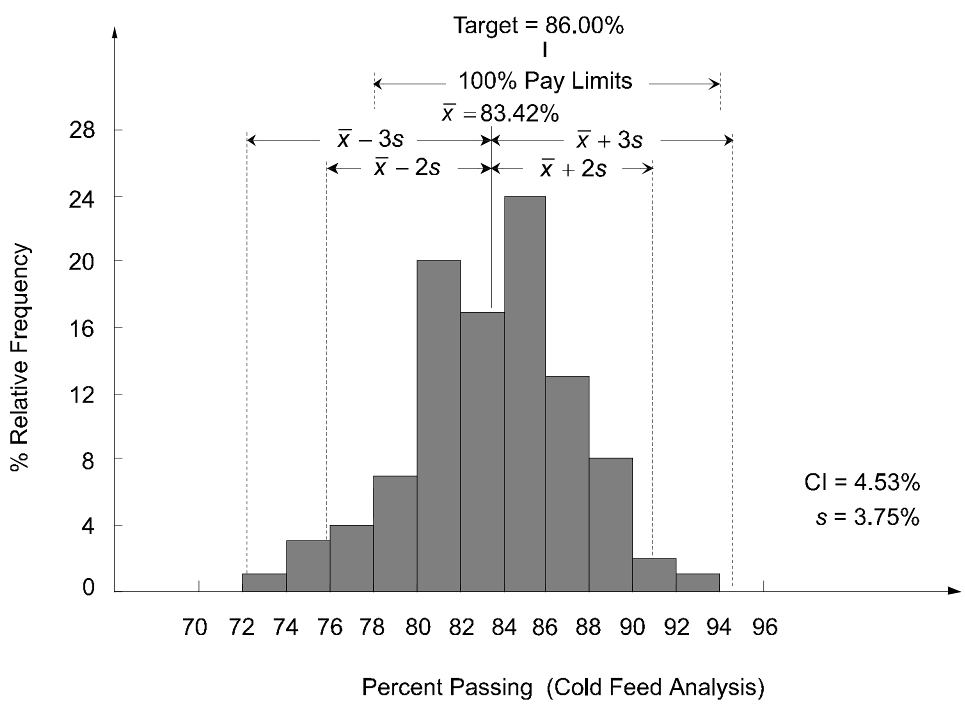
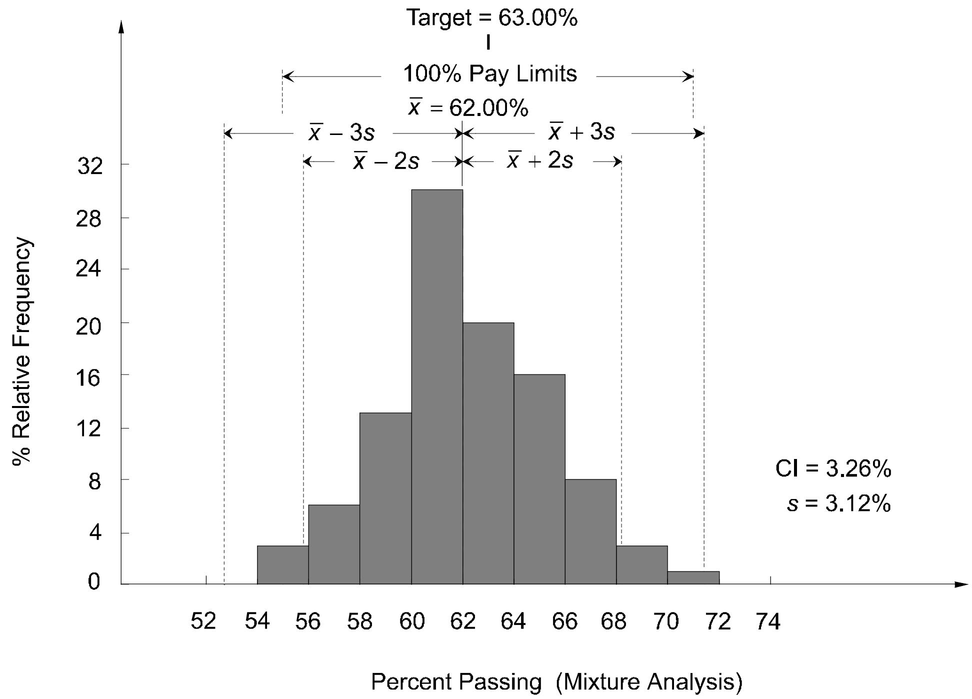


Figure D-5. Percent Passing Sieve 3/8″



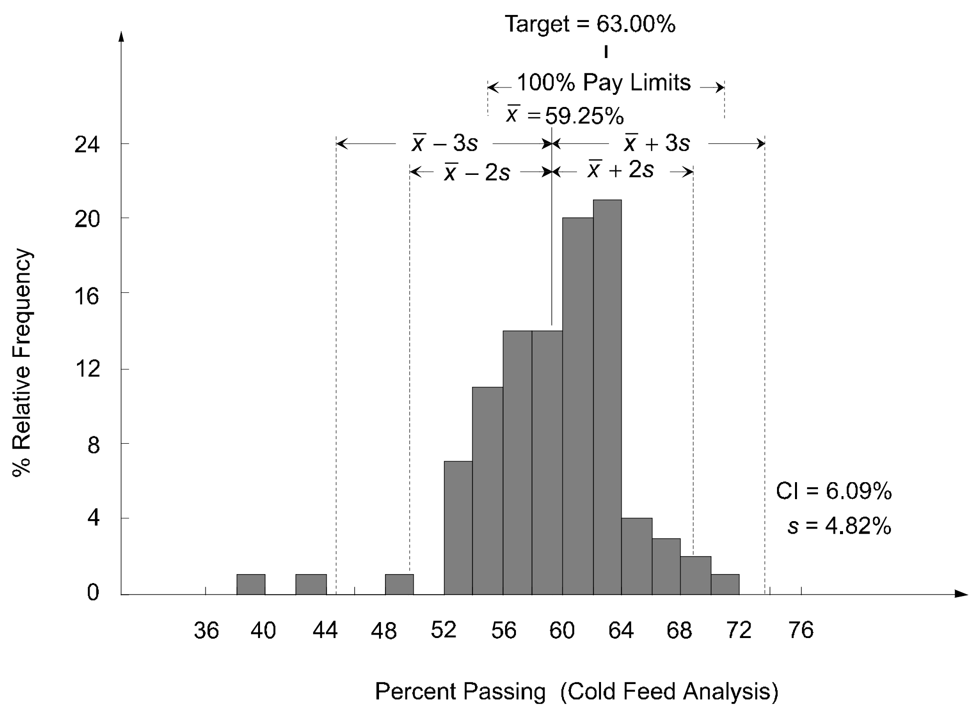
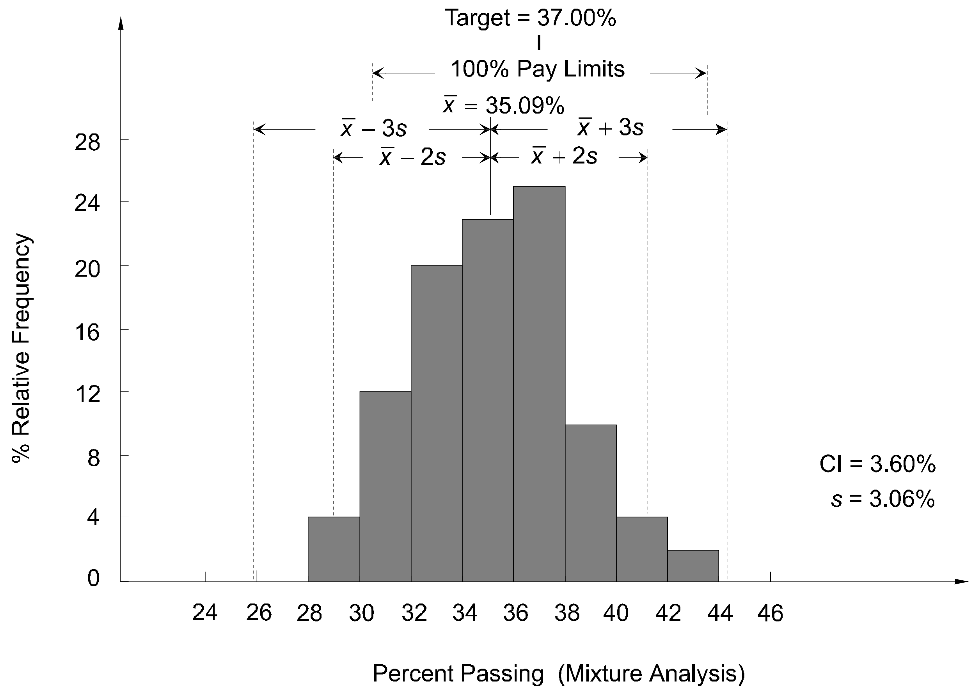


Figure D-6. Percent Passing Sieve No. 4



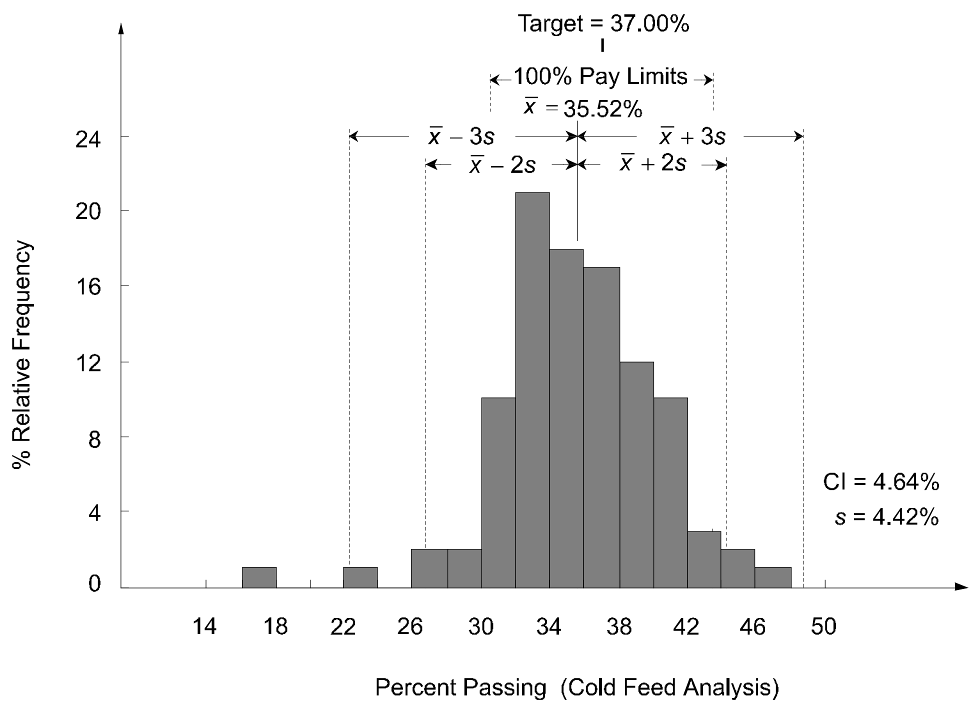
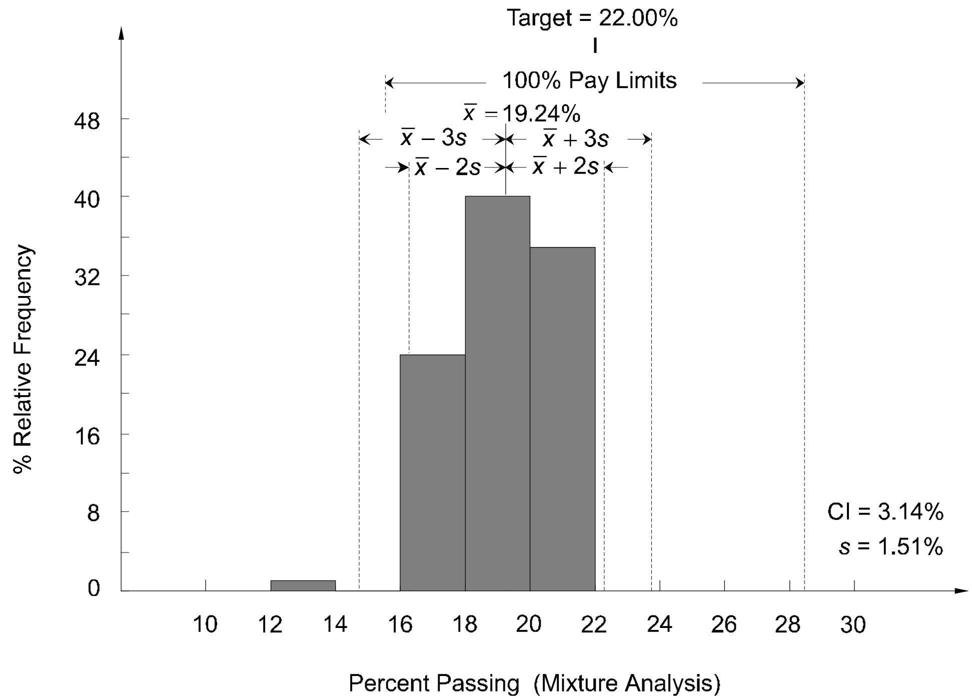


Figure D-7. Percent Passing Sieve No. 10



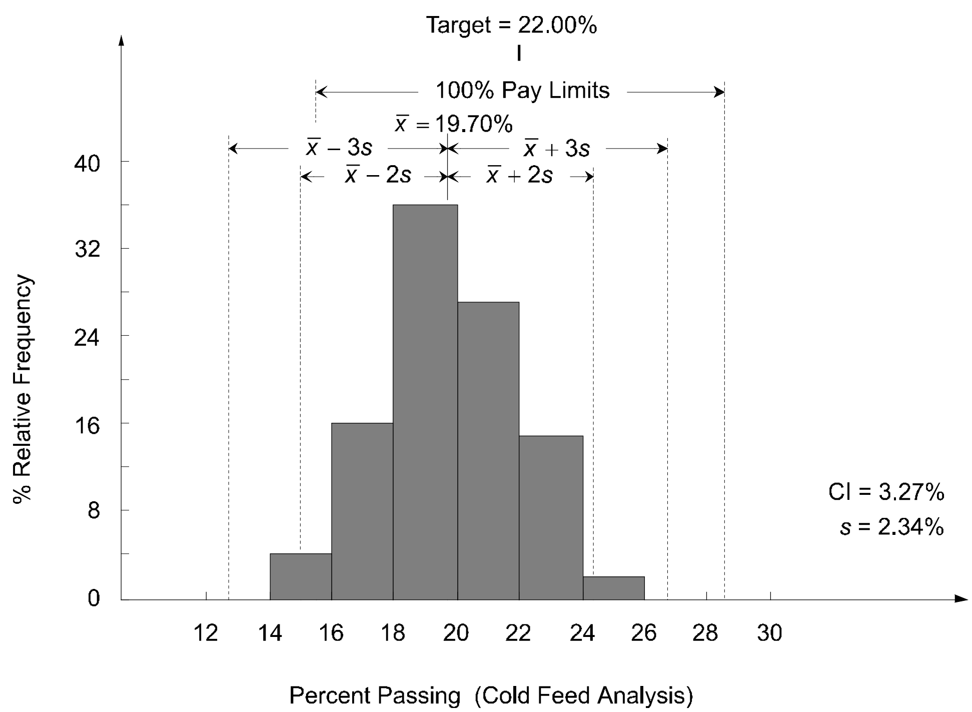


Figure D-8. Percent Passing Sieve No. 40

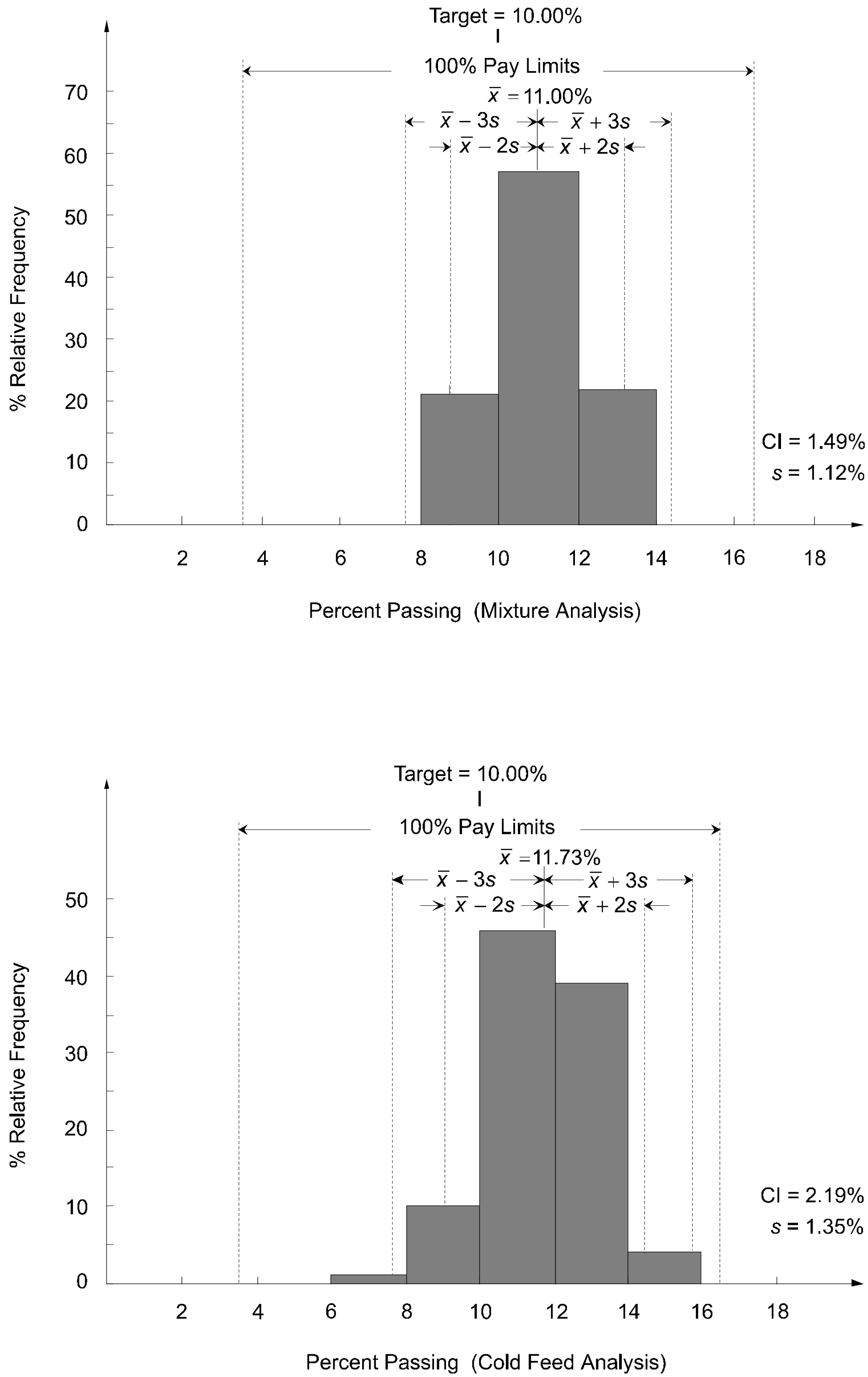
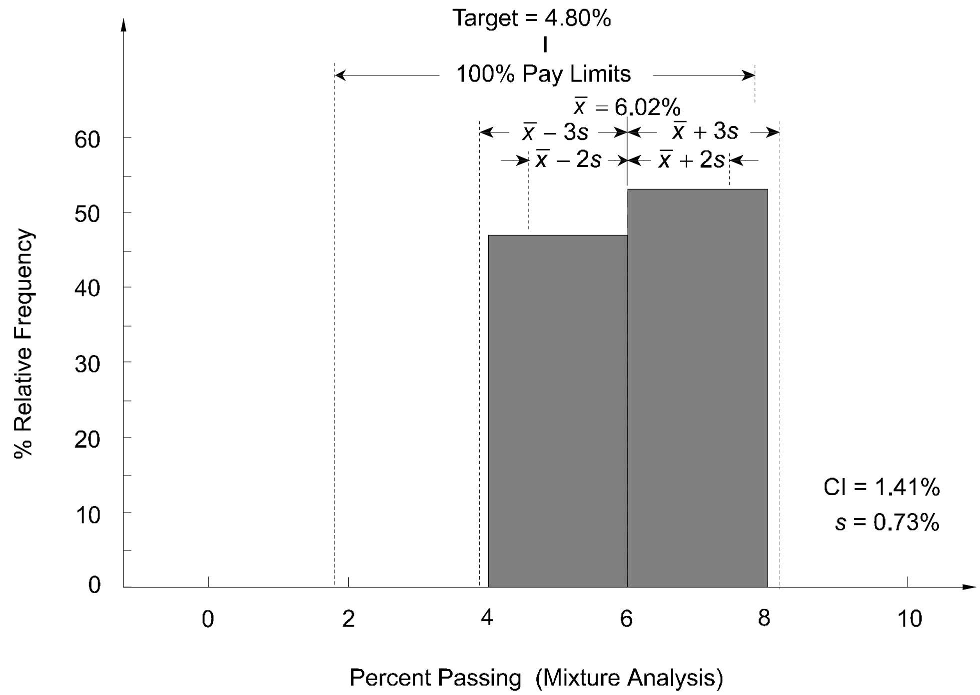


Figure D-9. Percent Passing Sieve No. 80



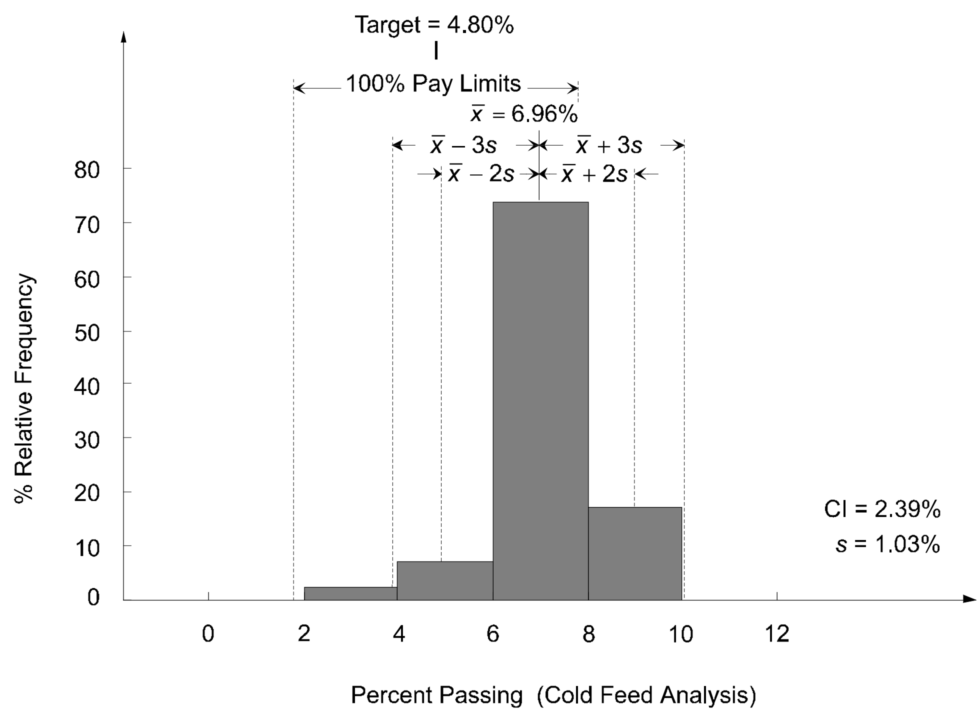
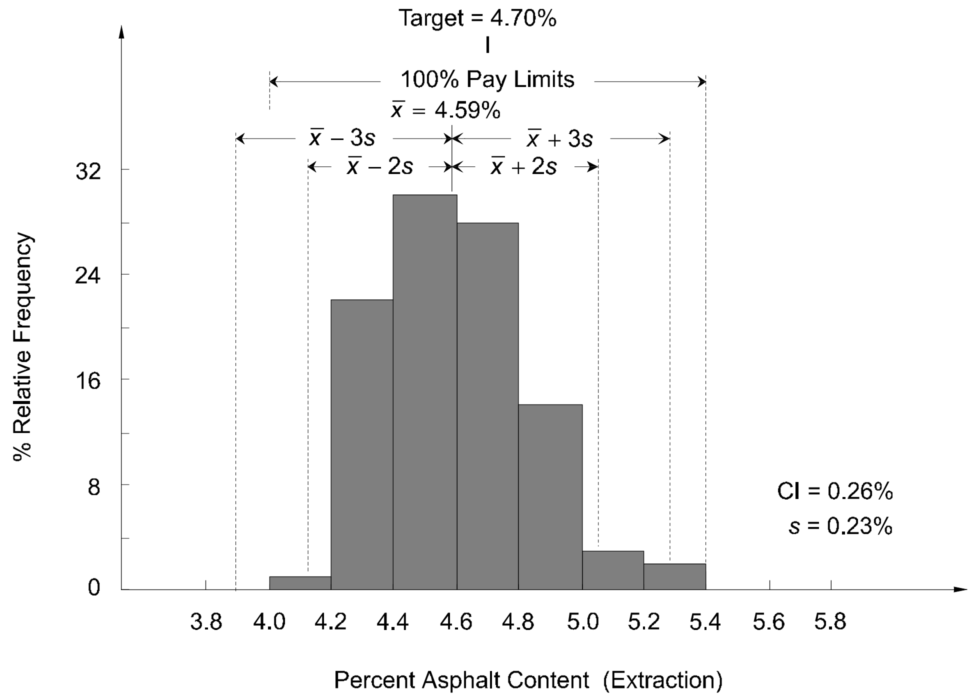


Figure D-10. Percent Passing Sieve No. 200



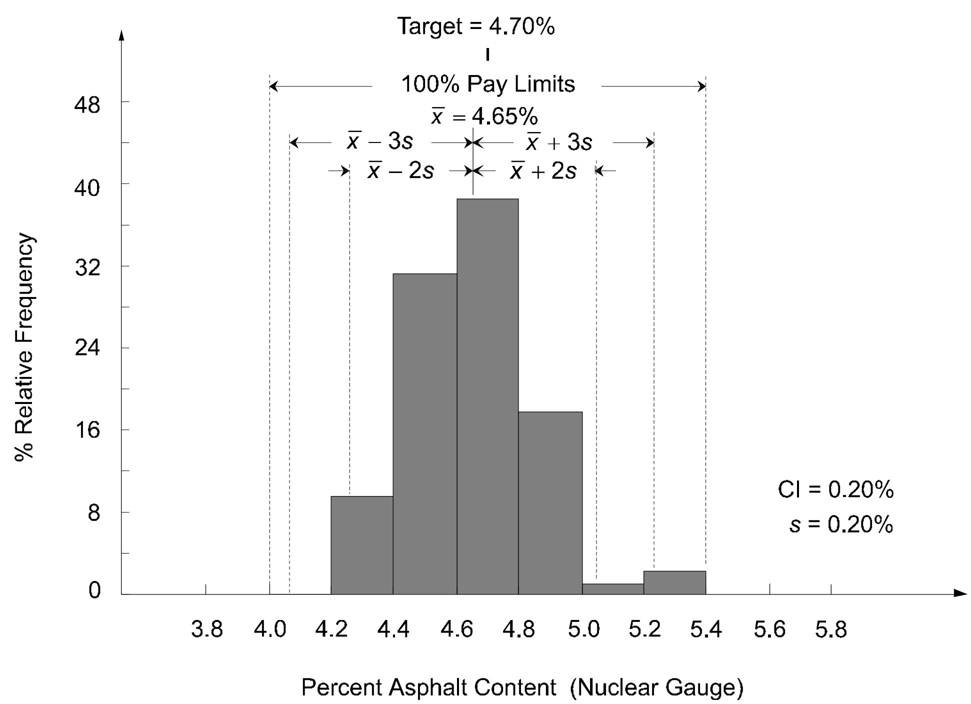


Figure D-11. Percent Asphalt Content

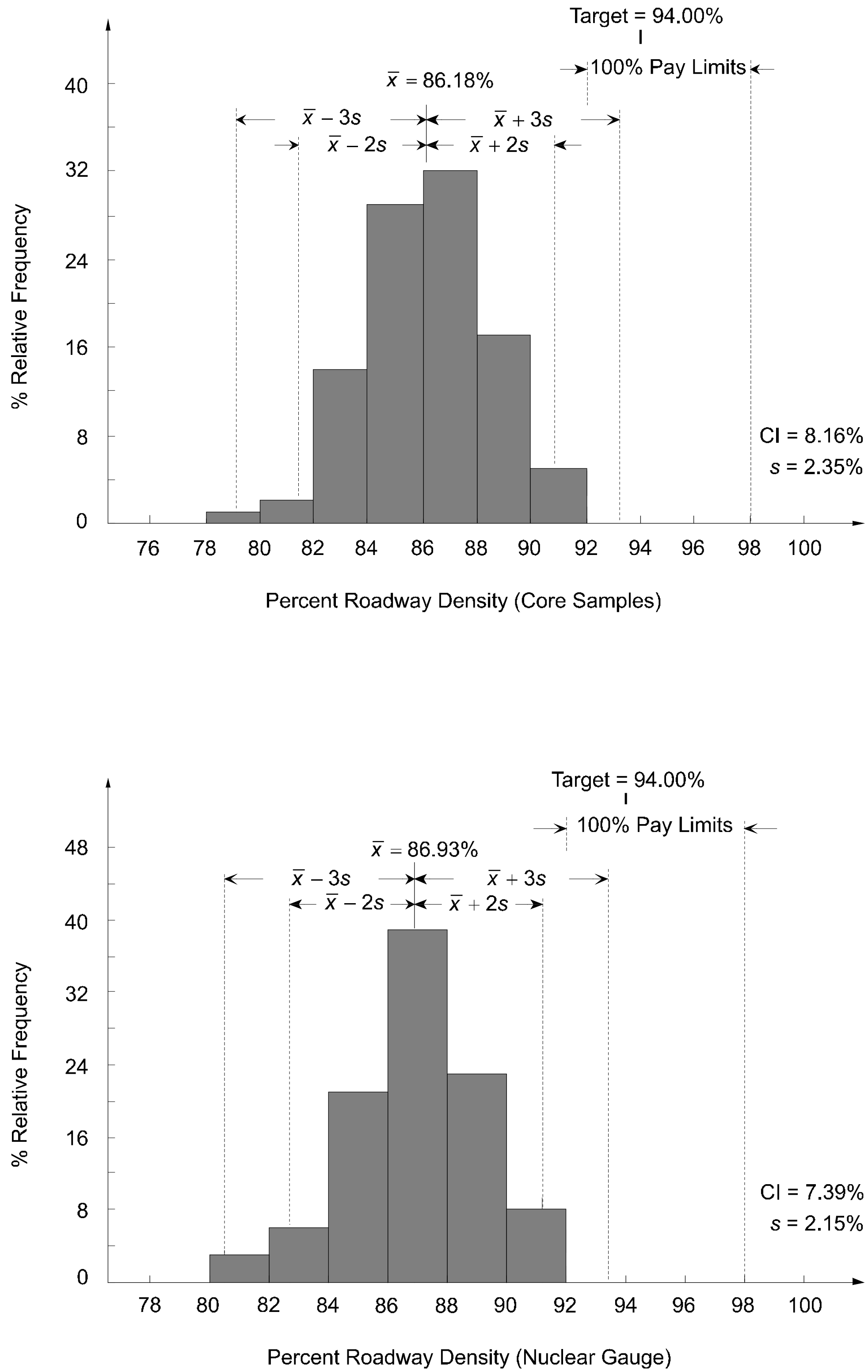


Figure D-12. Percent Roadway Density

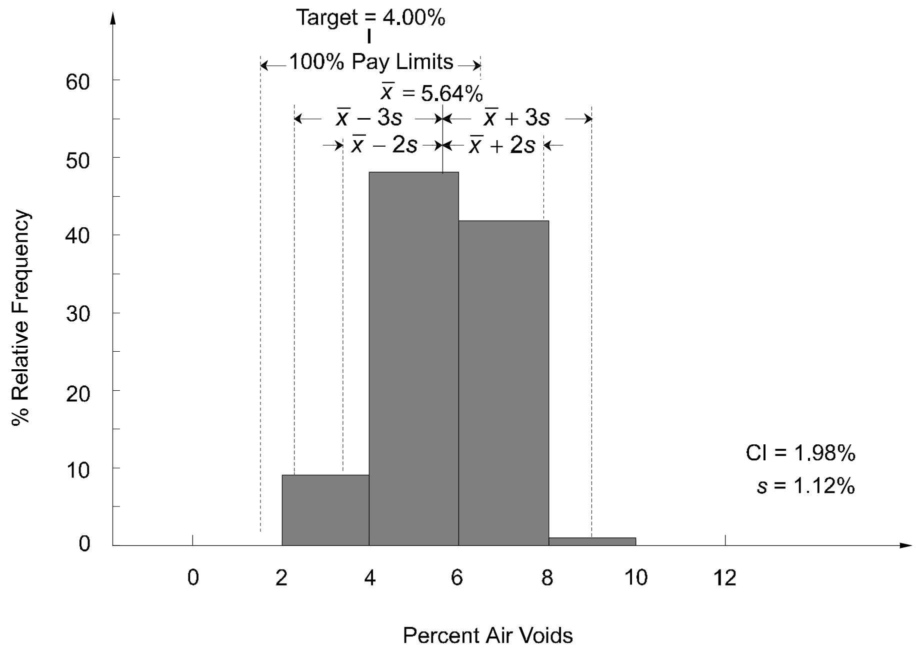


Figure D-13. Percent Air Voids

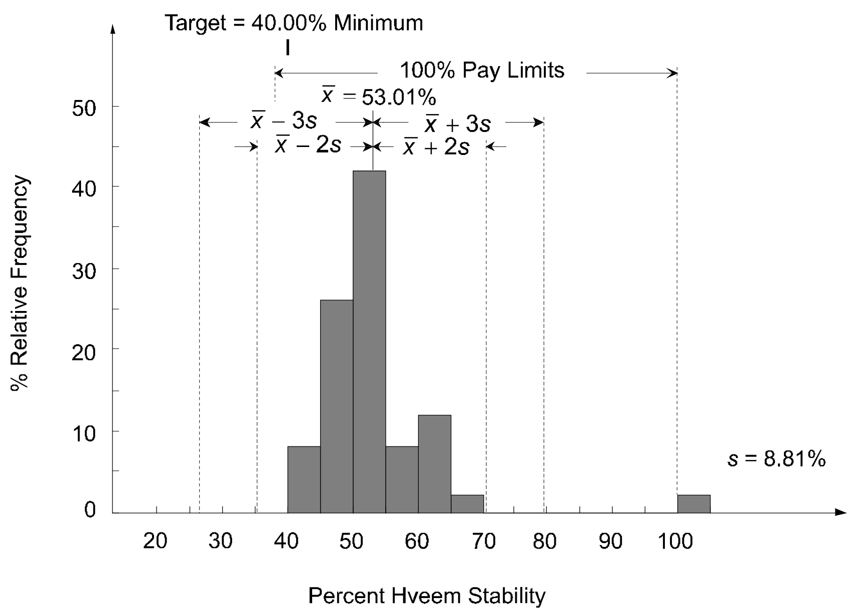
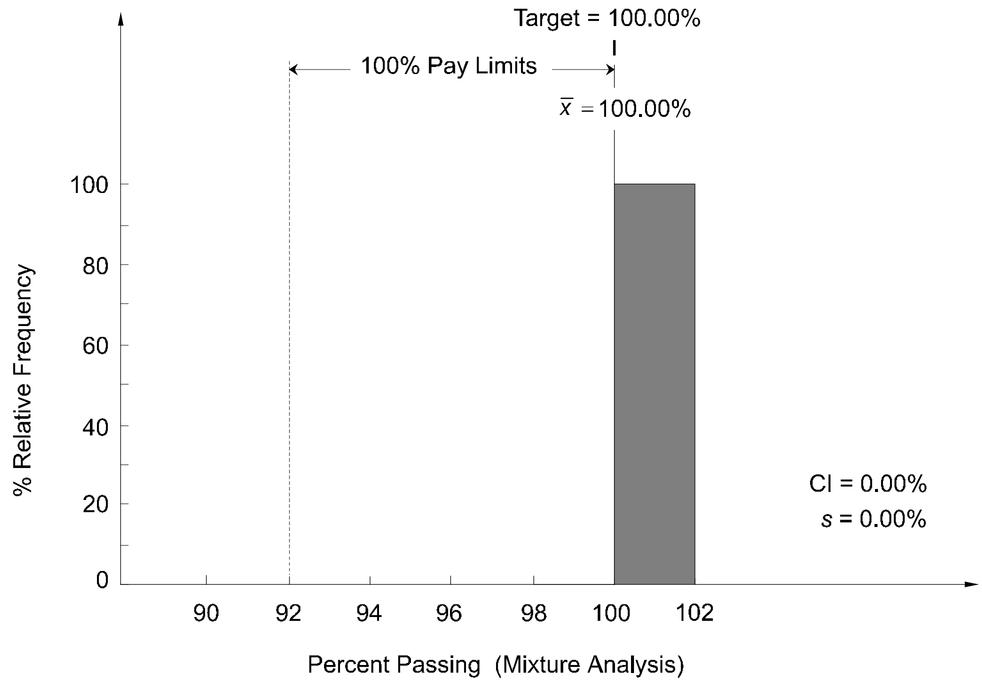


Figure D-14. Percent Hveem Stability

APPENDIX E

DISTRIBUTIONS OF QUALITY CHARACTERISTICS PROJECT 3, US-62



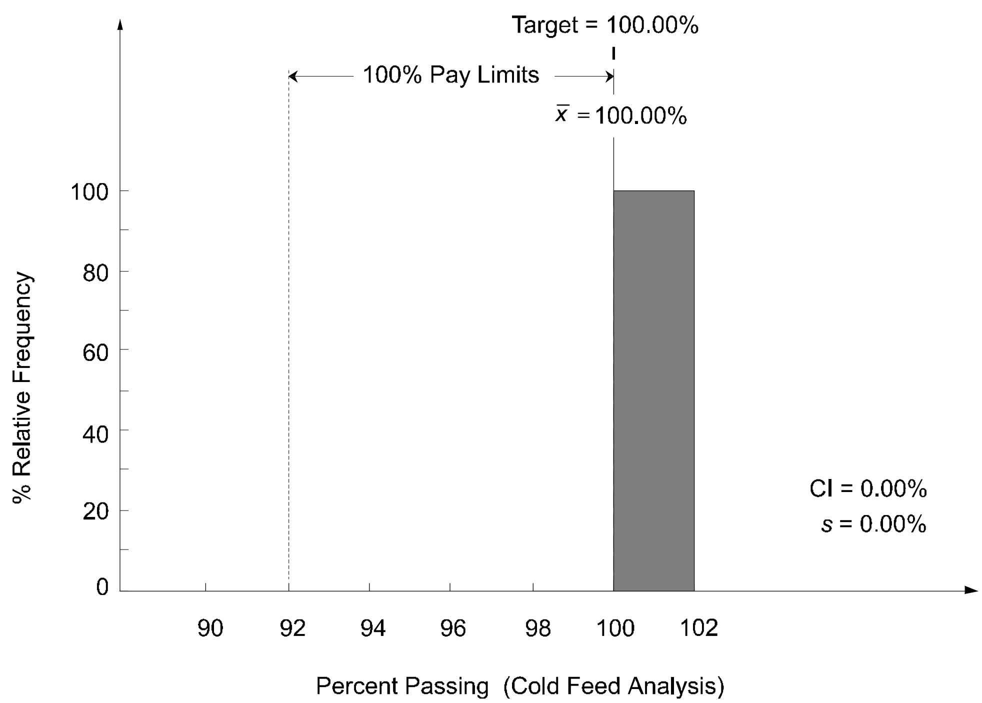


Figure E-1. Percent Passing Sieve 1½ ″

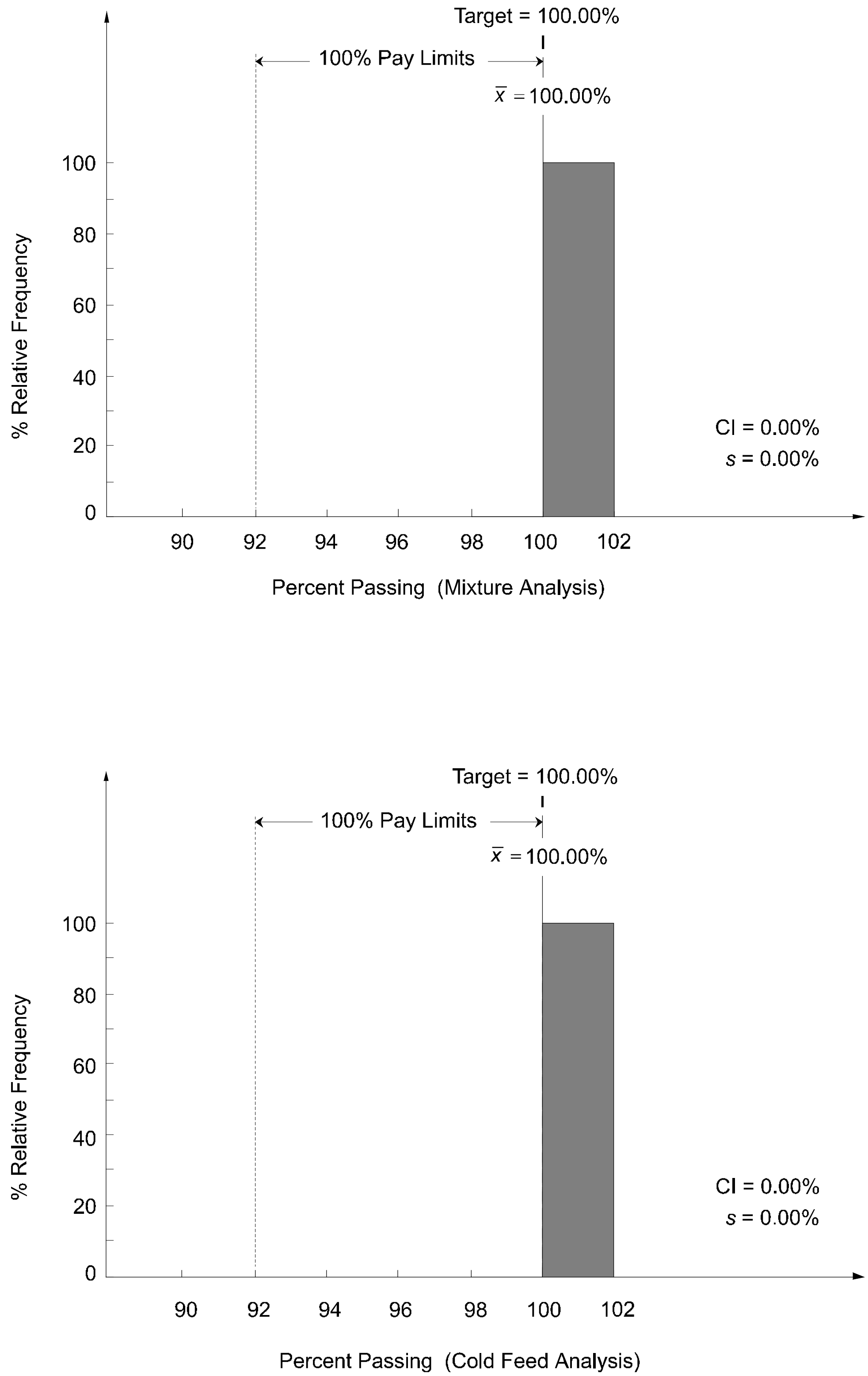
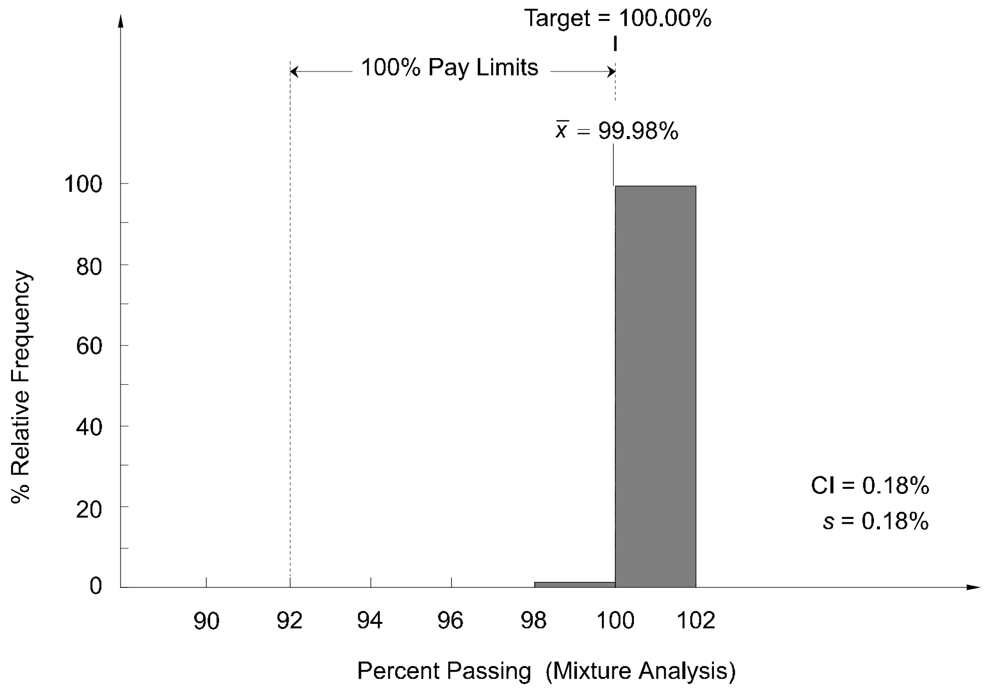


Figure E-2. Percent Passing Sieve 1″



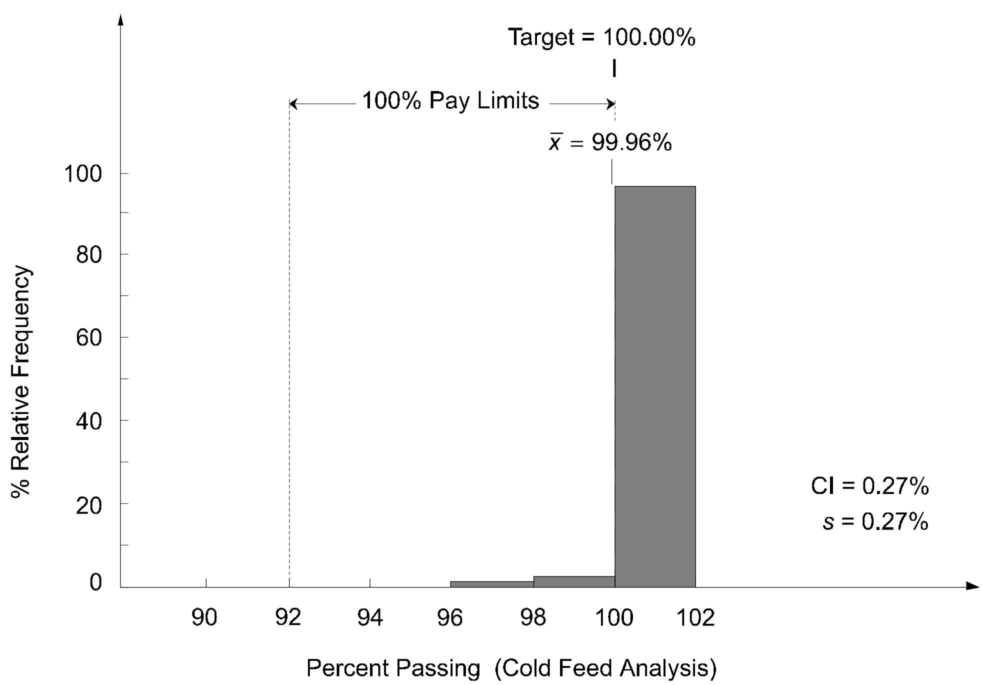
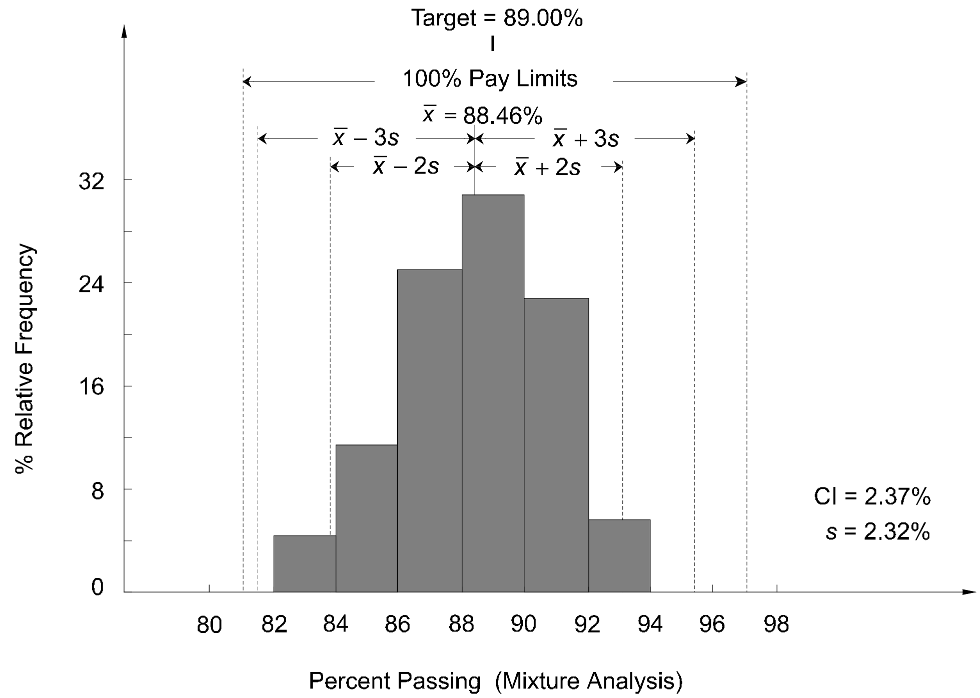


Figure E-3. Percent Passing Sieve ¾″



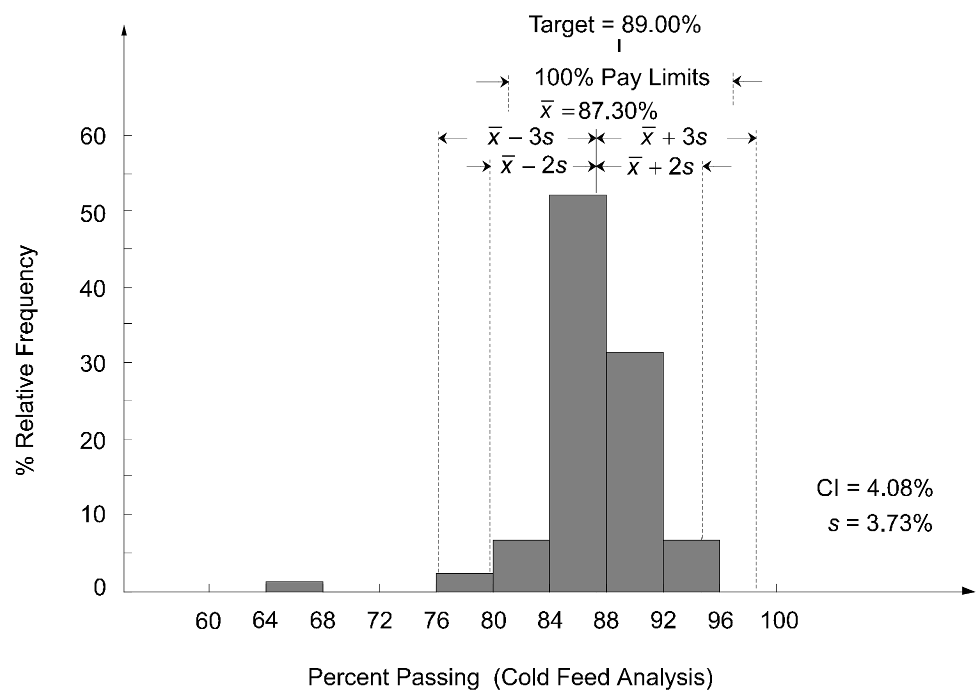
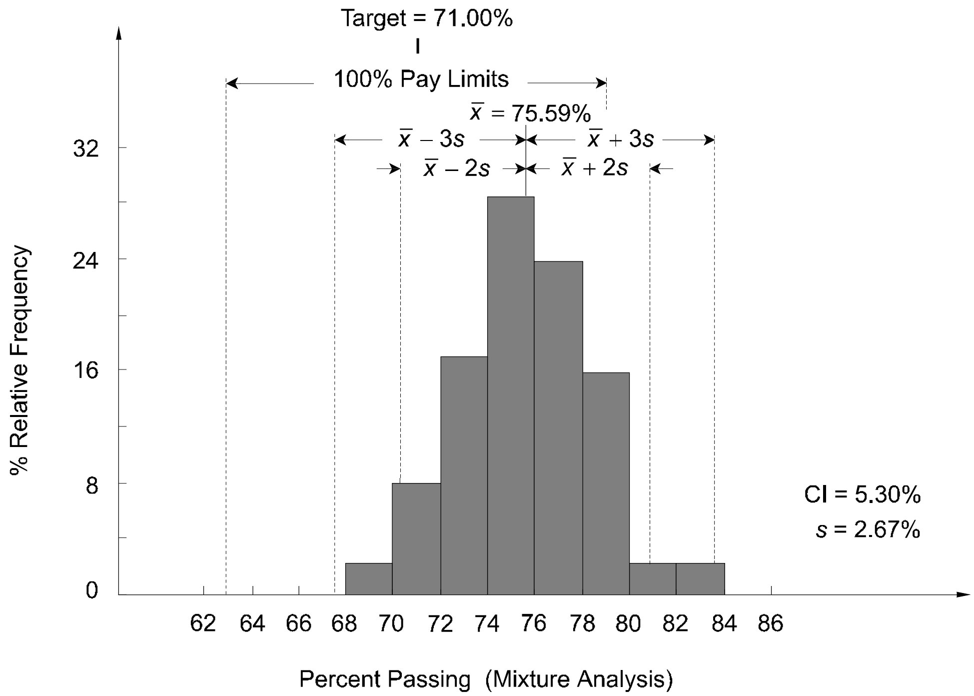


Figure E-4. Percent Passing Sieve ½″



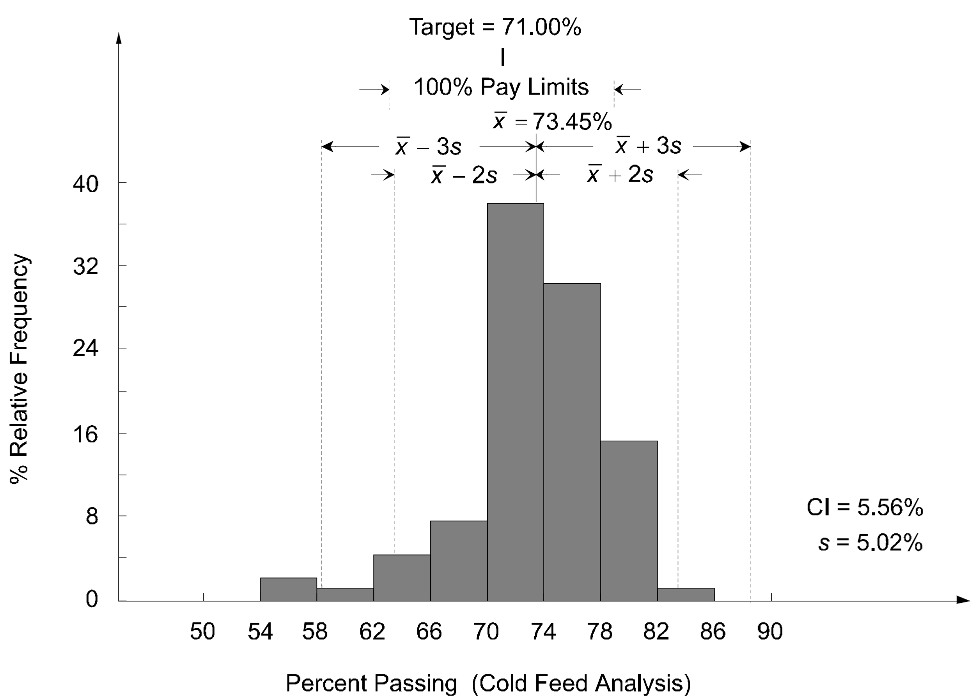
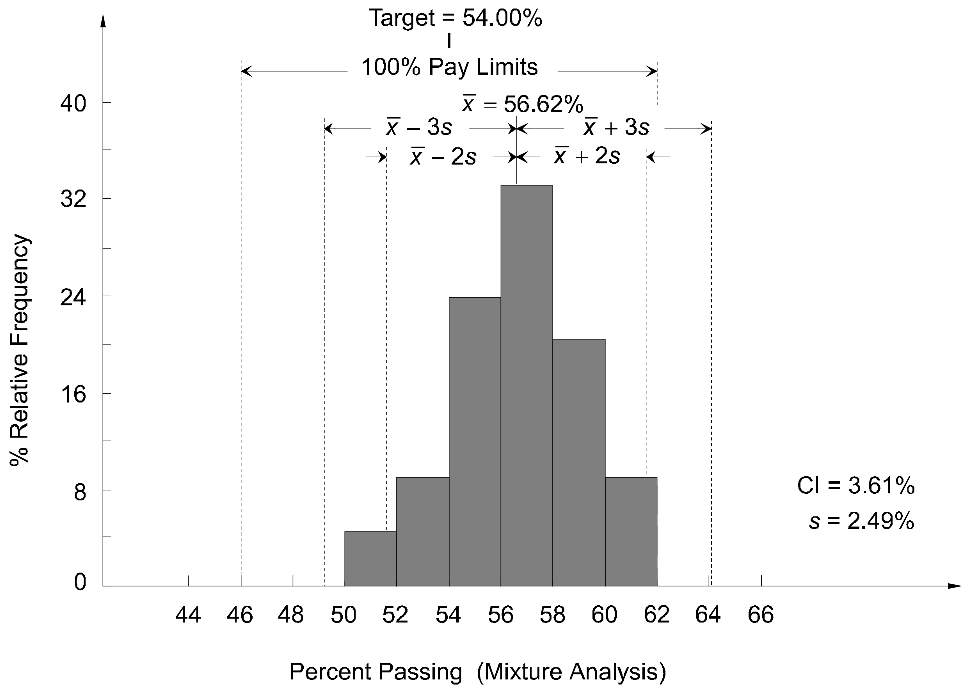


Figure E-5. Percent Passing Sieve 3/8″



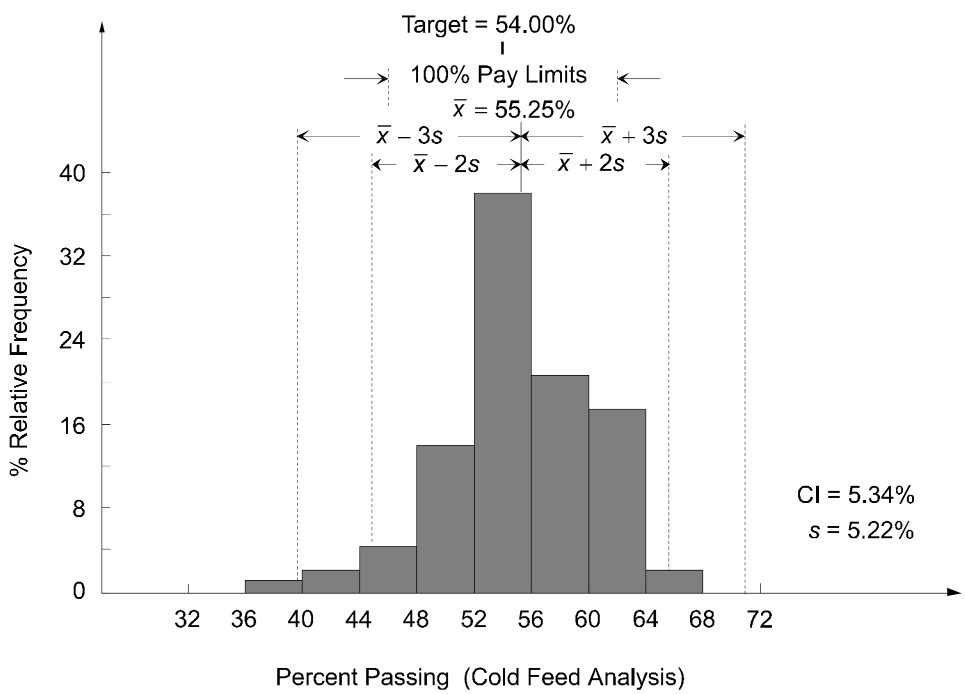
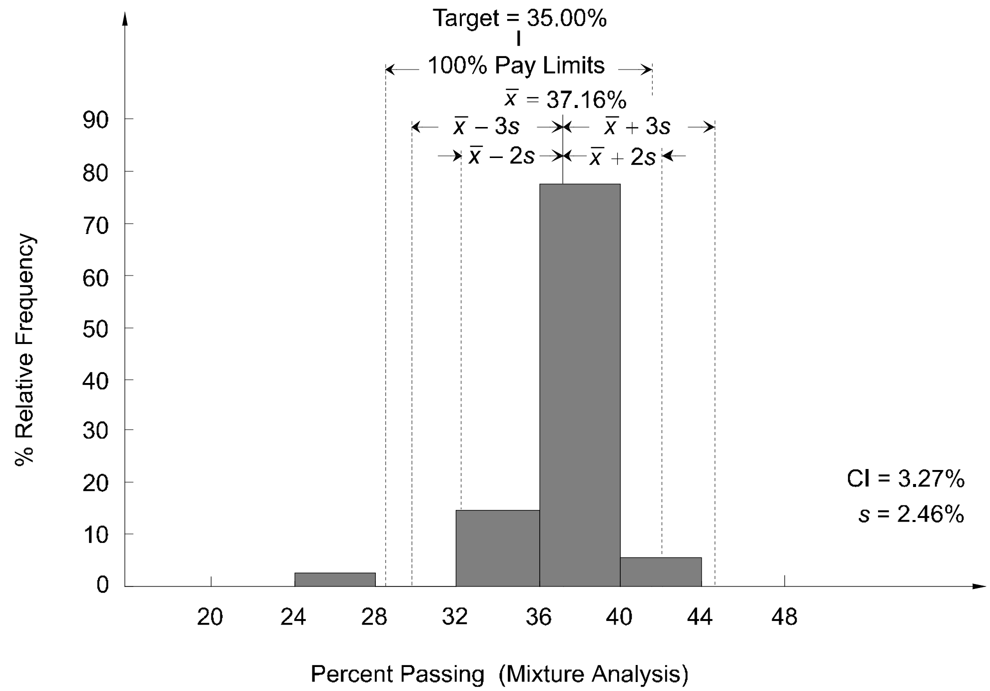


Figure E-6. Percent Passing Sieve No. 4



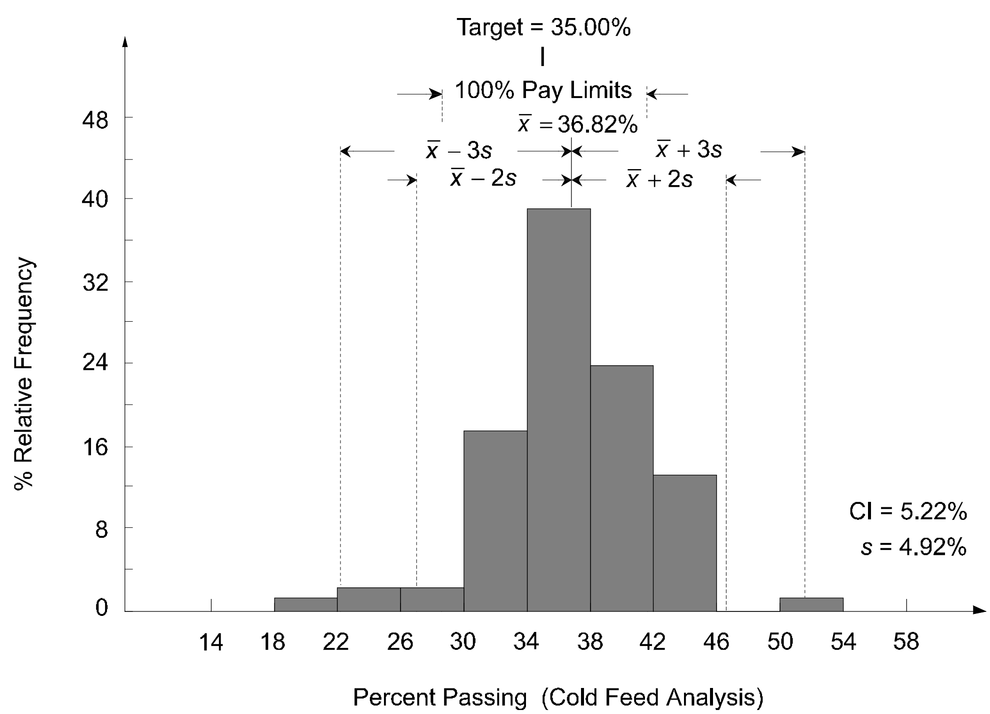
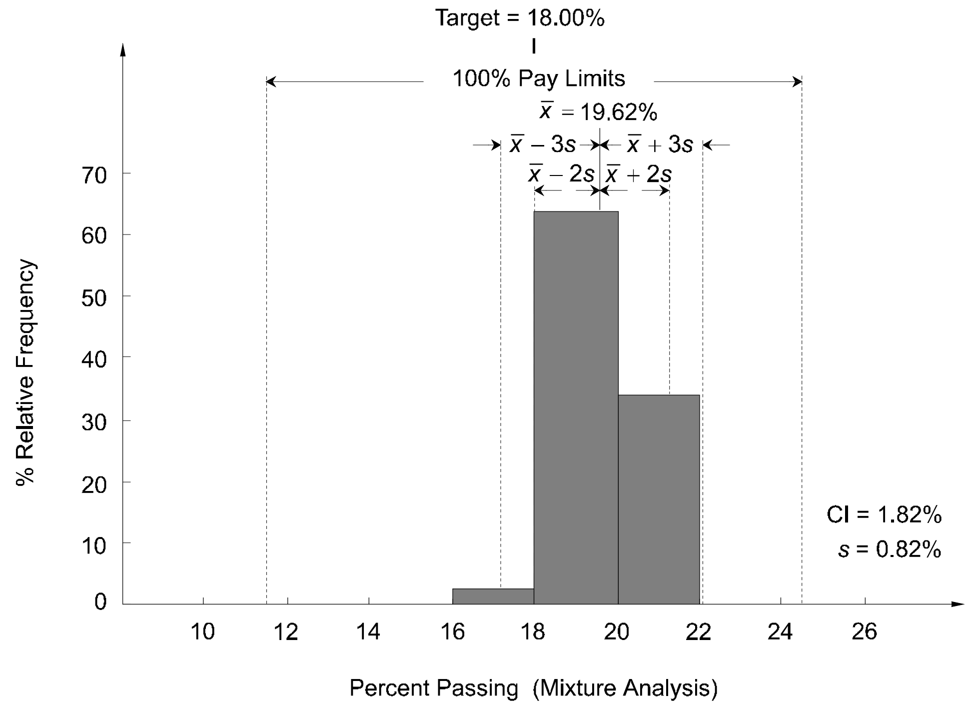


Figure E-7. Percent Passing Sieve No. 10



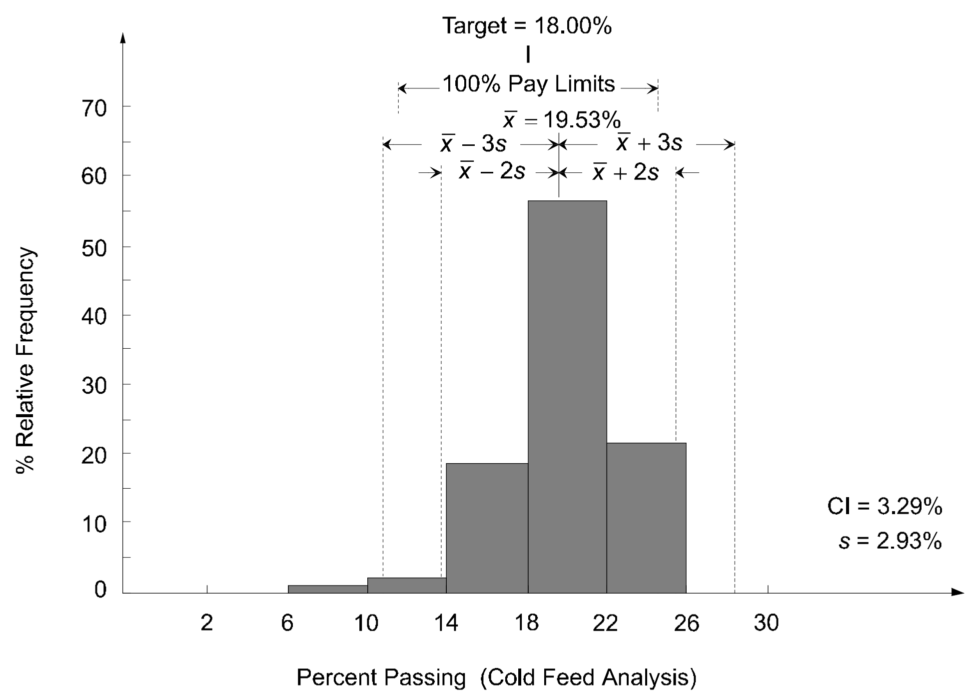
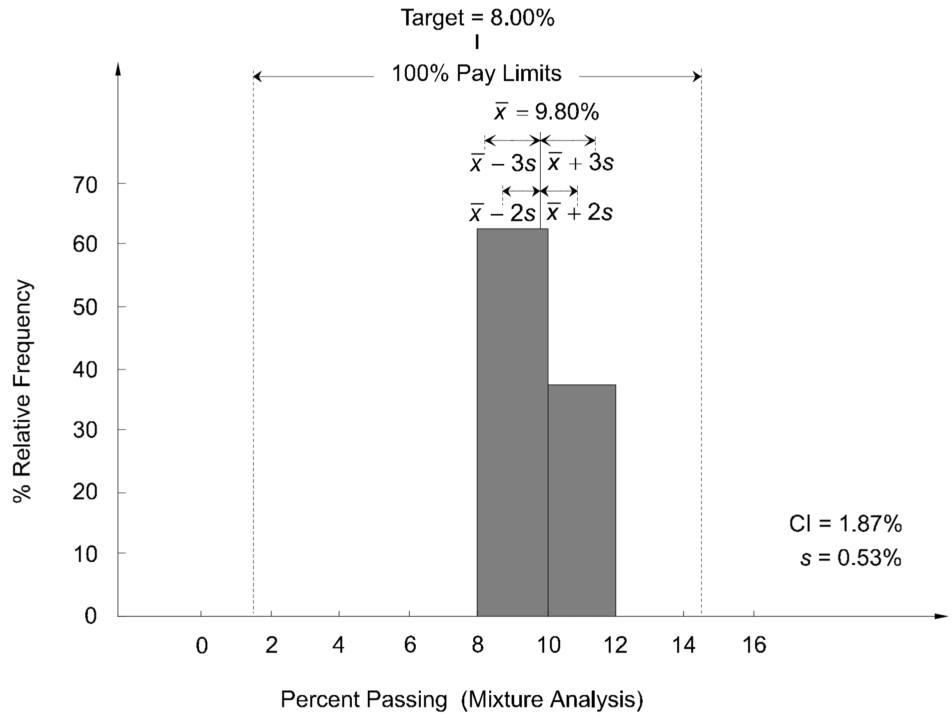


Figure E-8. Percent Passing Sieve No. 40



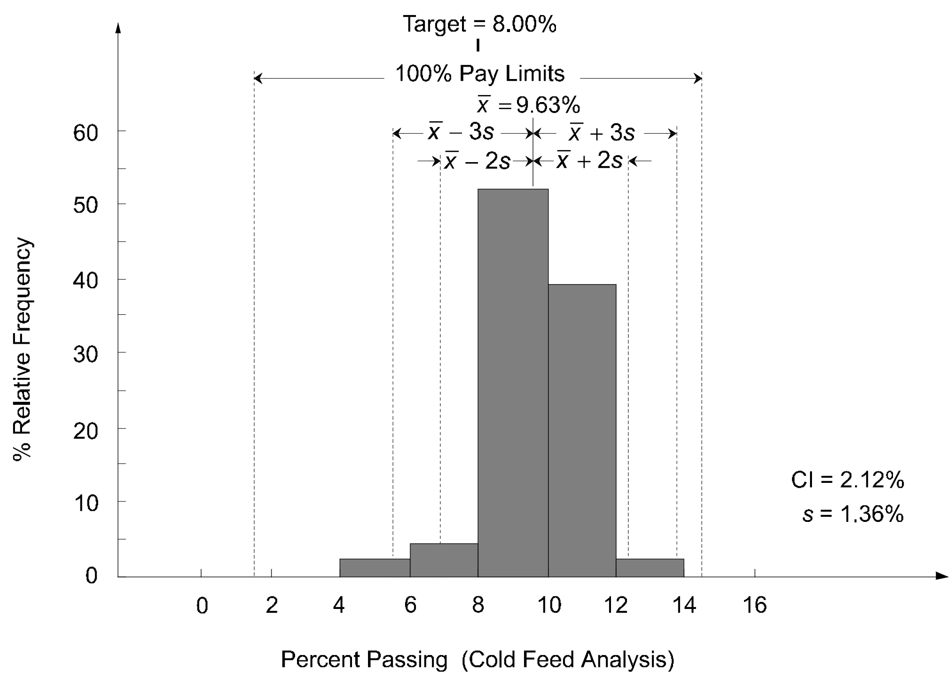
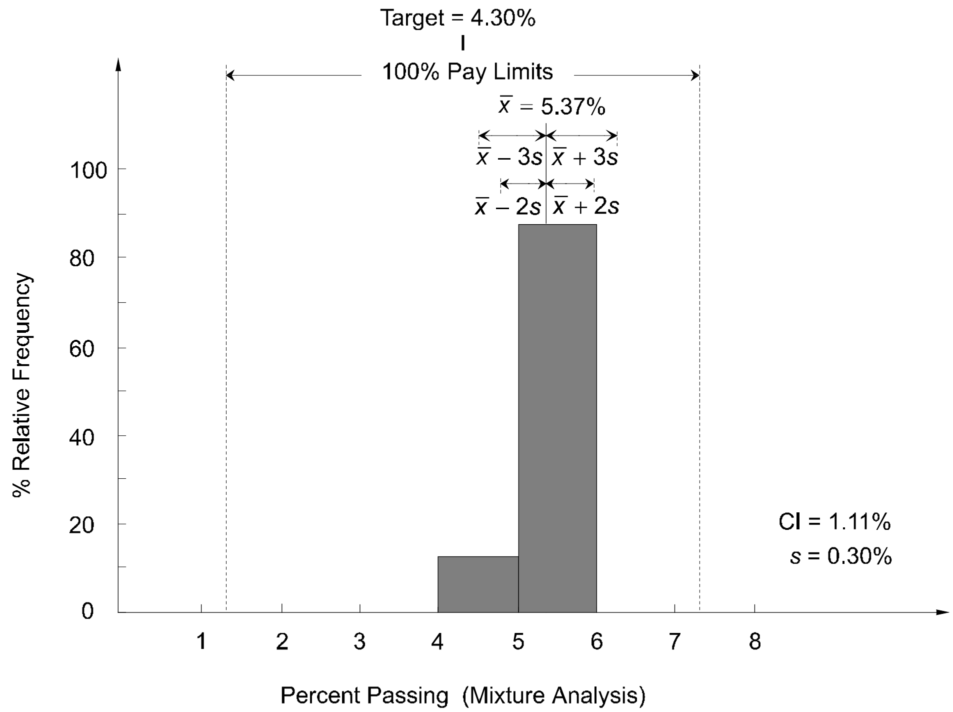


Figure E-9. Percent Passing Sieve No. 80



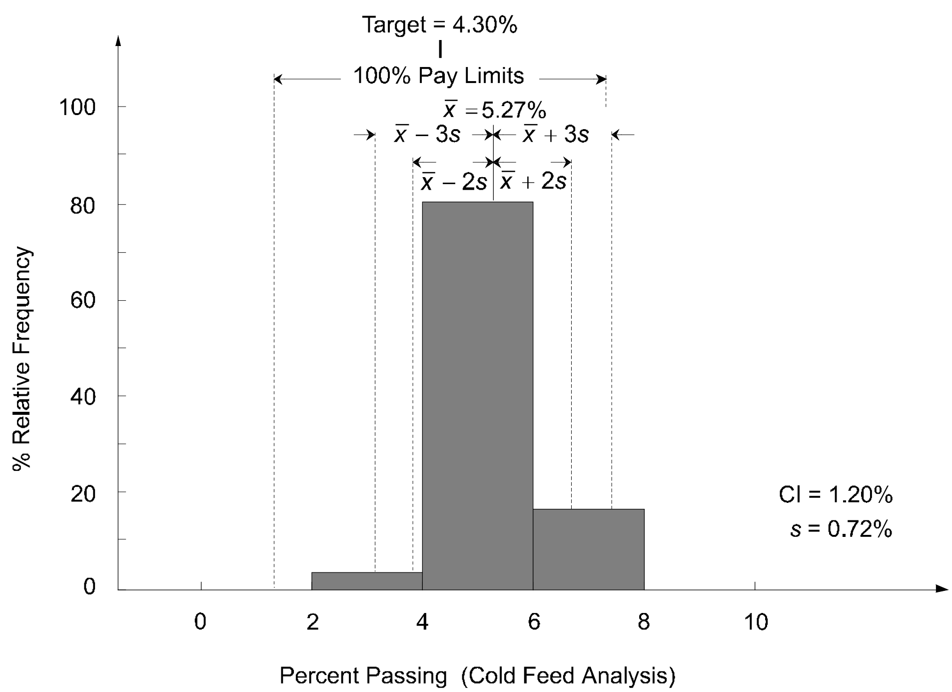
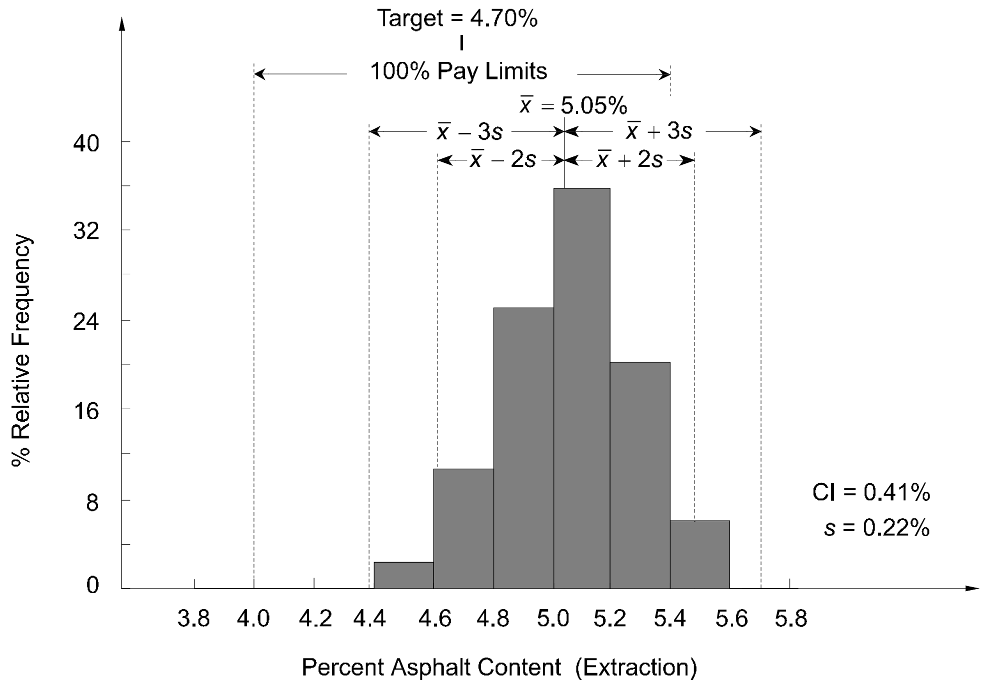


Figure E-10. Percent Passing Sieve No. 200



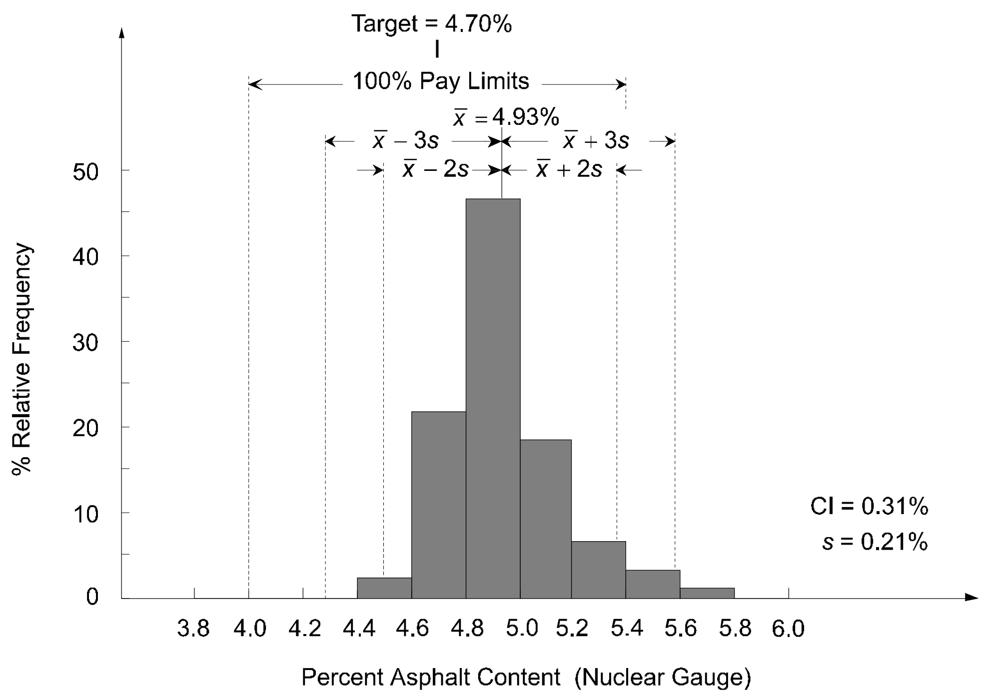


Figure E-11. Percent Asphalt Content

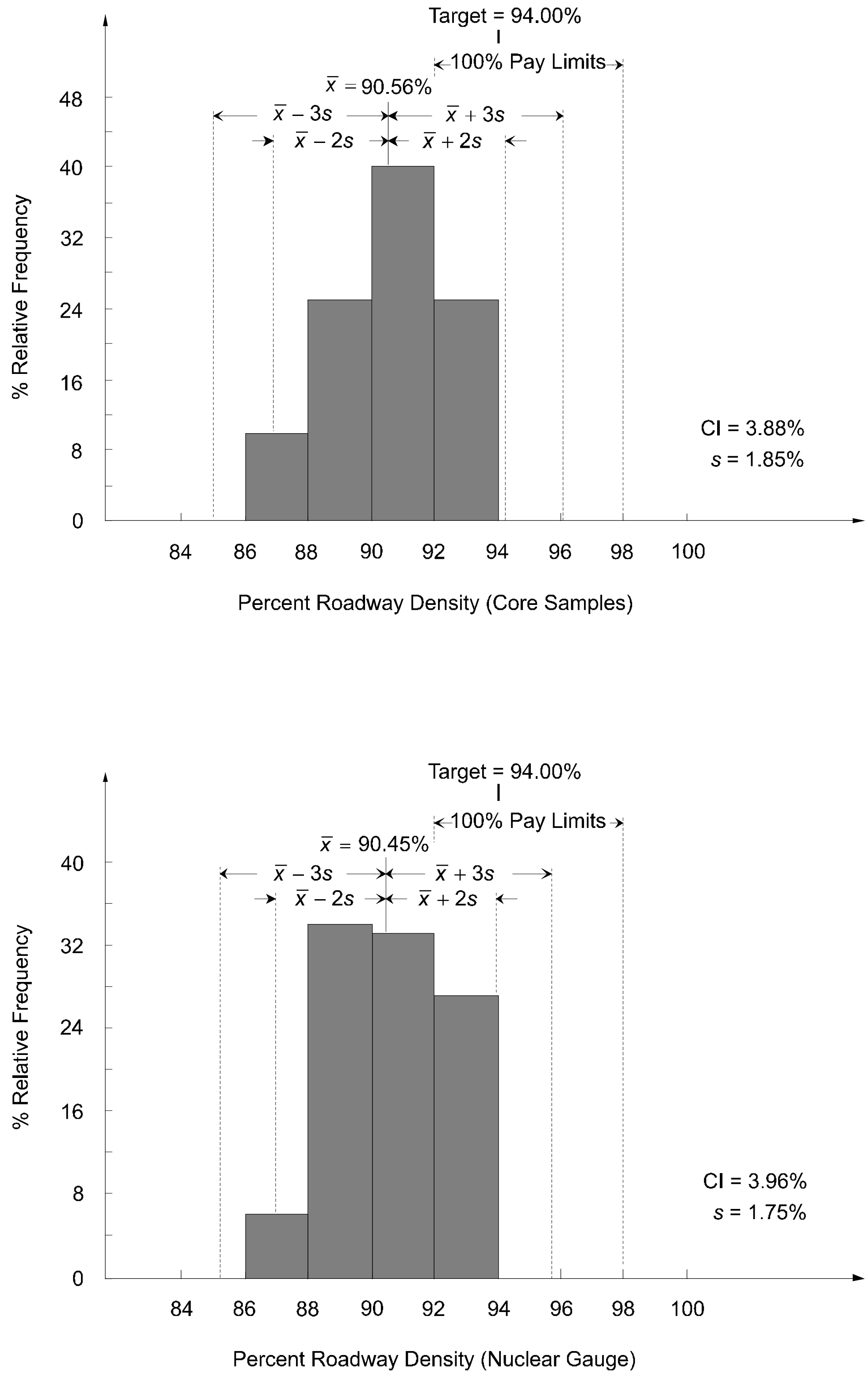


Figure E-12. Percent Roadway Density

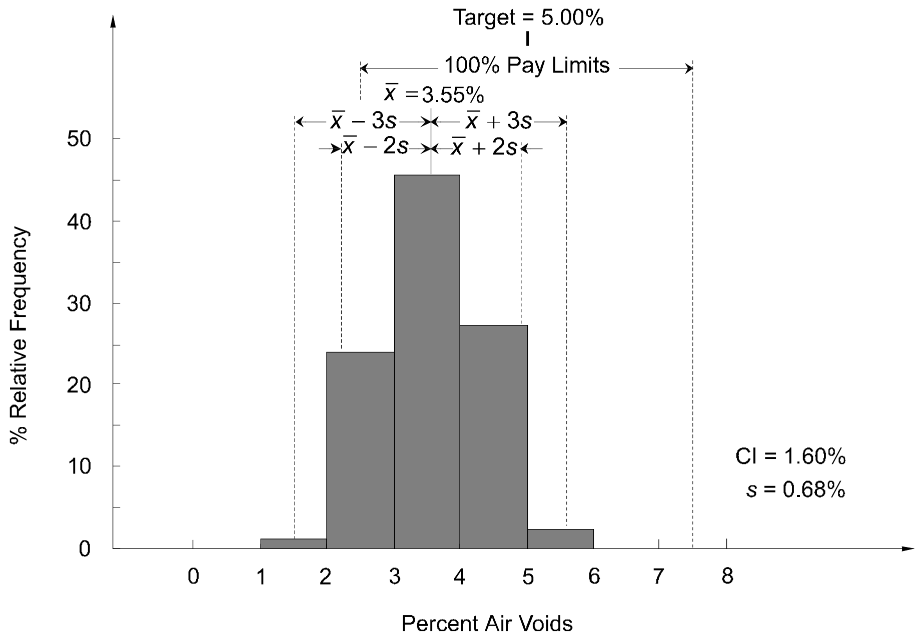


Figure E-13. Percent Air Voids

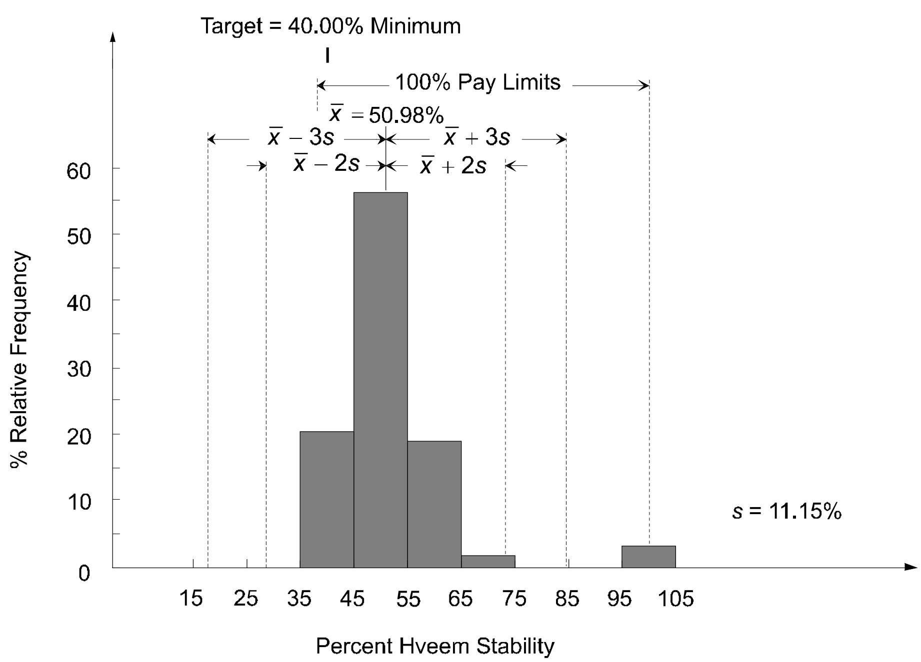
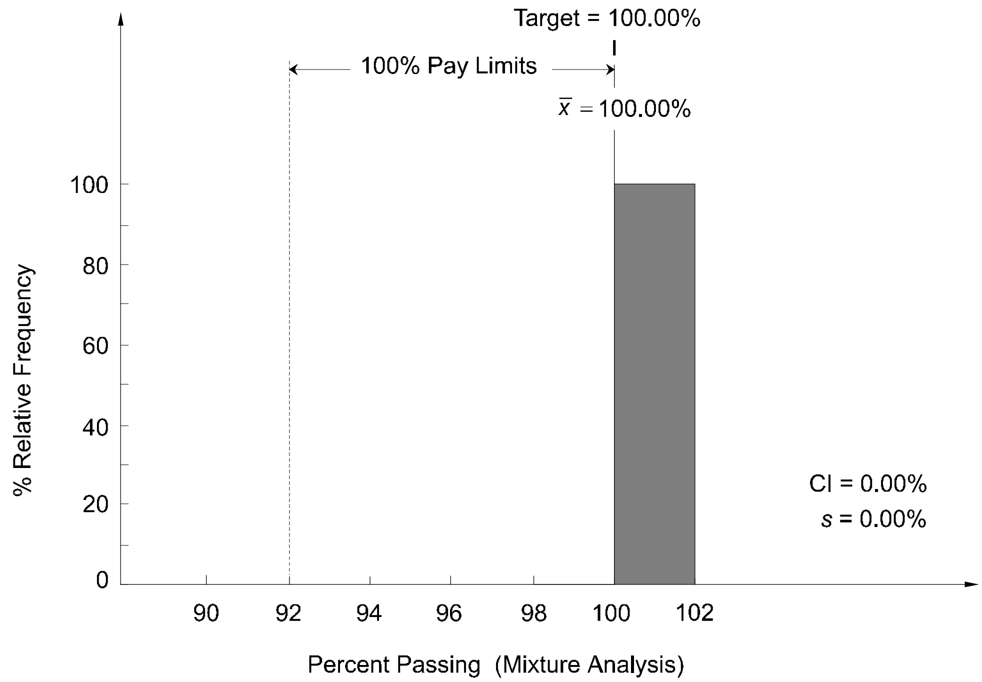


Figure E-14. Percent Hveem Stability

APPENDIX F

DISTRIBUTIONS OF QUALITY CHARACTERISTICS PROJECT 4, US-69



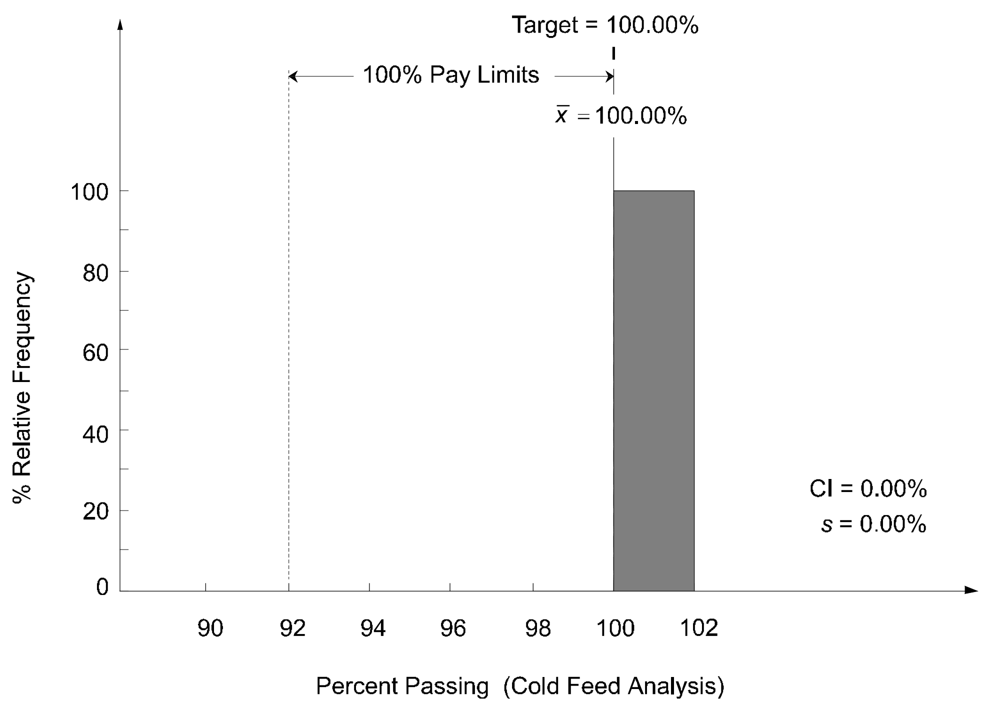


Figure F-1. Percent Passing Sieve 1½″

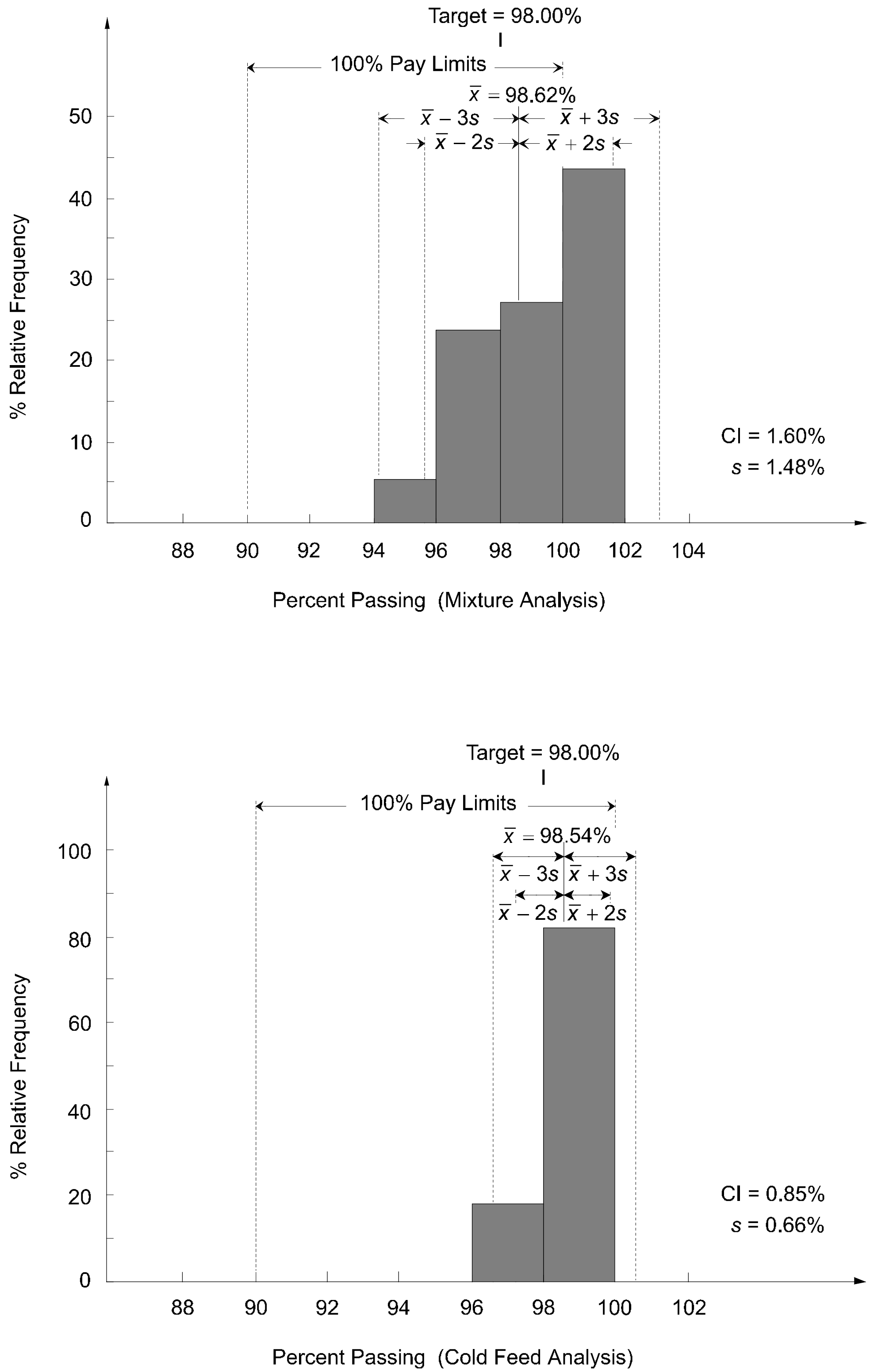
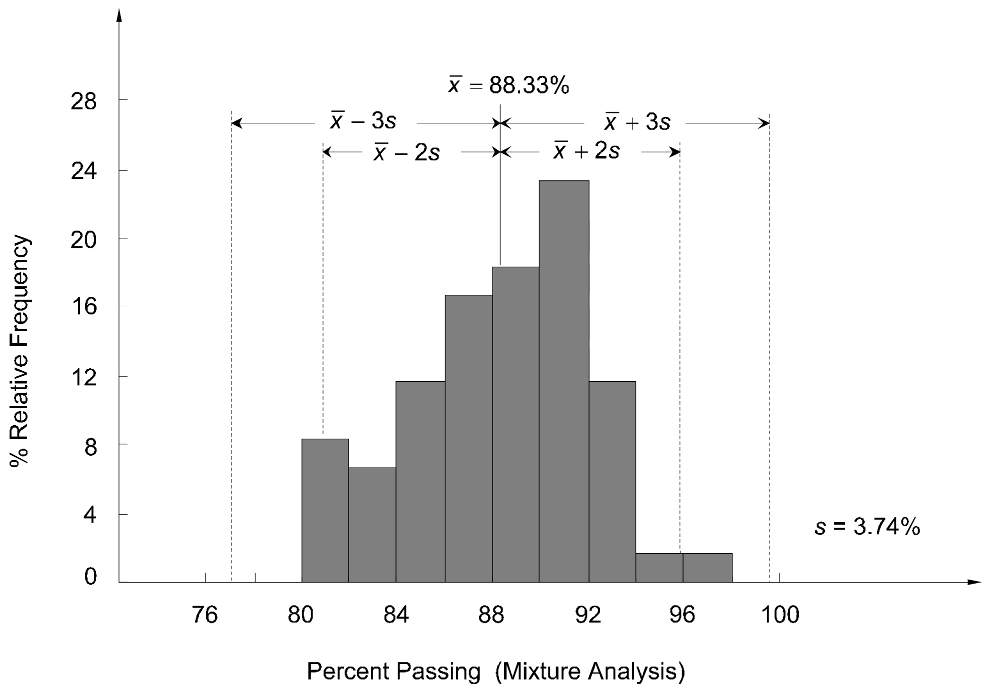


Figure F-2. Percent Passing Sieve 1″



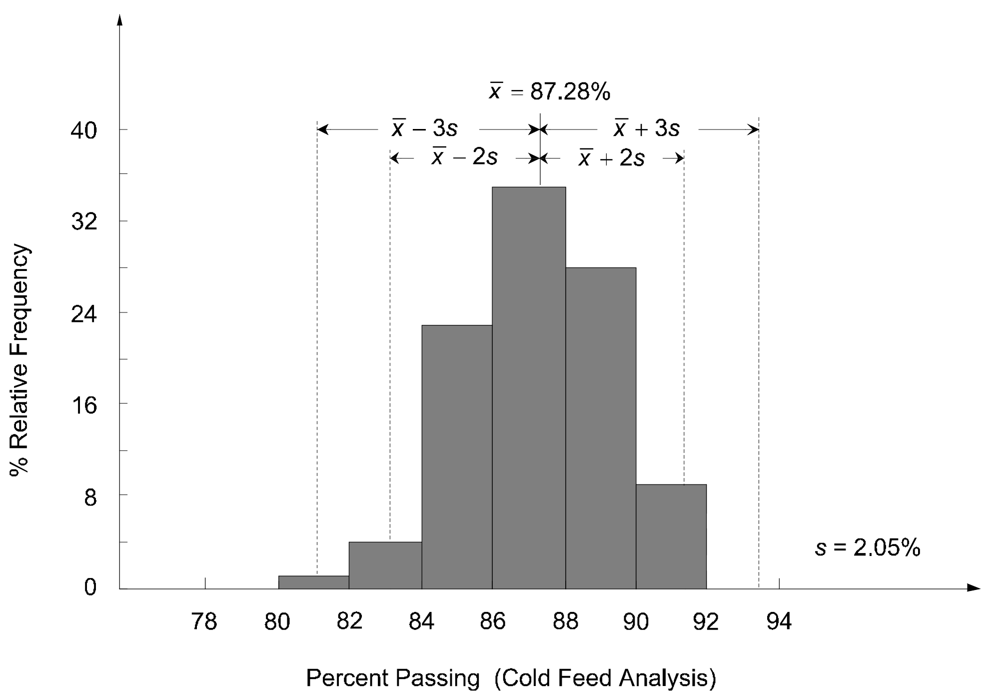
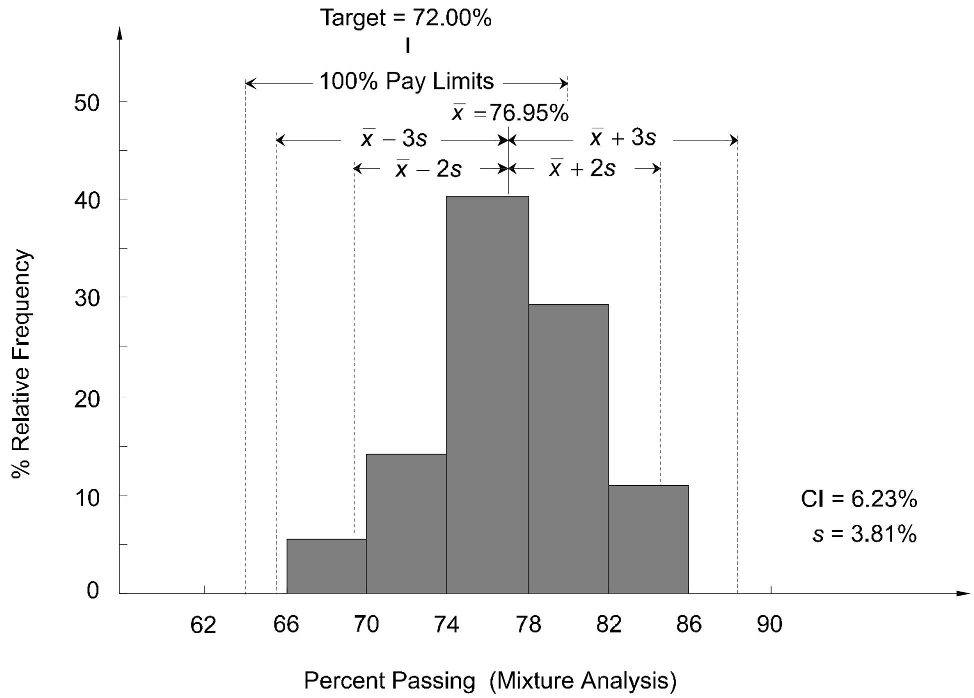


Figure F-3. Percent Passing Sieve ¾″



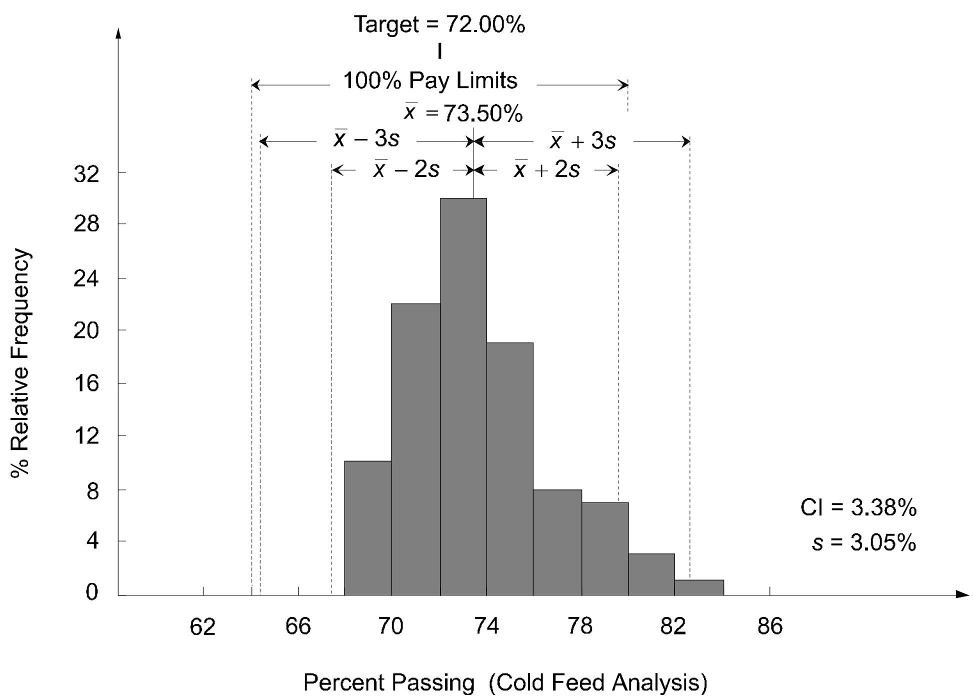
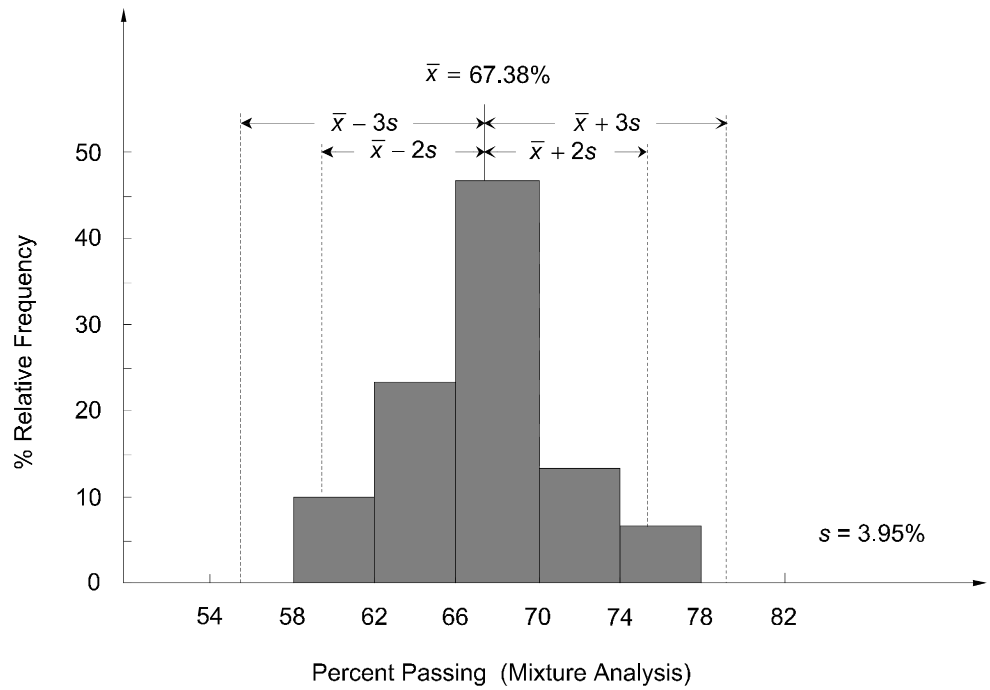


Figure F-4. Percent Passing Sieve ½″



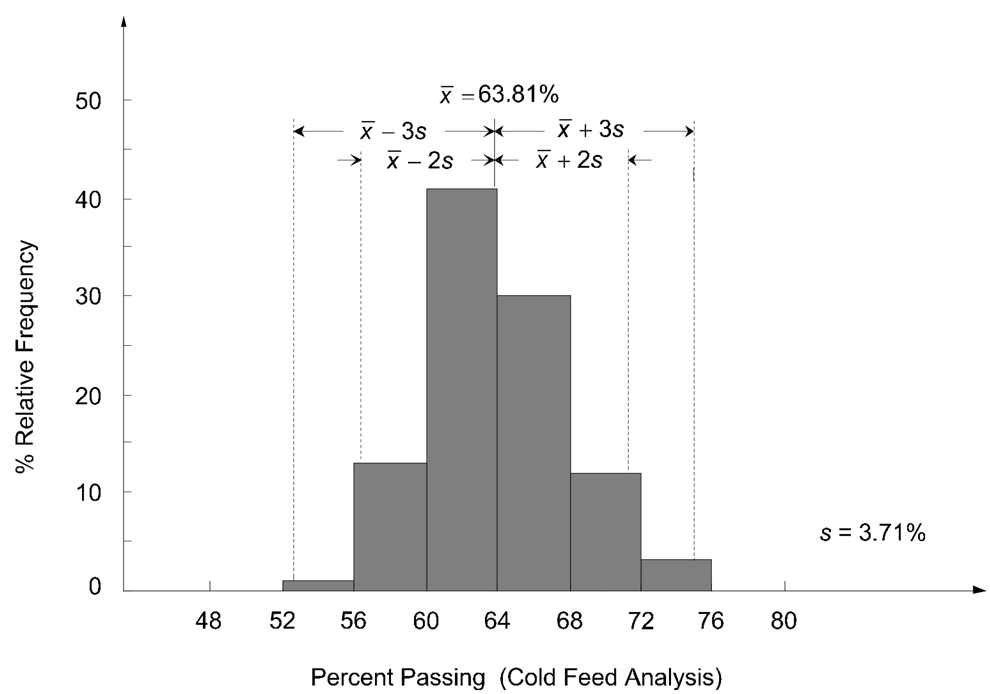
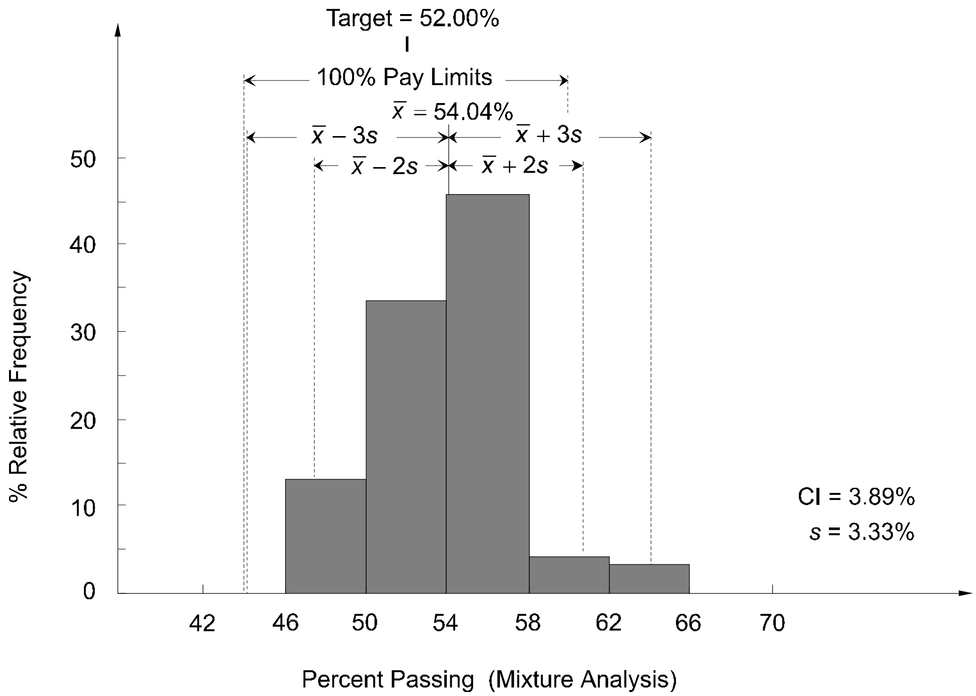


Figure F-5. Percent Passing Sieve 3/8″



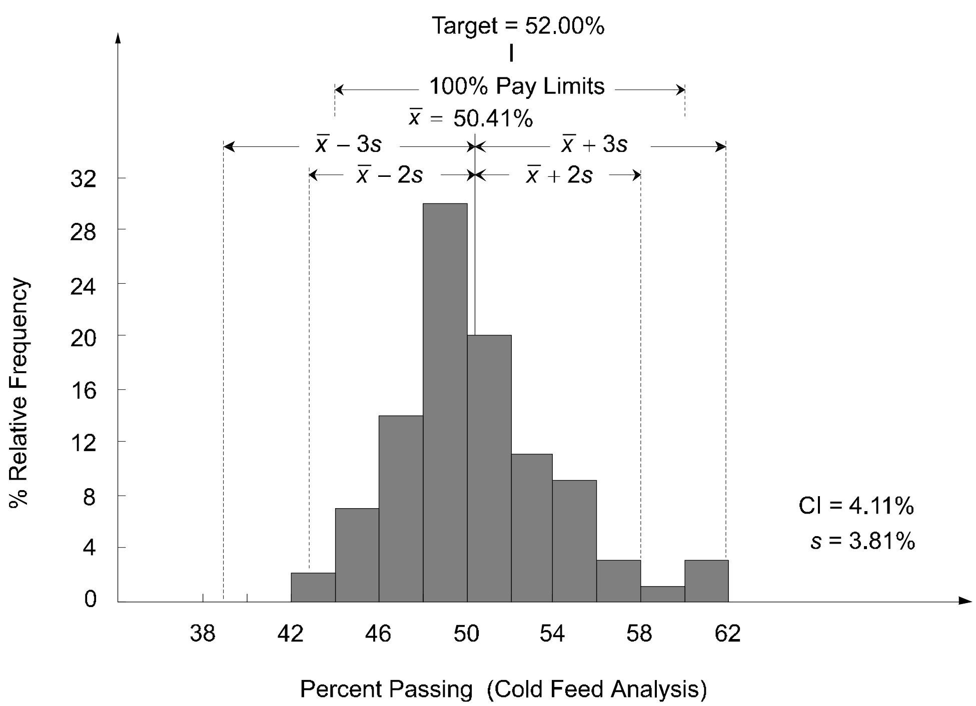
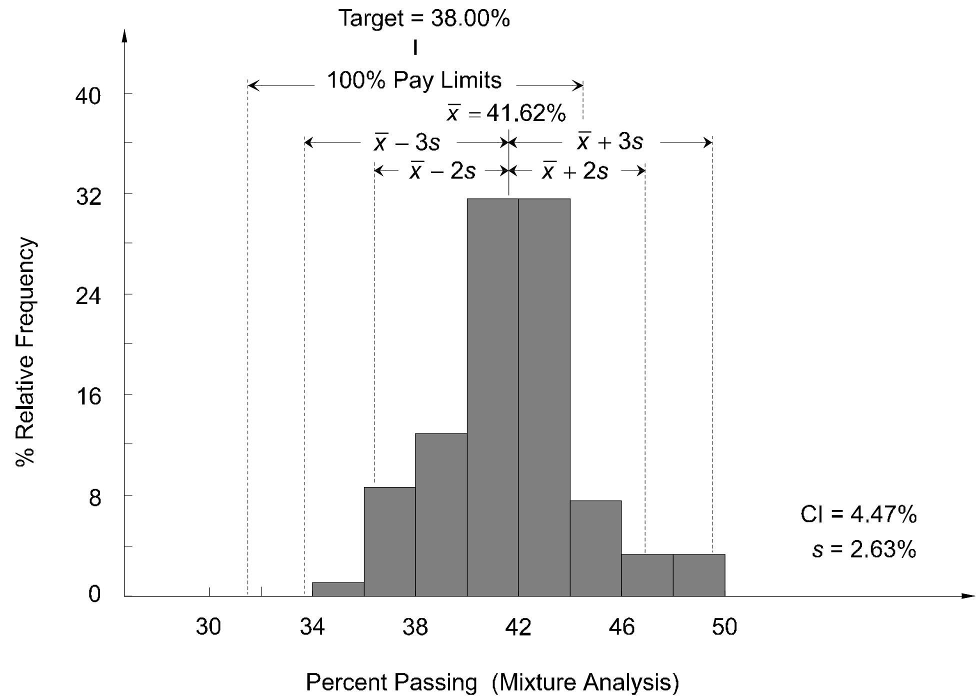


Figure F-6. Percent Passing Sieve No. 4



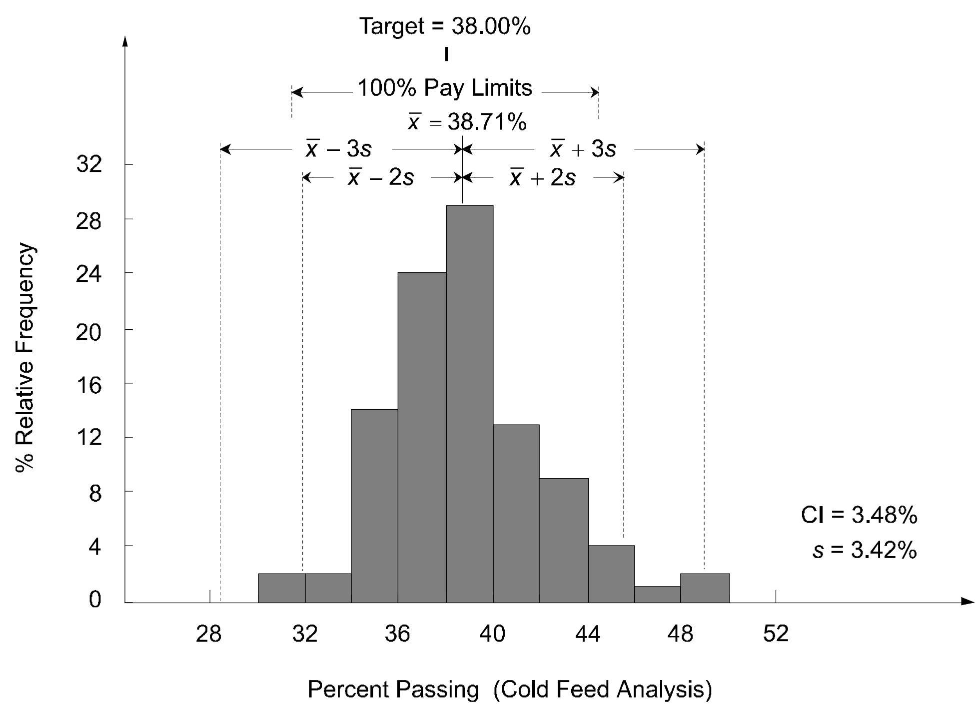
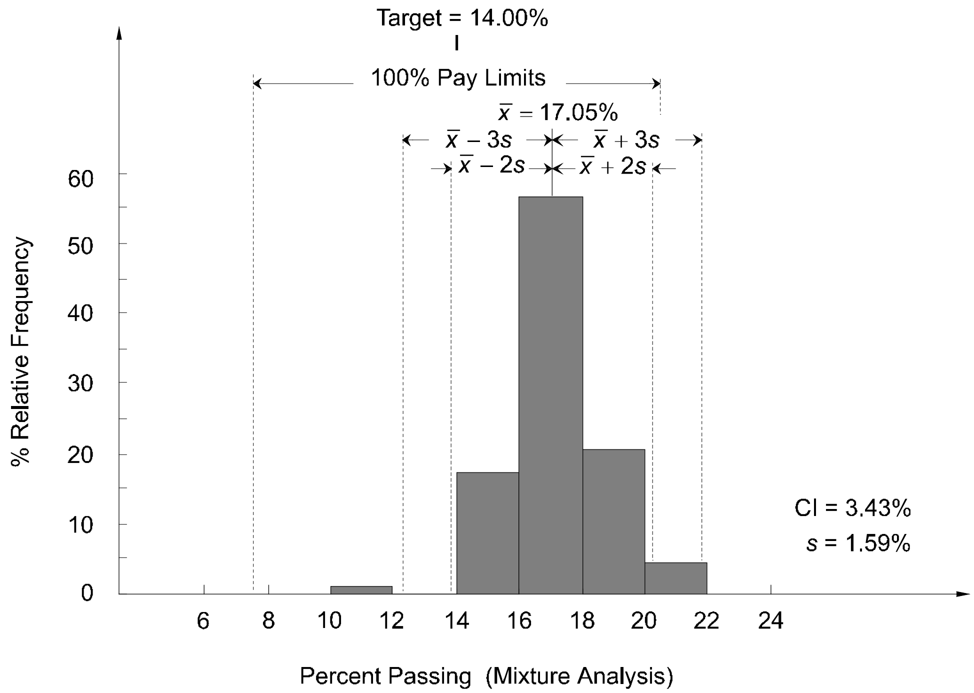


Figure F-7. Percent Passing Sieve No. 10



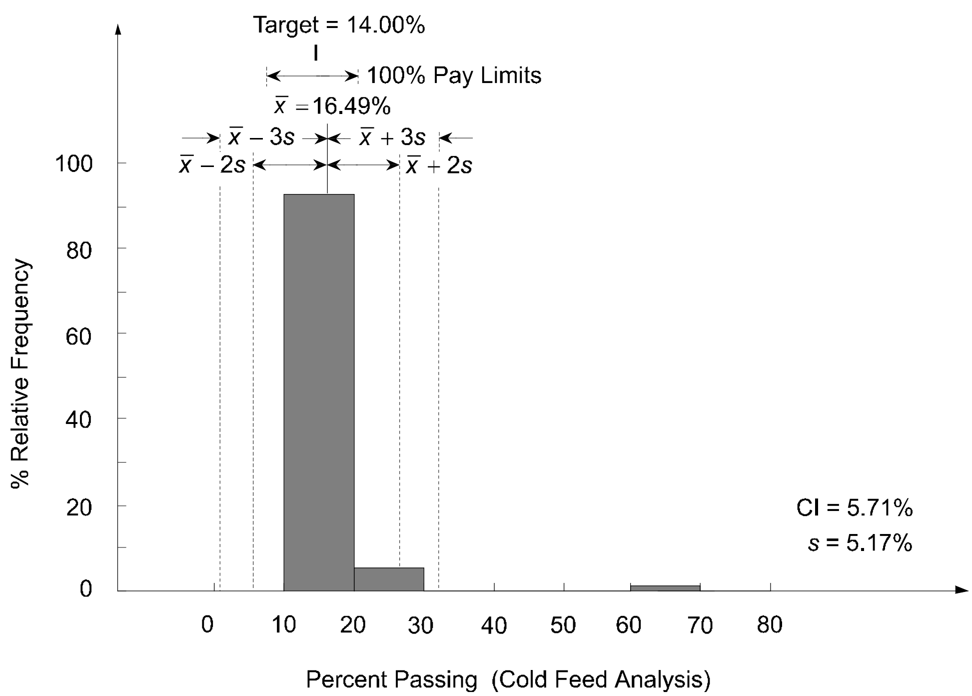
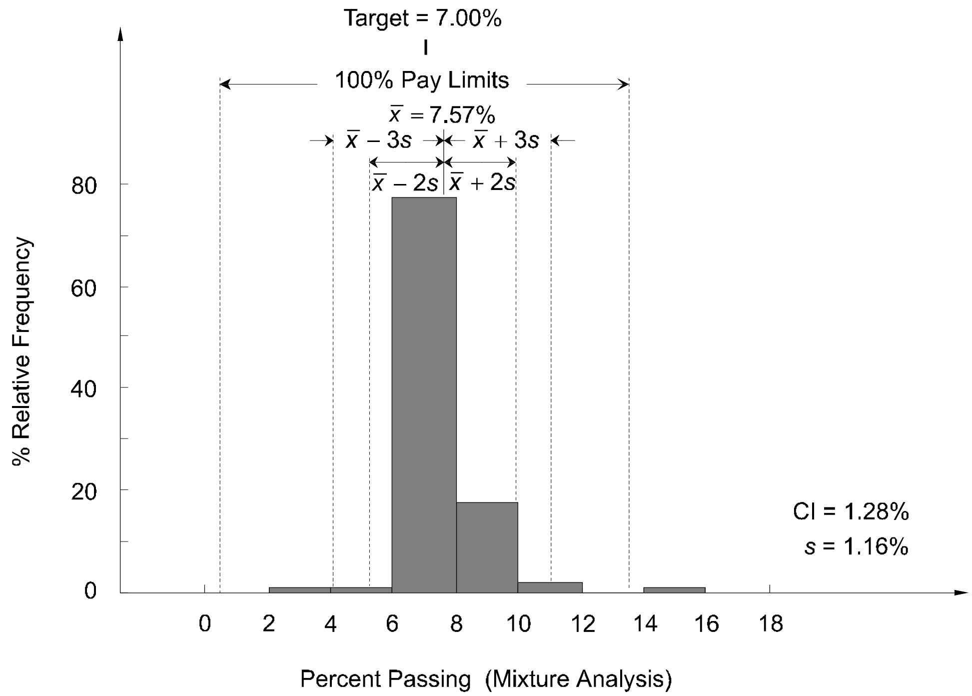


Figure F-8. Percent Passing Sieve No. 40



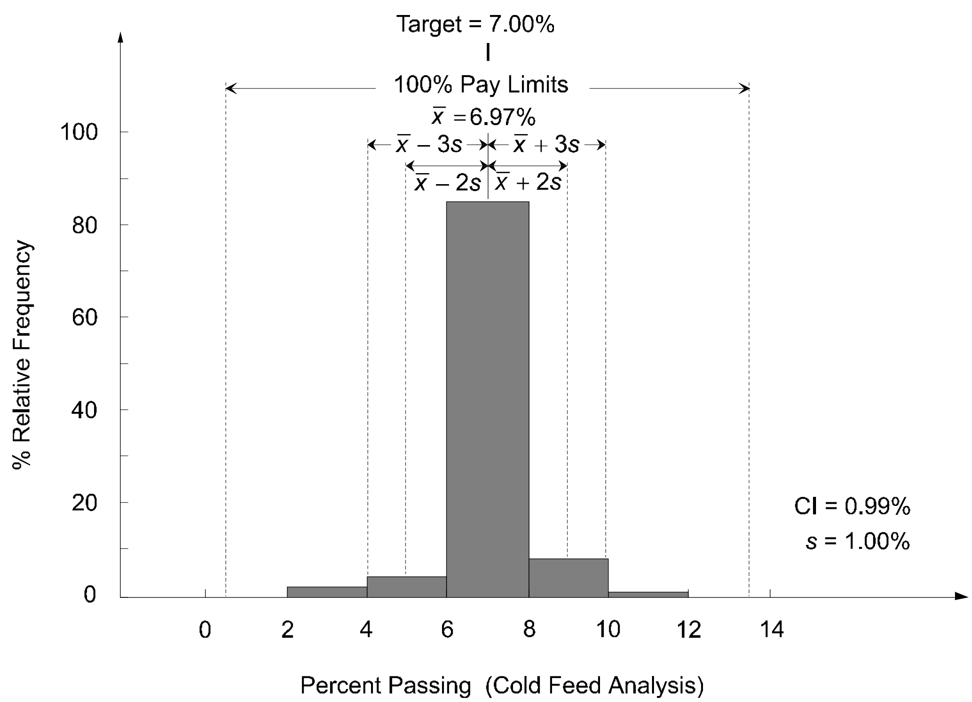
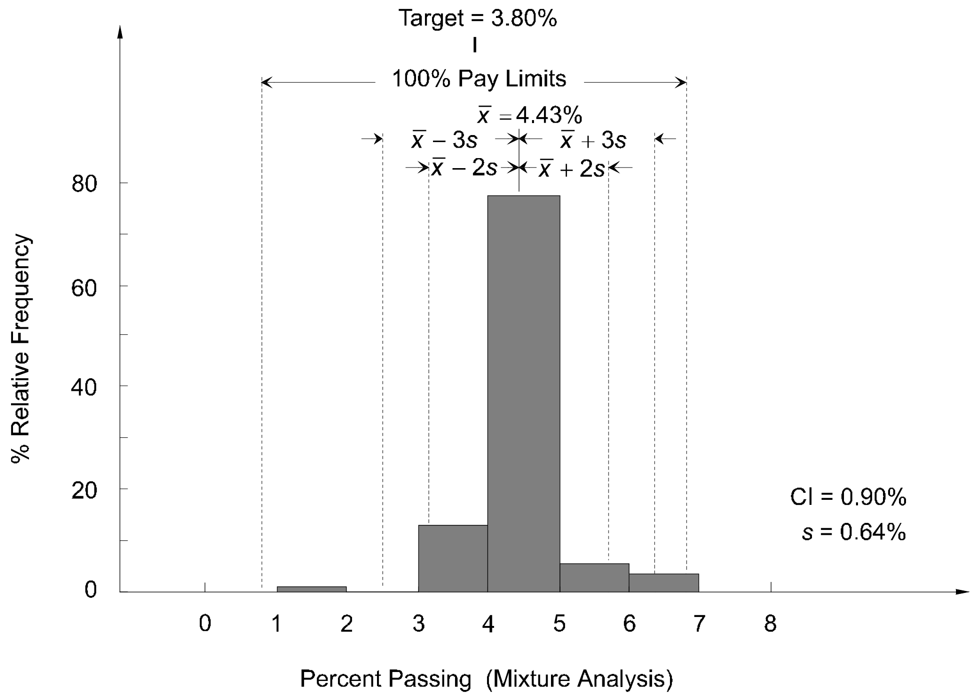


Figure F-9. Percent Passing Sieve No. 80



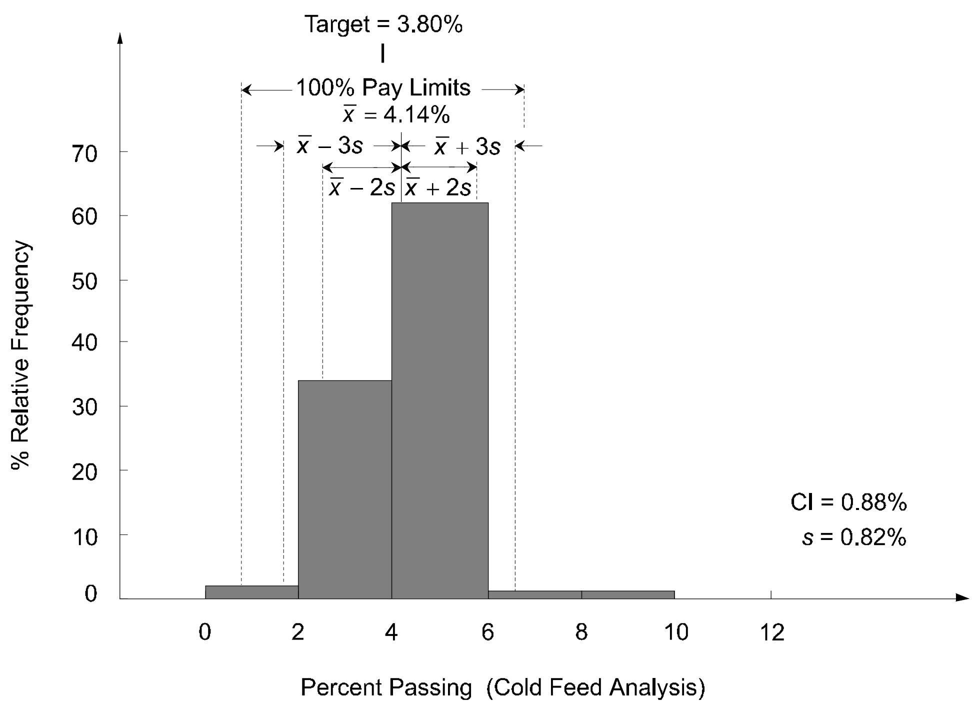
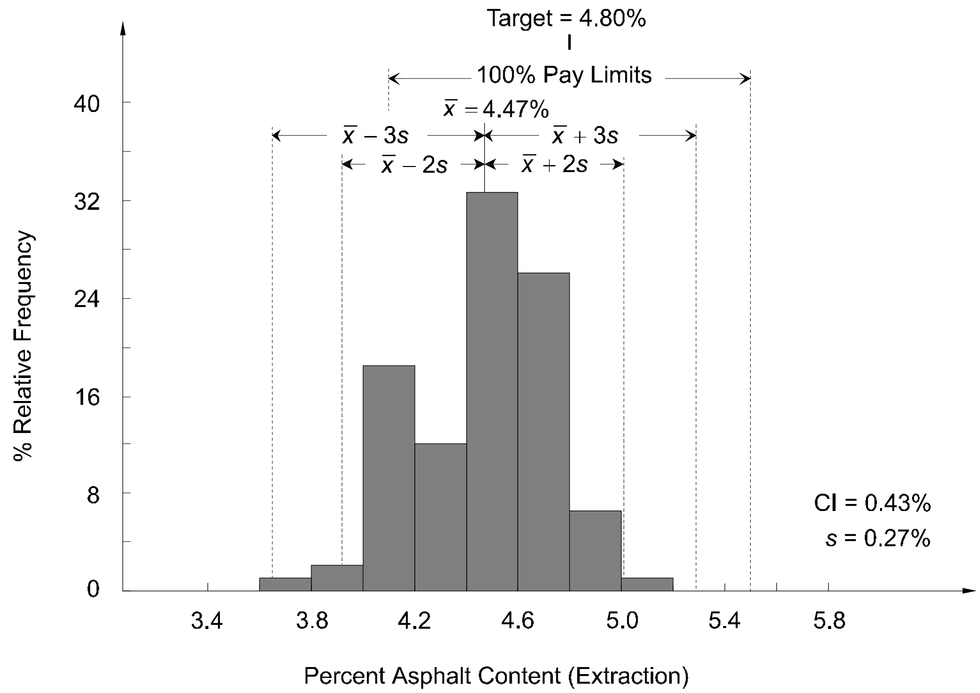


Figure F-10. Percent Passing Sieve No. 200



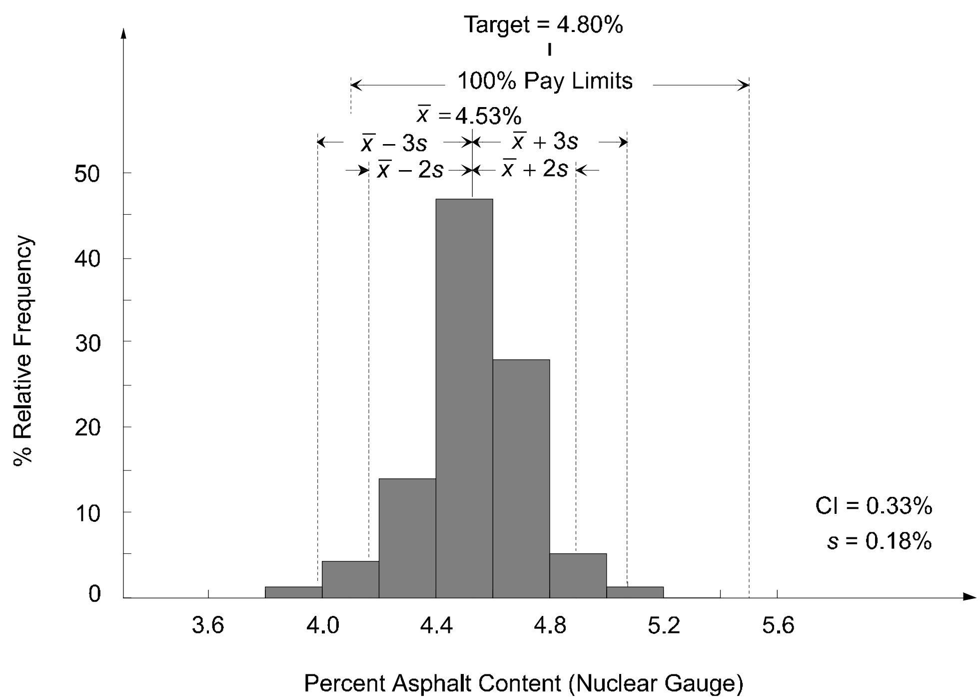


Figure F-11. Percent Asphalt Content

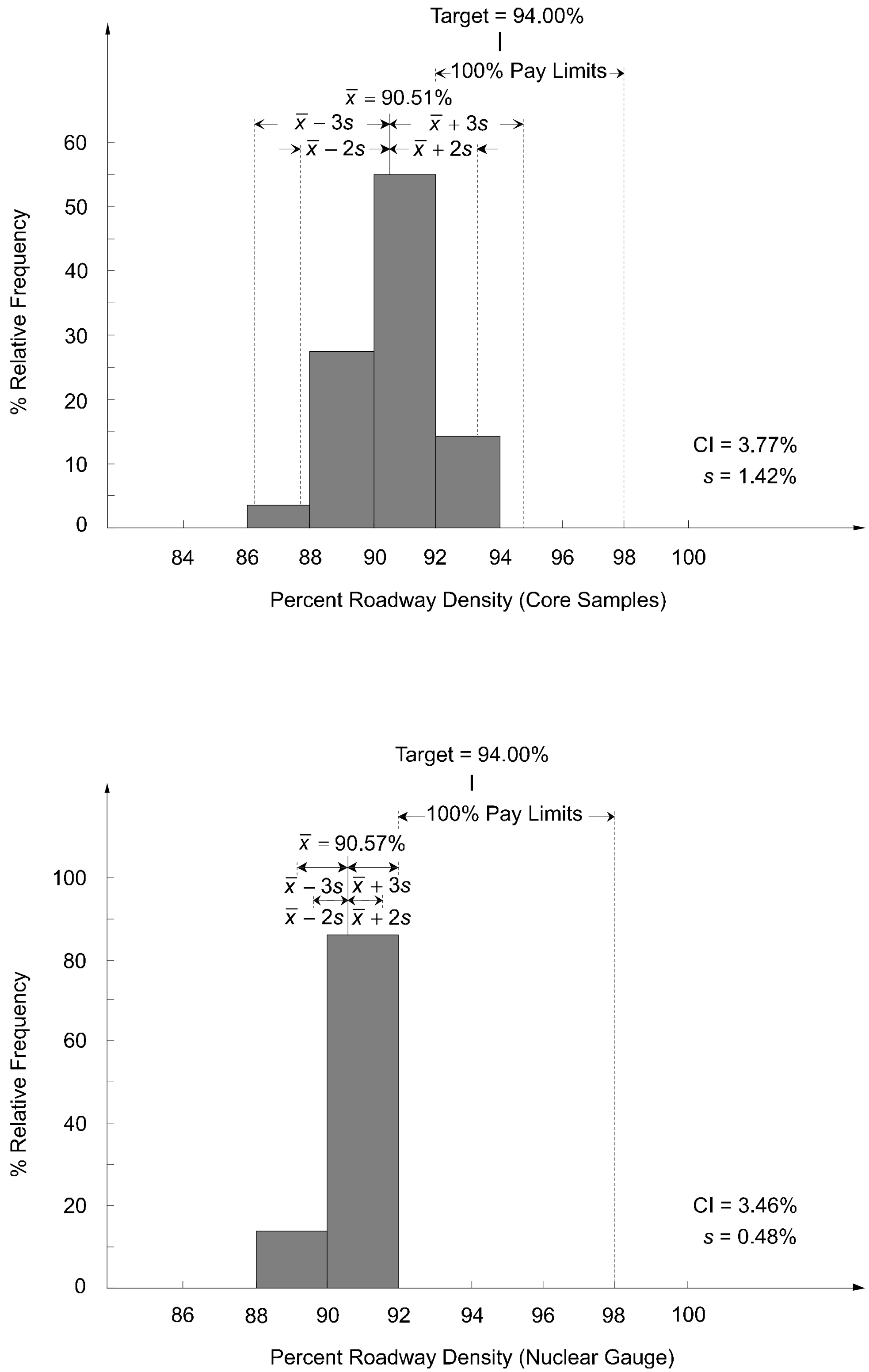


Figure F-12. Percent Roadway Density

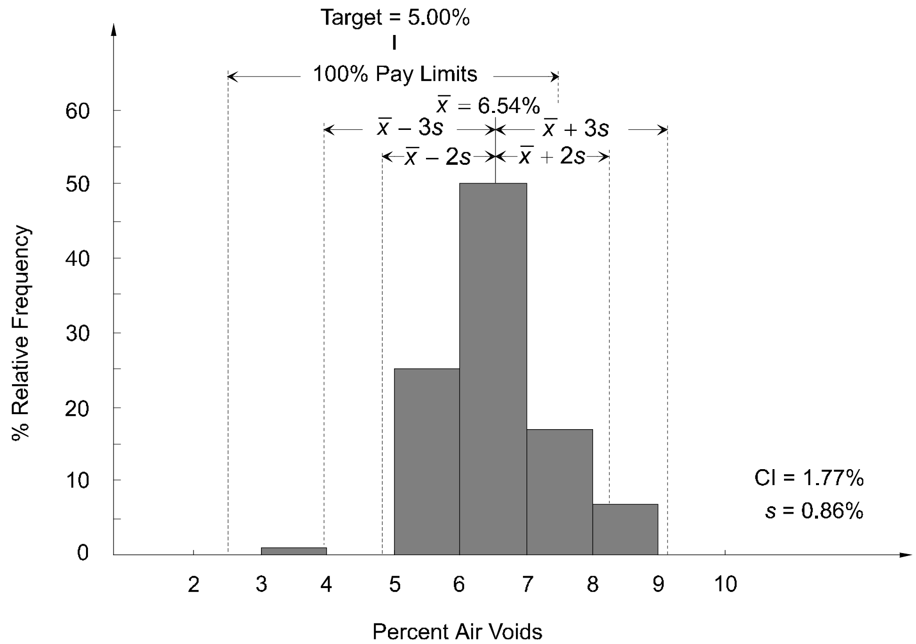


Figure F-13. Percent Air Voids

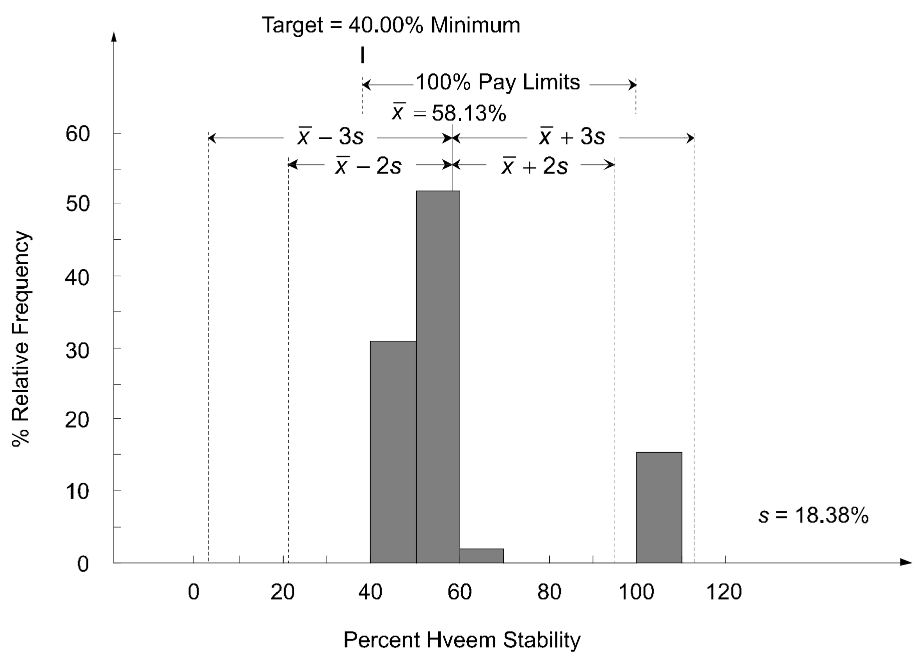
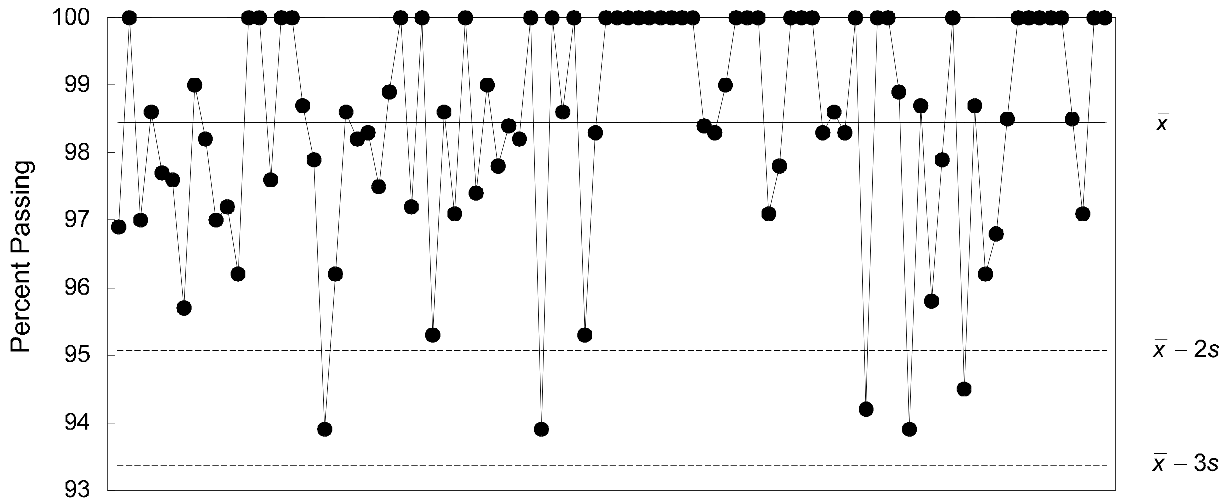


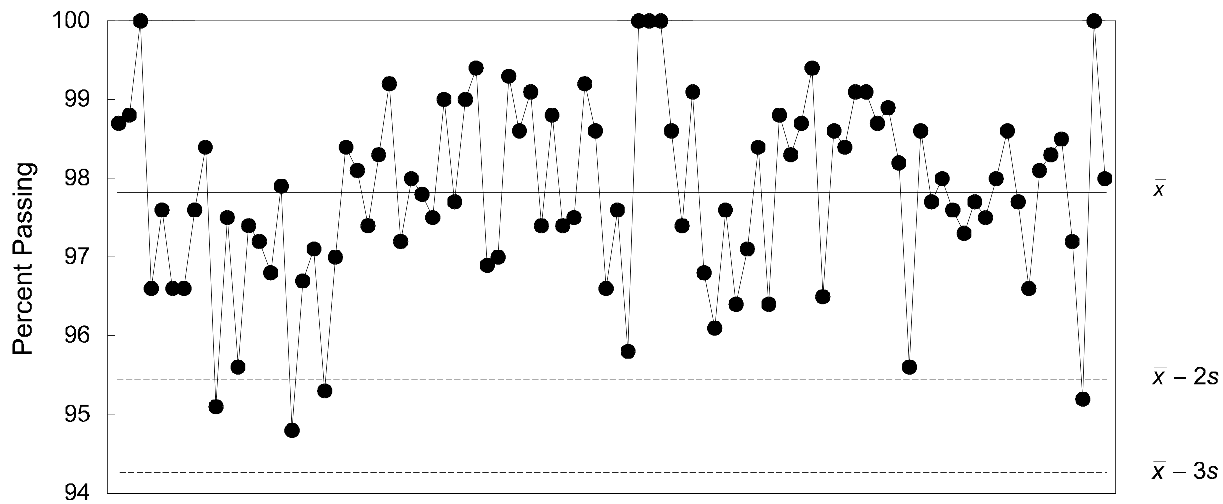
Figure F-14. Percent Hveem Stability

APPENDIX G

X-CHARTS OF QUALITY CHARACTERISTICS PROJECT 1, US-412

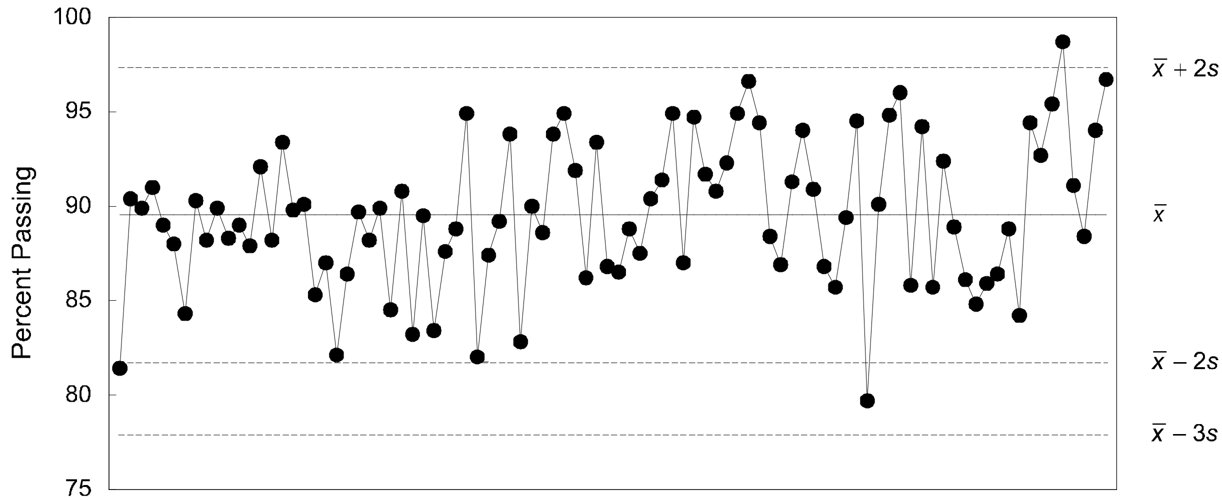


Mixture Analysis

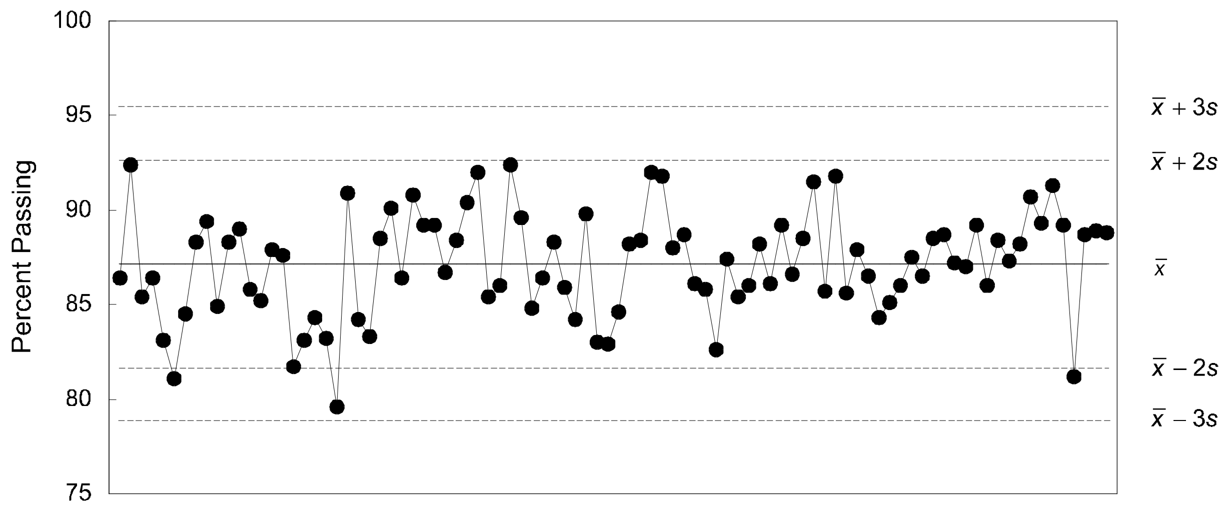


Cold Feed Analysis

Figure G-1. Percent Passing Sieve 1″

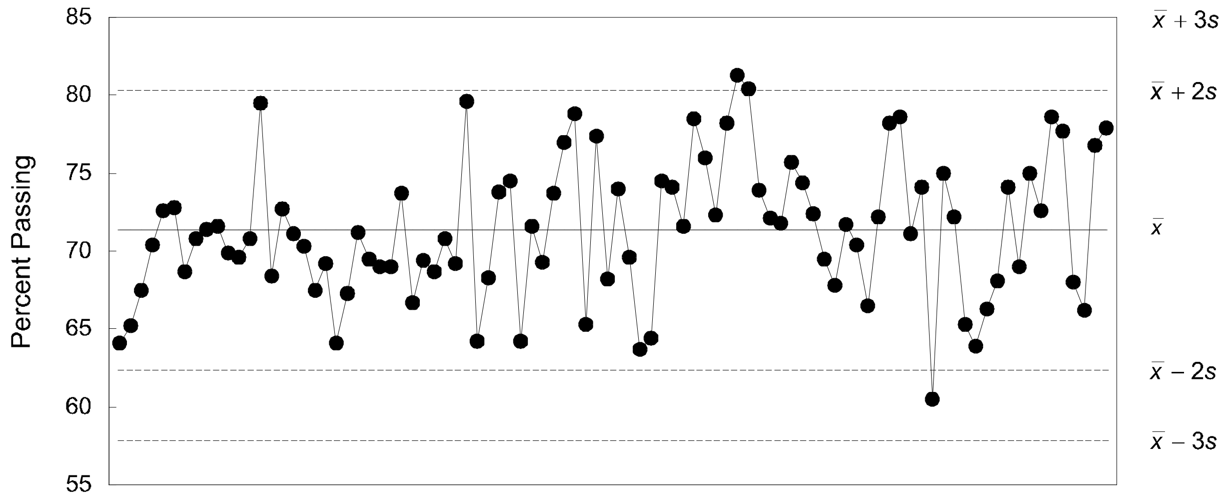


Mixture Analysis

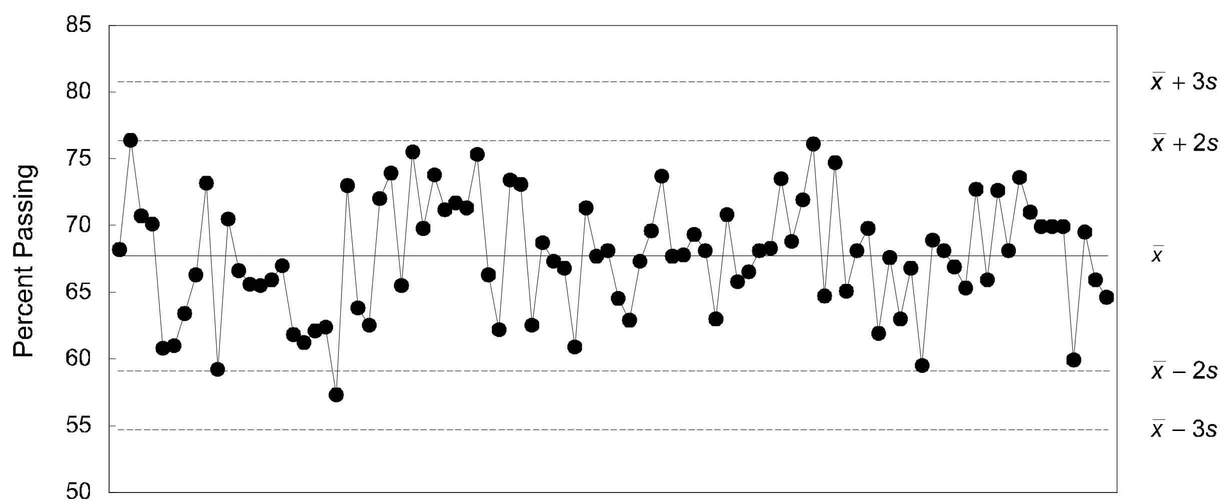


Cold Feed Analysis

Figure G-2. Percent Passing Sieve ¾″

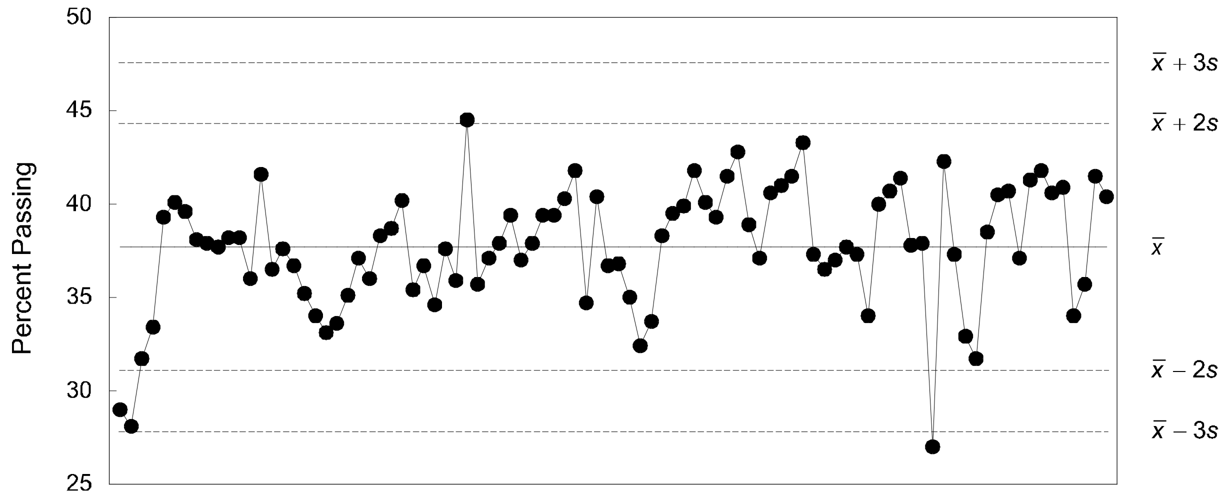


Mixture Analysis

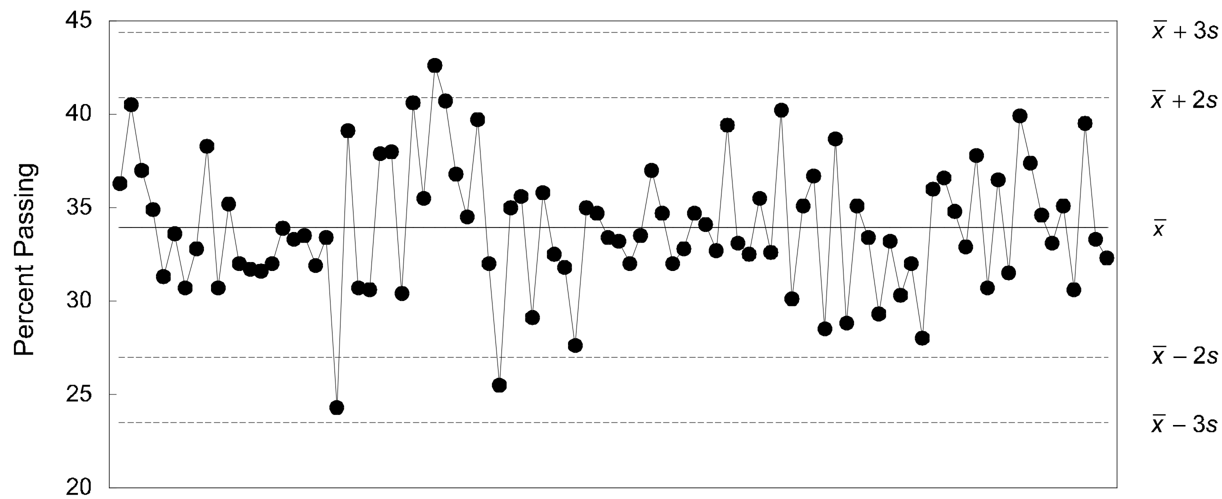


Cold Feed Analysis

Figure G-3. Percent Passing Sieve ½″

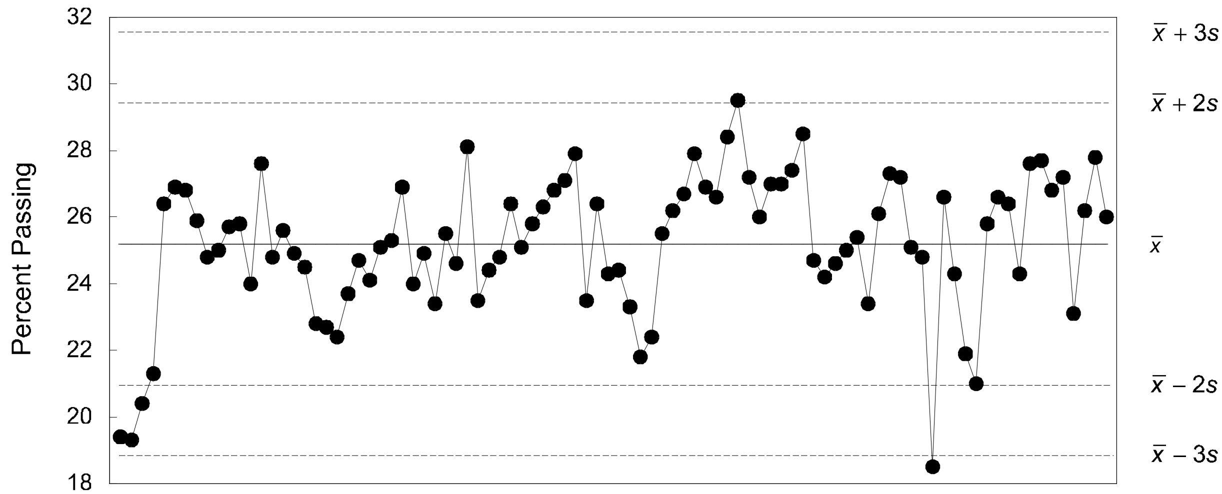


Mixture Analysis

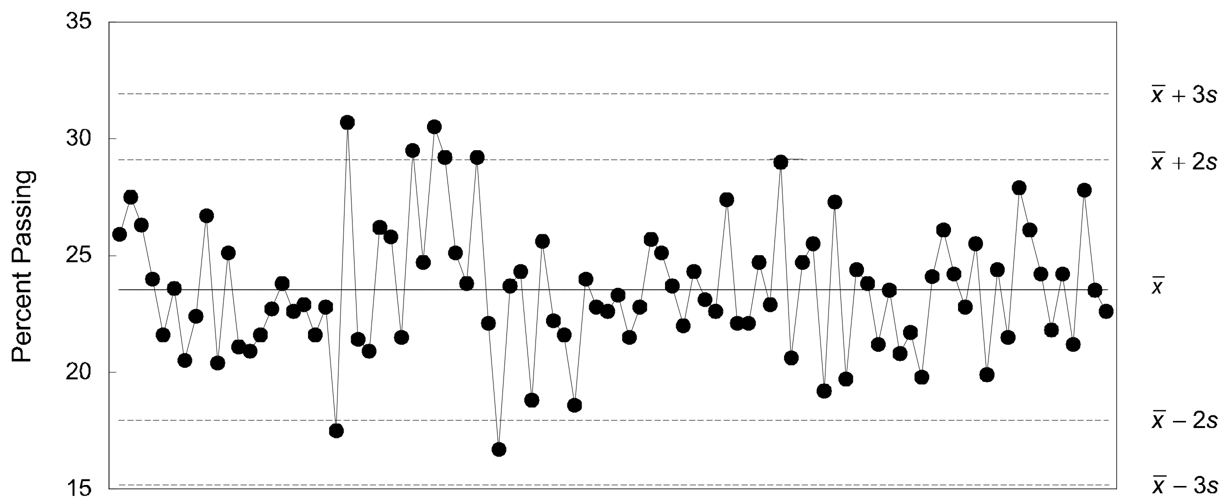


Cold Feed Analysis

Figure G-4. Percent Passing Sieve No. 4

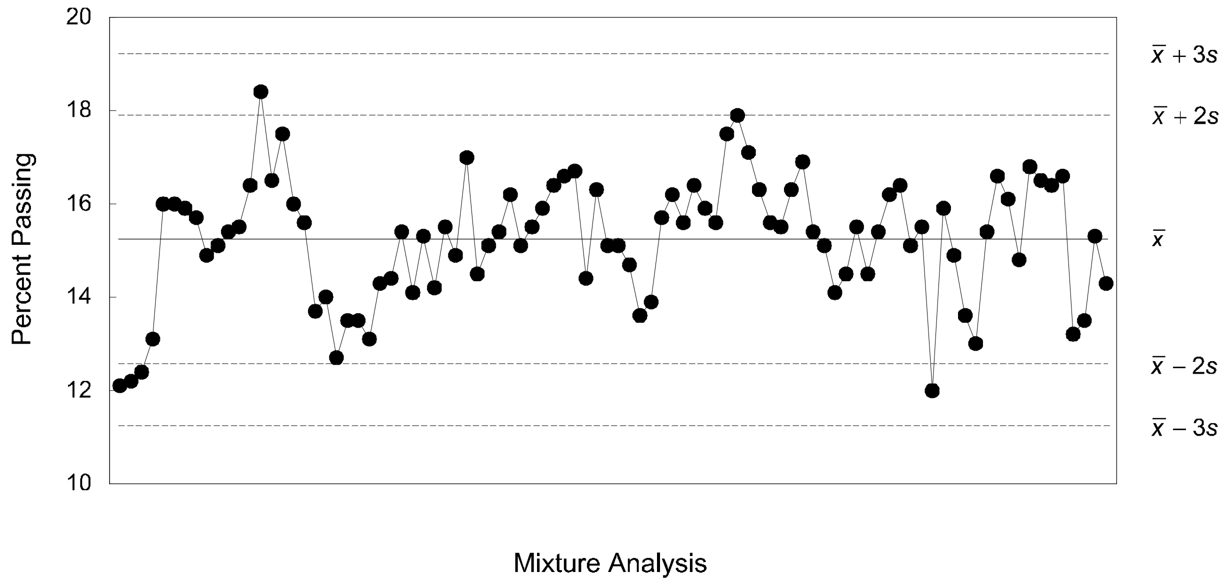


Mixture Analysis



Cold Feed Analysis

Figure G-5. Percent Passing Sieve No. 10



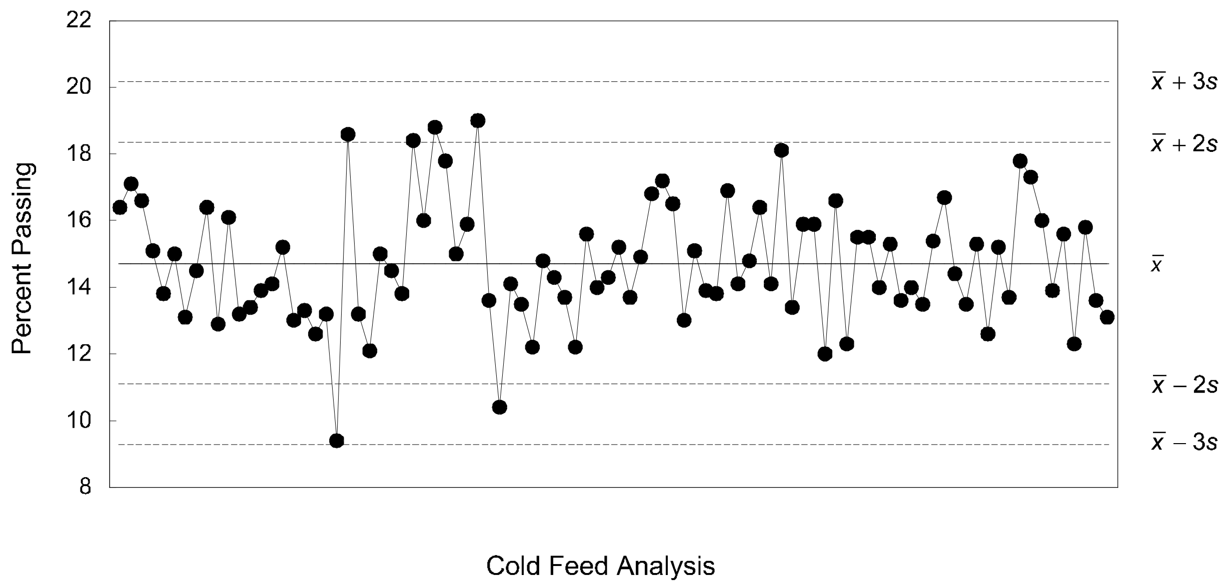
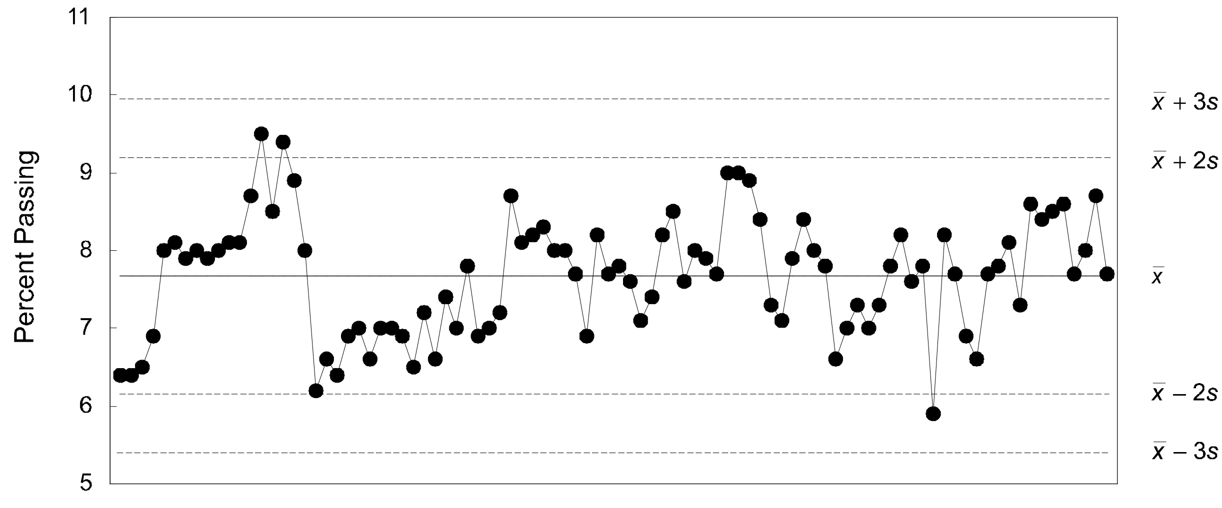
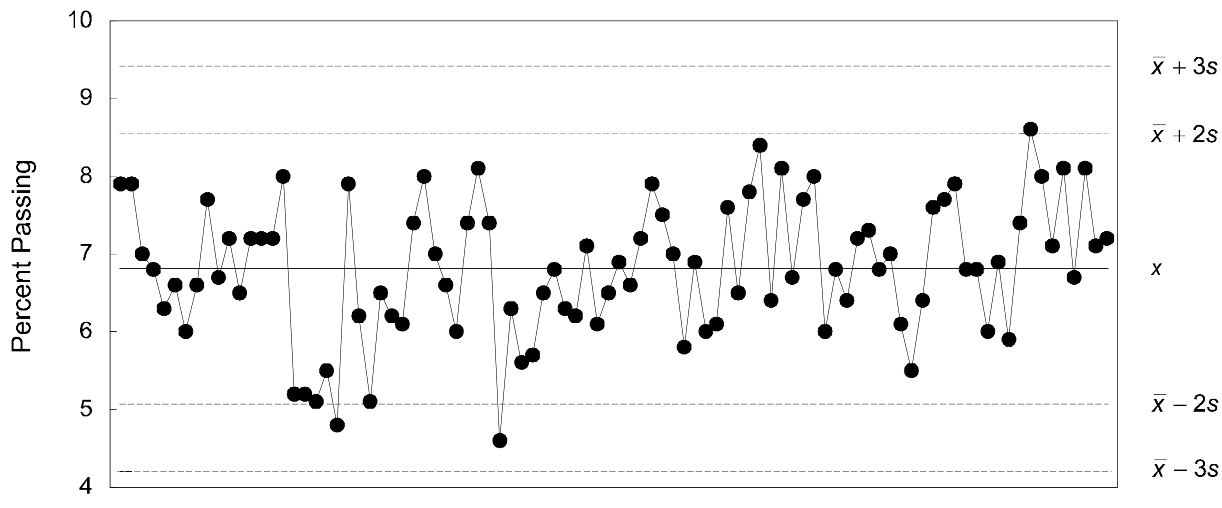


Figure G-6. Percent Passing Sieve No. 40

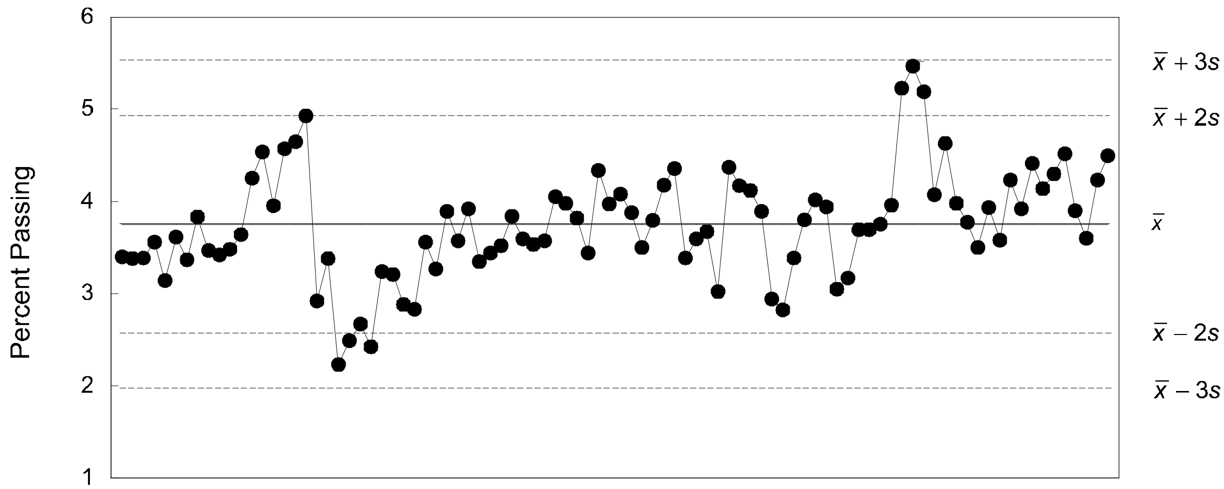


Mixture Analysis

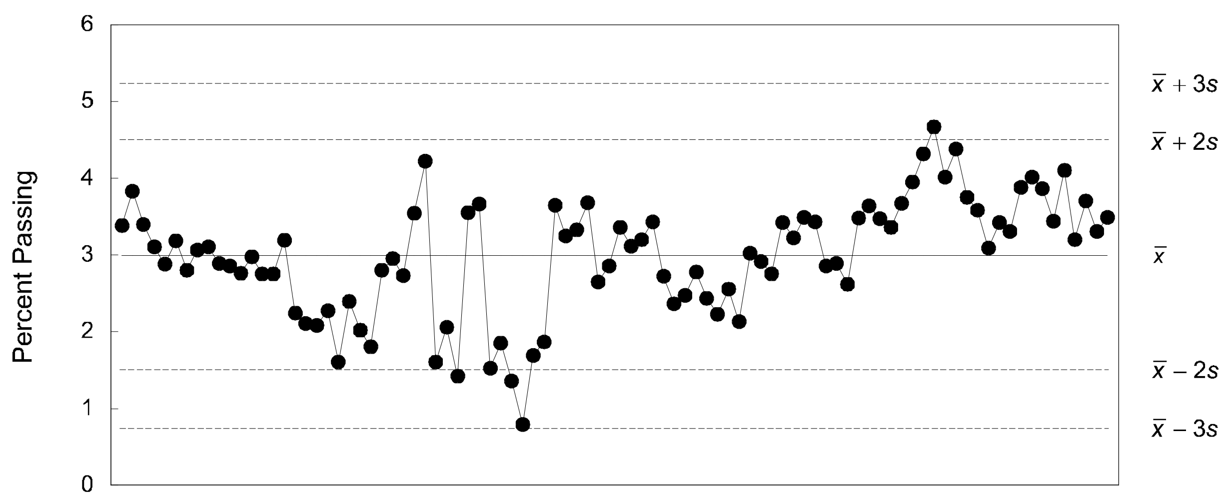


Cold Feed Analysis

Figure G-7. Percent Passing Sieve No. 80

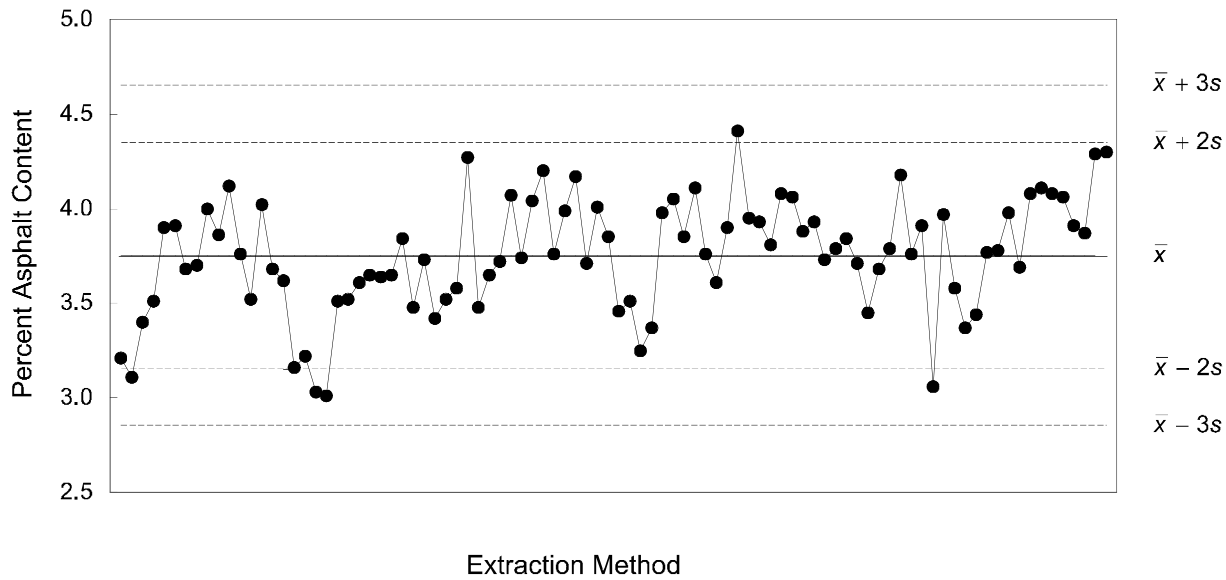


Mixture Analysis



Cold Feed Analysis

Figure G-8. Percent Passing Sieve No. 200



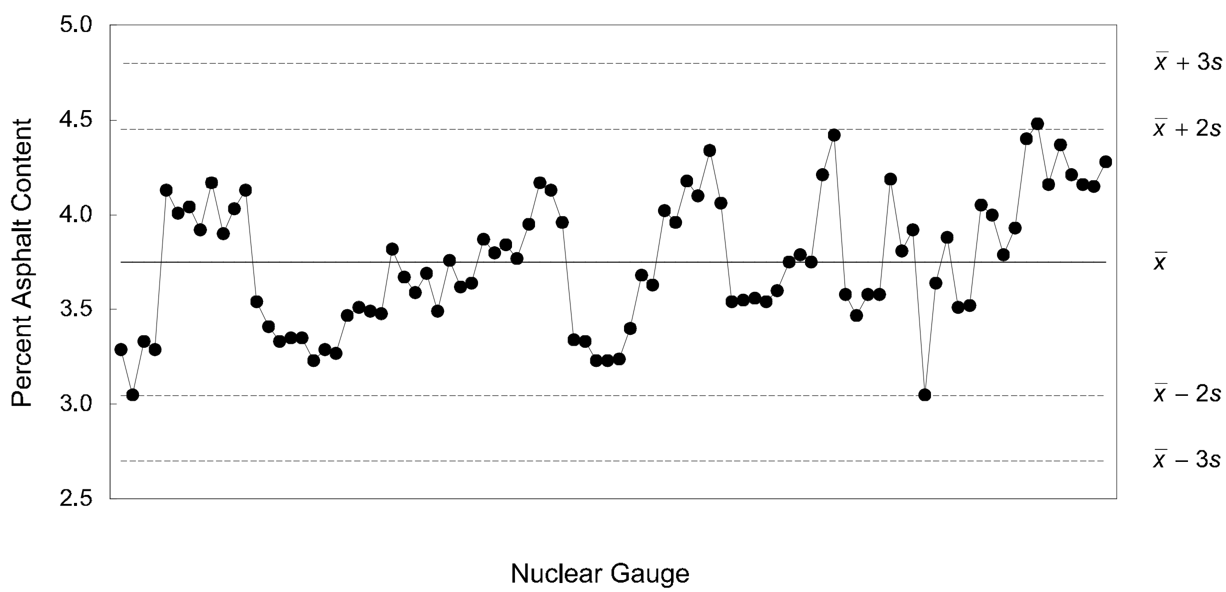
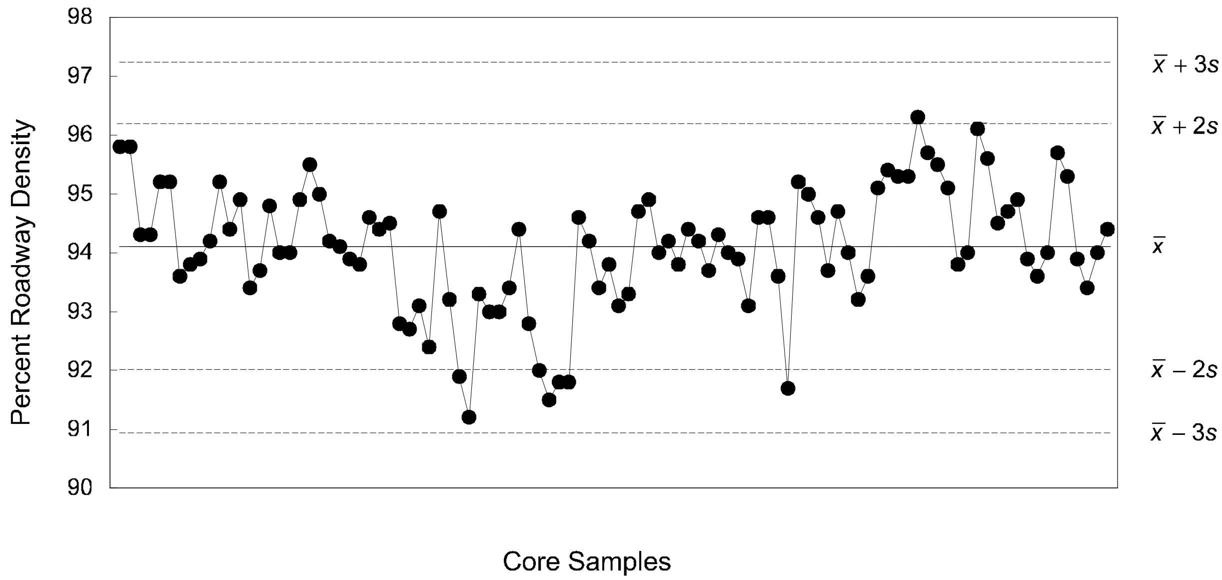


Figure G-9. Percent Asphalt Content



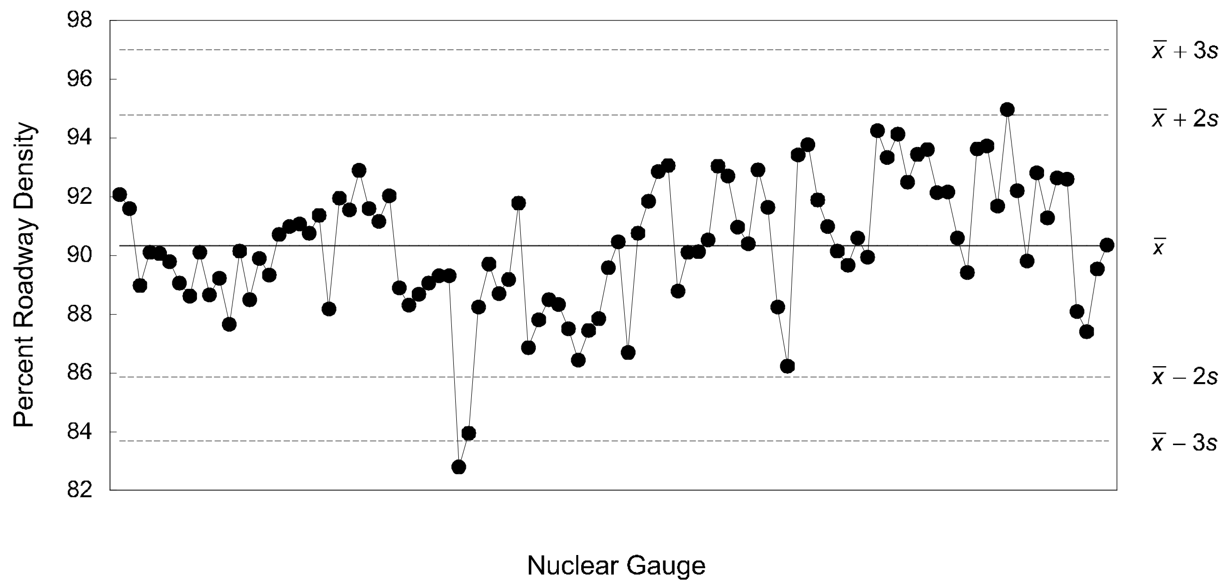


Figure G-10. Percent Roadway Density

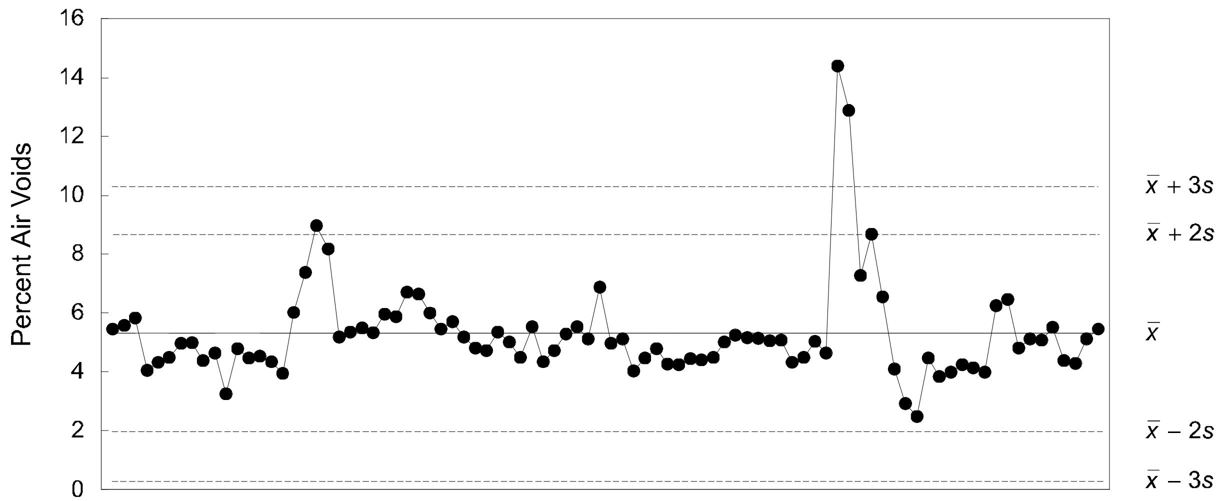


Figure G-11. Percent Air Voids

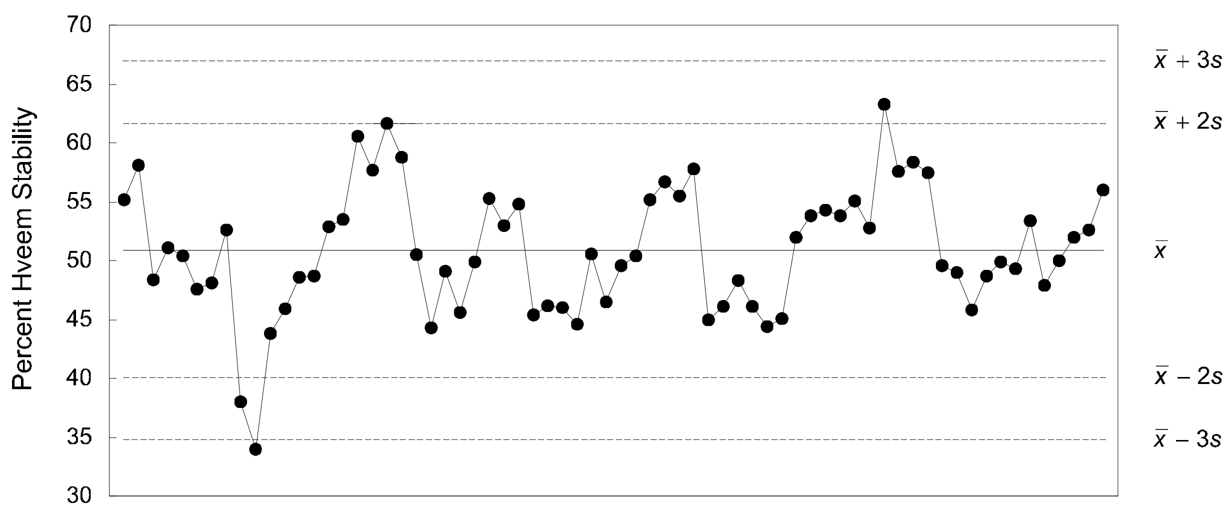
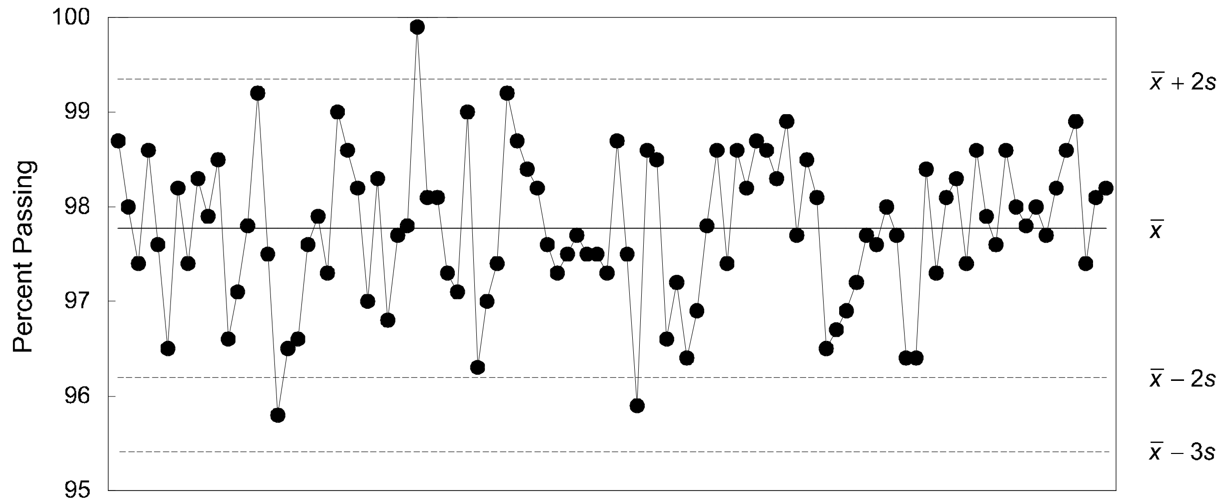


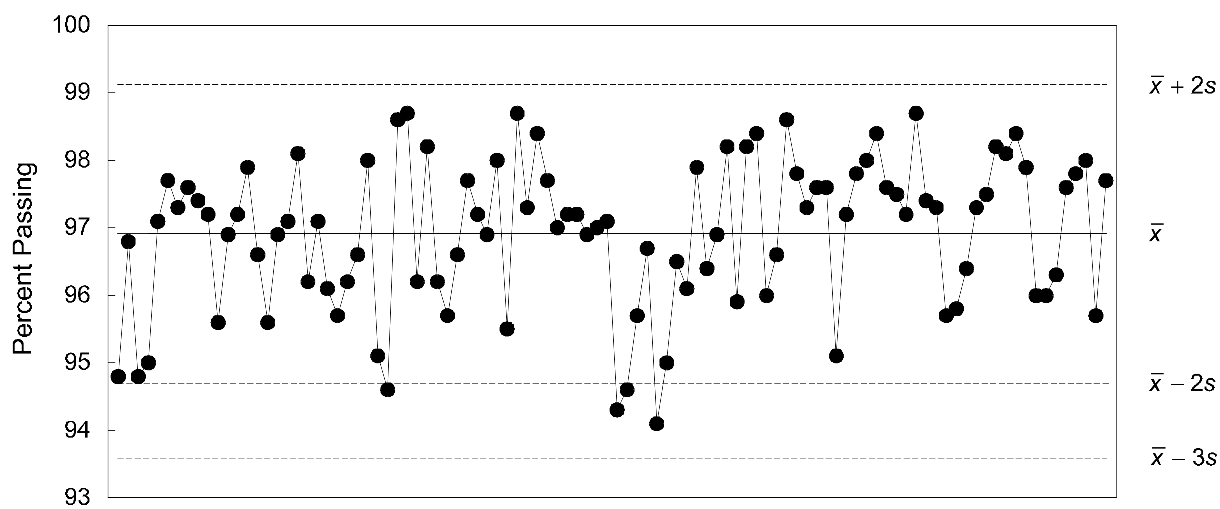
Figure G-12. Percent Hveem Stability

APPENDIX H

X-CHARTS OF QUALITY CHARACTERISTICS PROJECT 2, US-70

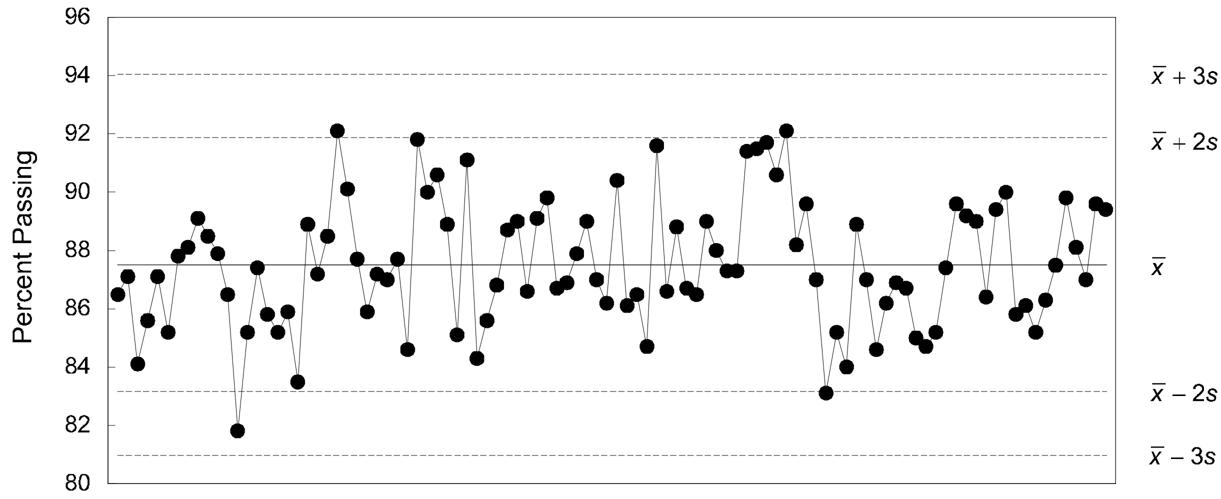


Mixture Analysis

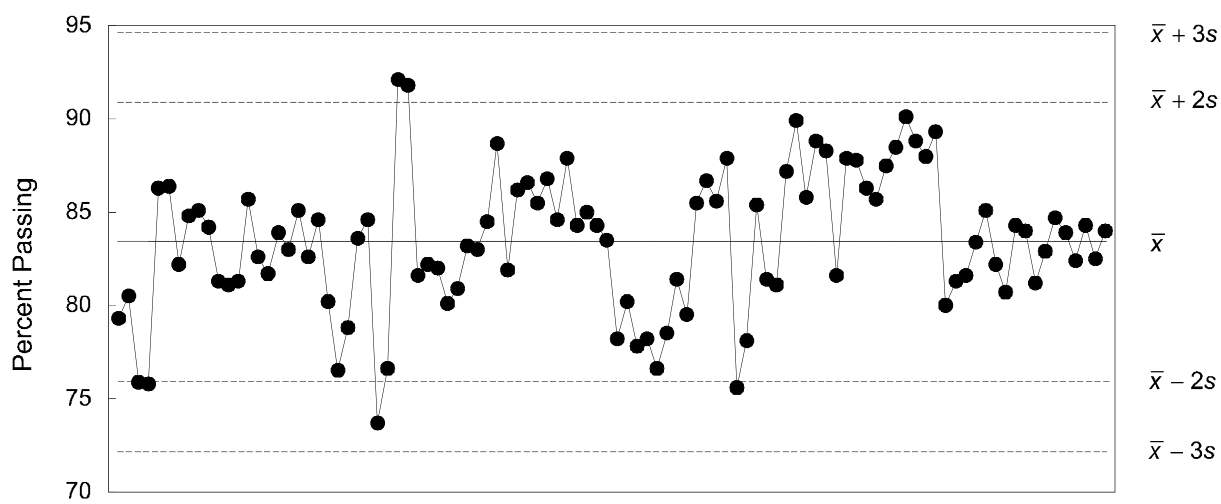


Cold Feed Analysis

Figure H-1. Percent Passing Sieve ½″

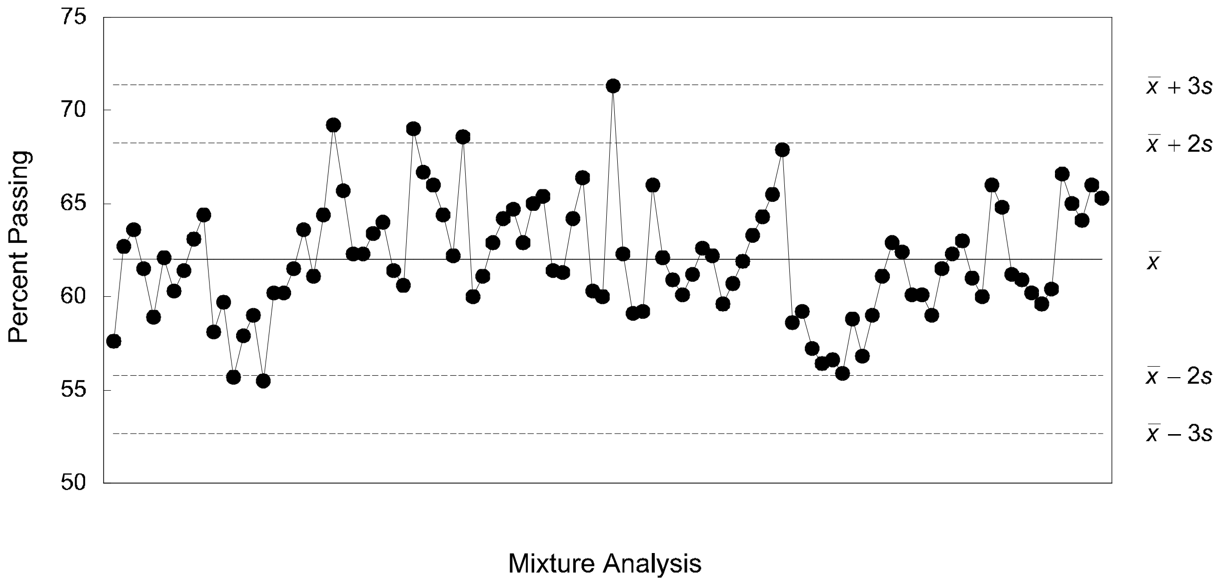


Mixture Analysis



Cold Feed Analysis

Figure H-2. Percent Passing Sieve 3/8″



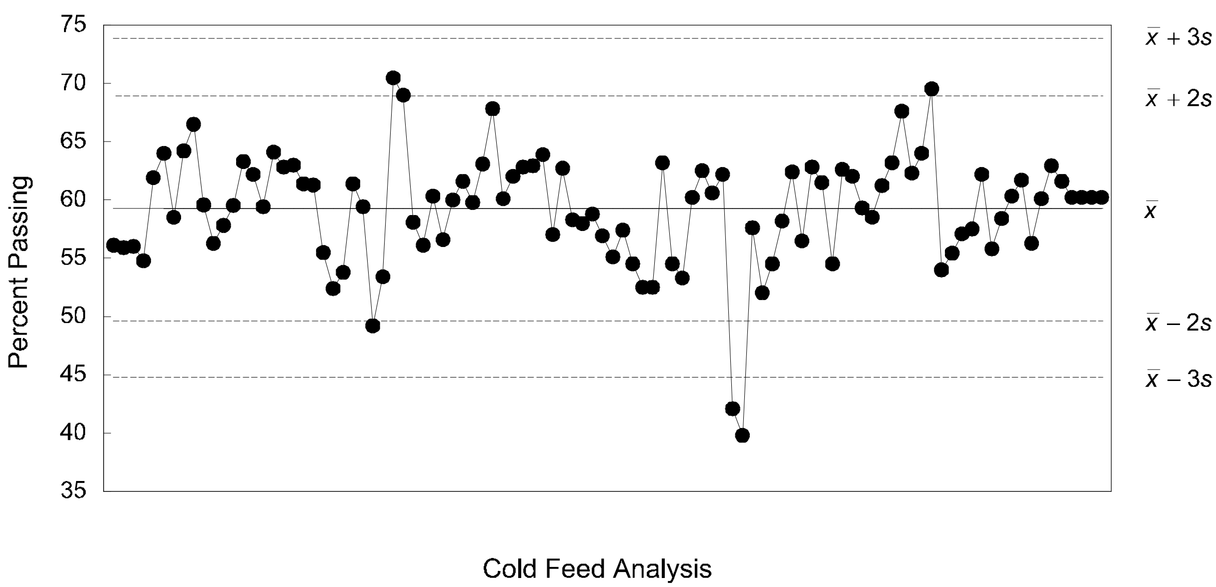
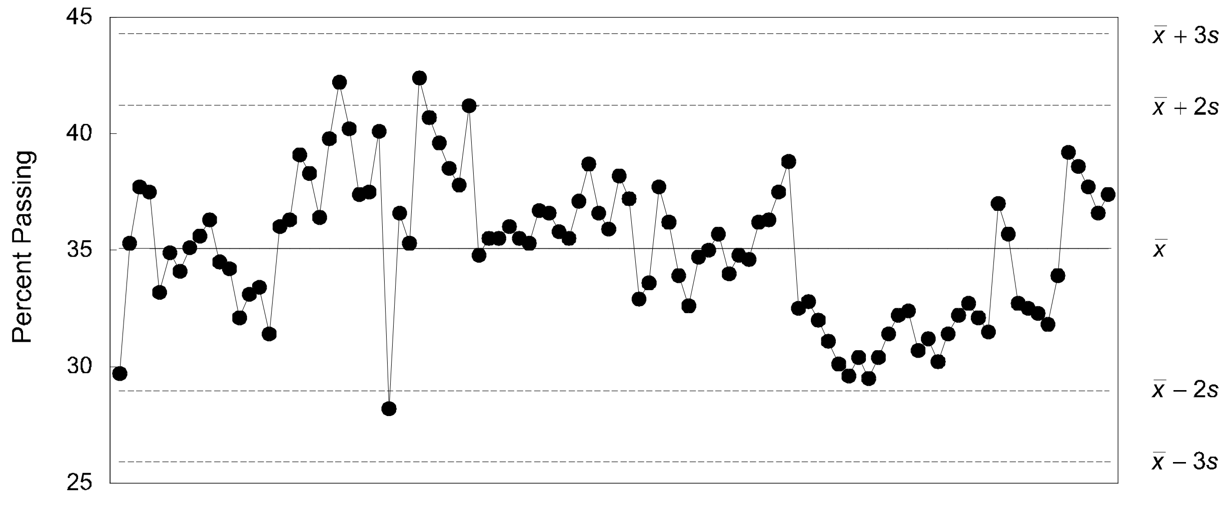
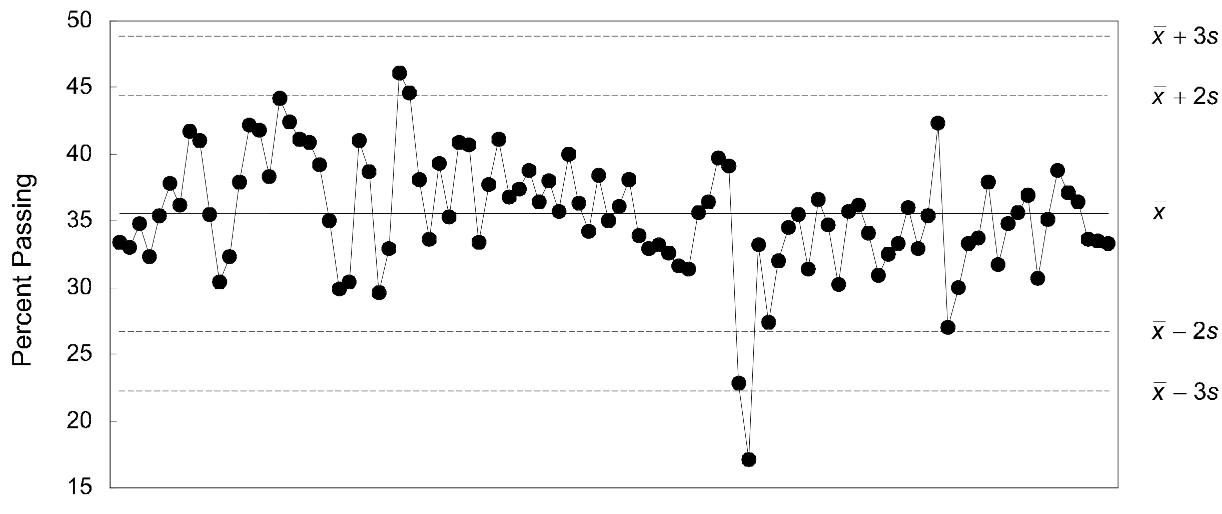


Figure H-3. Percent Passing Sieve No. 4

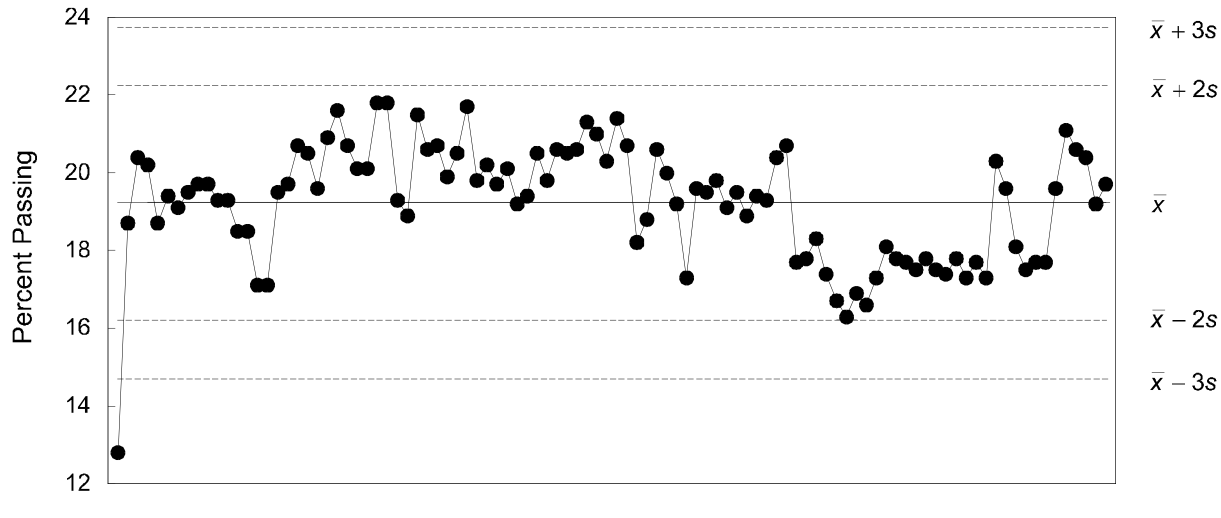


Mixture Analysis

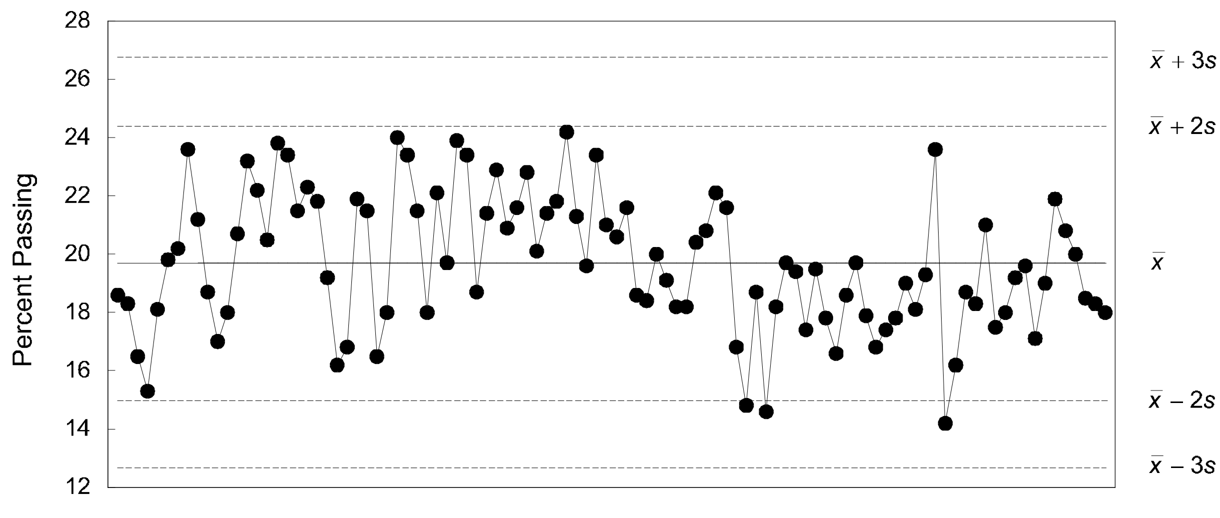


Cold Feed Analysis

Figure H-4. Percent Passing Sieve No. 10

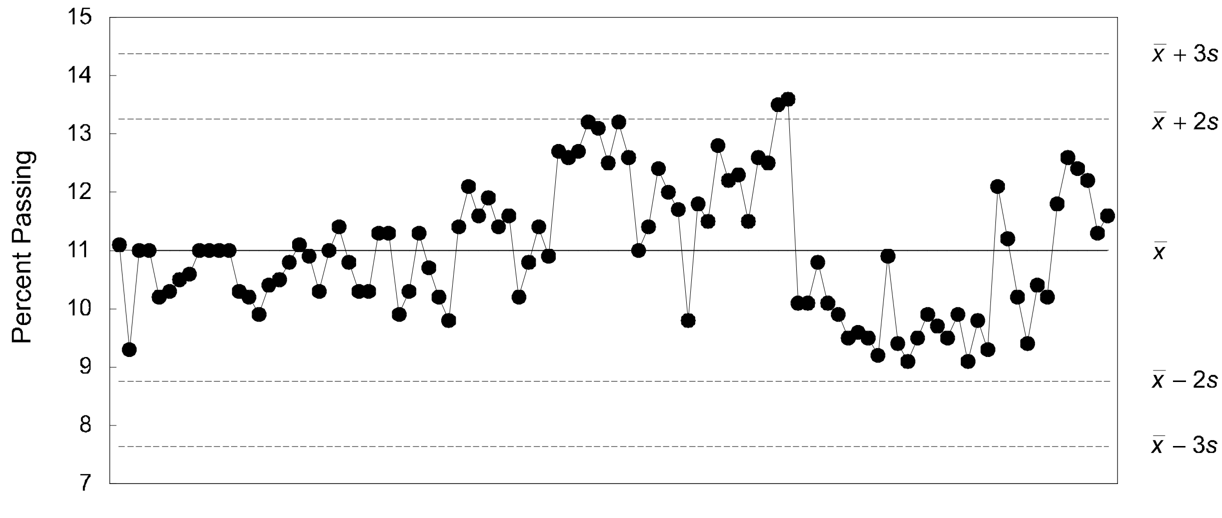


Mixture Analysis

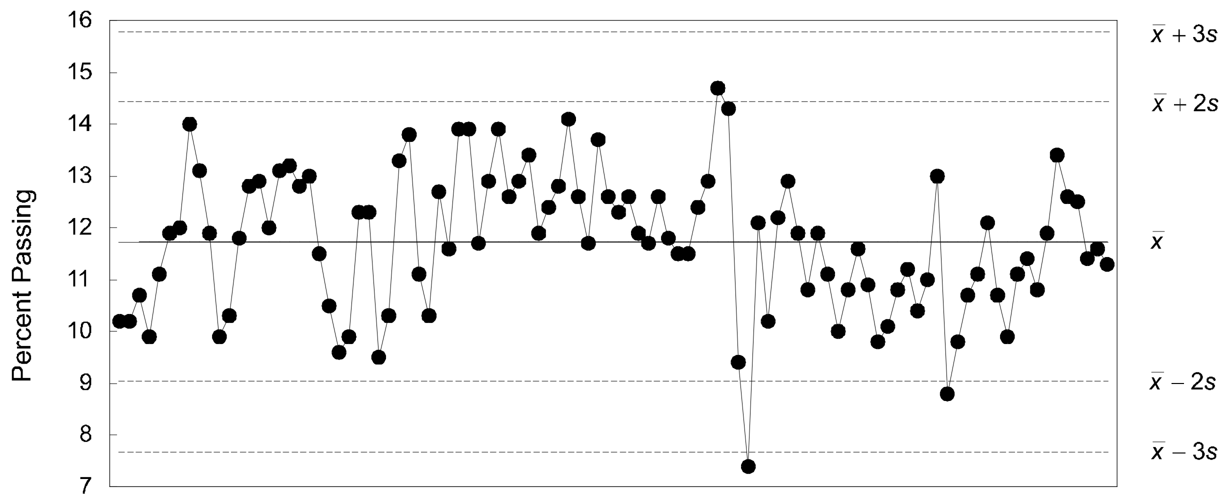


Cold Feed Analysis

Figure H-5. Percent Passing Sieve No. 40

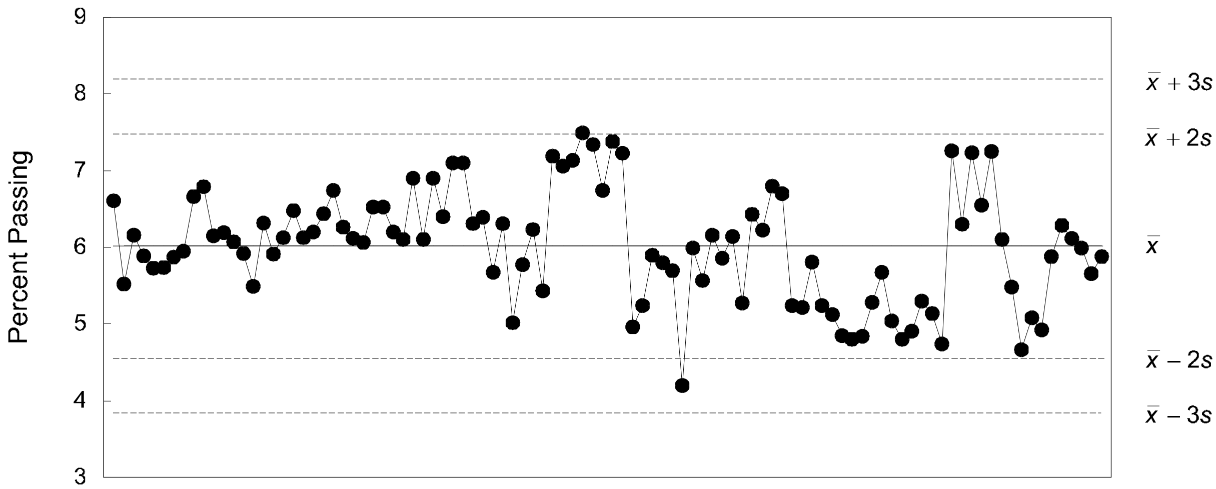


Mixture Analysis

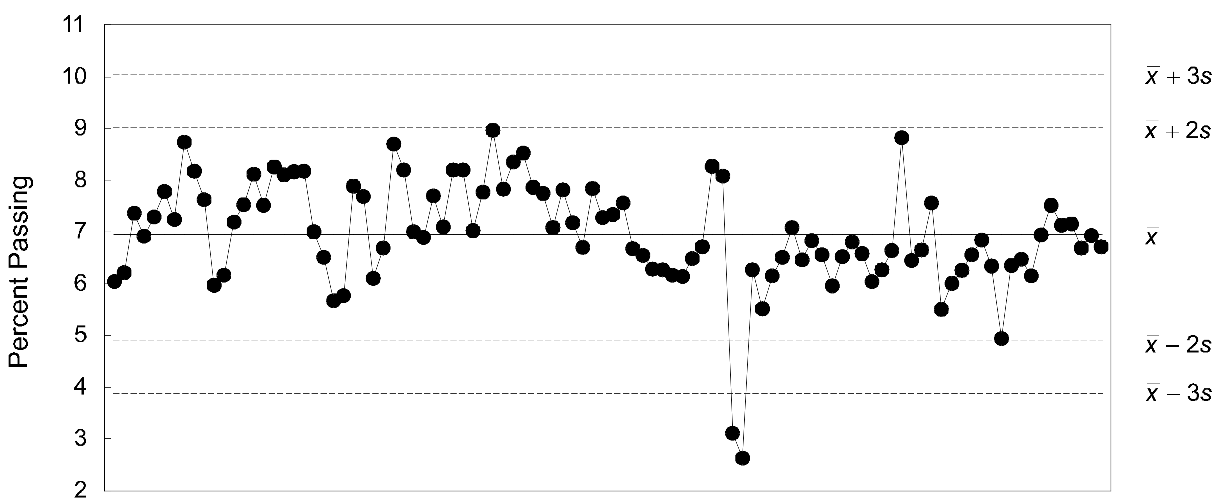


Cold Feed Analysis

Figure H-6. Percent Passing Sieve No. 80

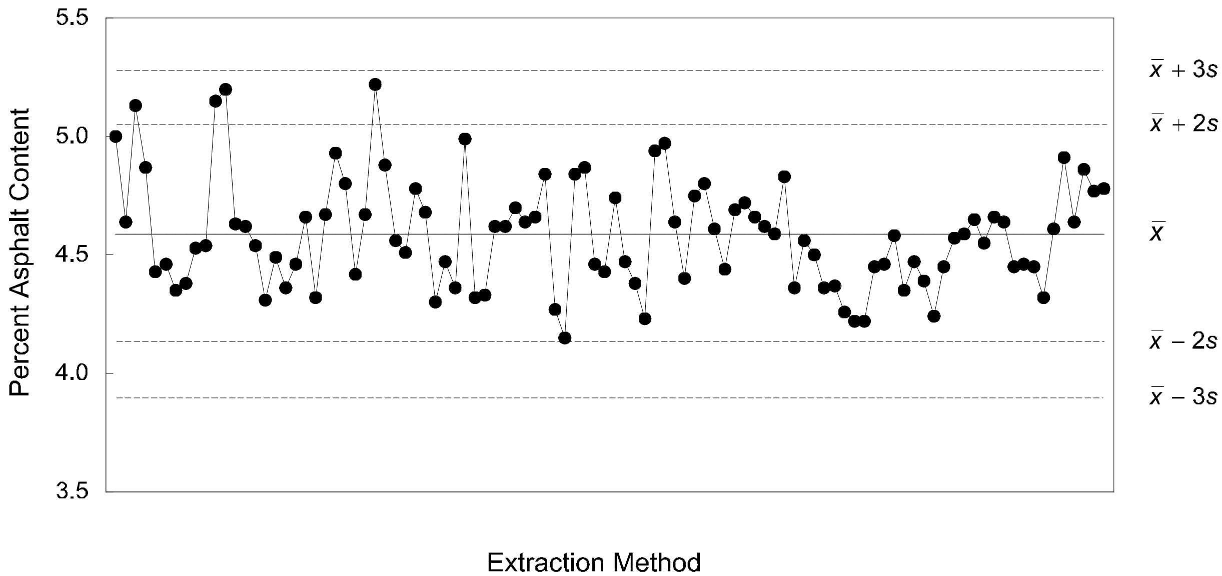


Mixture Analysis



Cold Feed Analysis

Figure H-7. Percent Passing Sieve No. 200



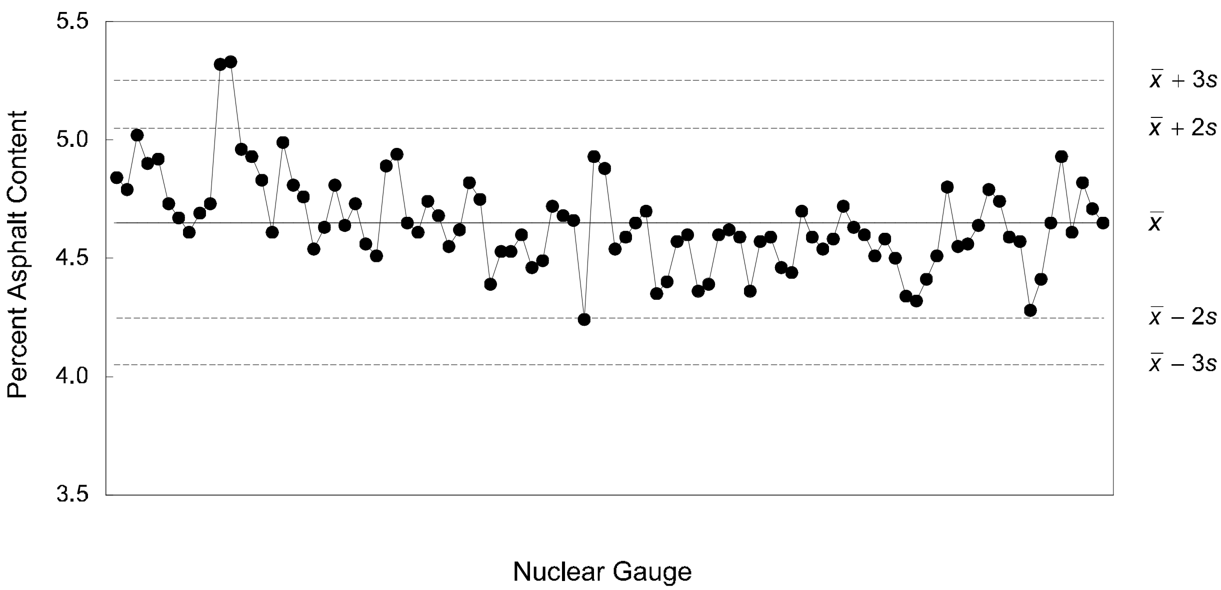
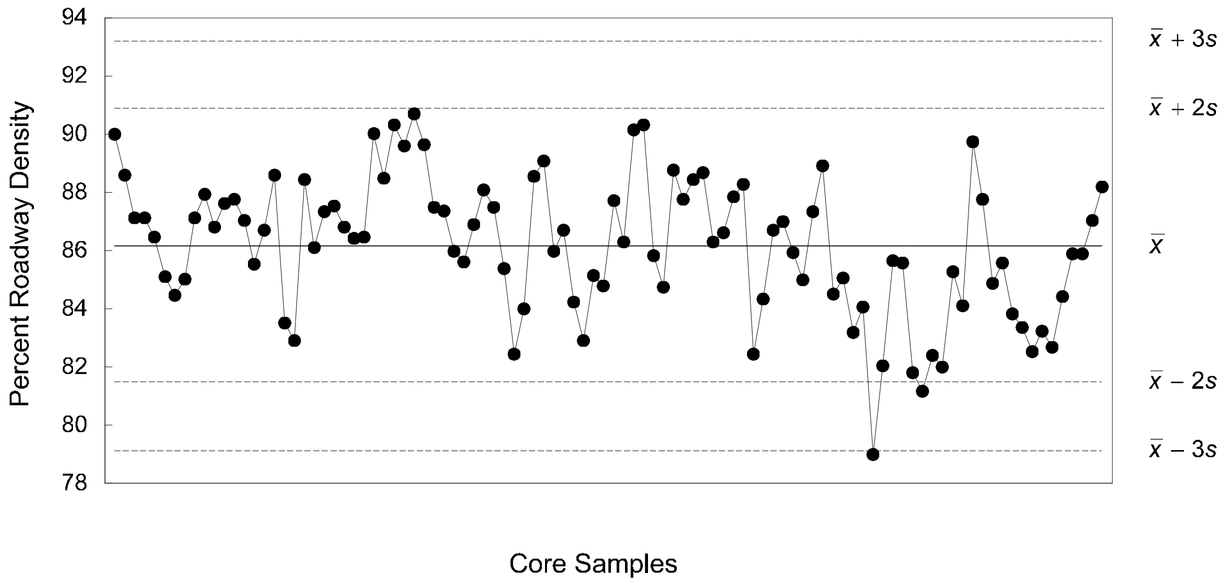


Figure H-8. Percent Asphalt Content



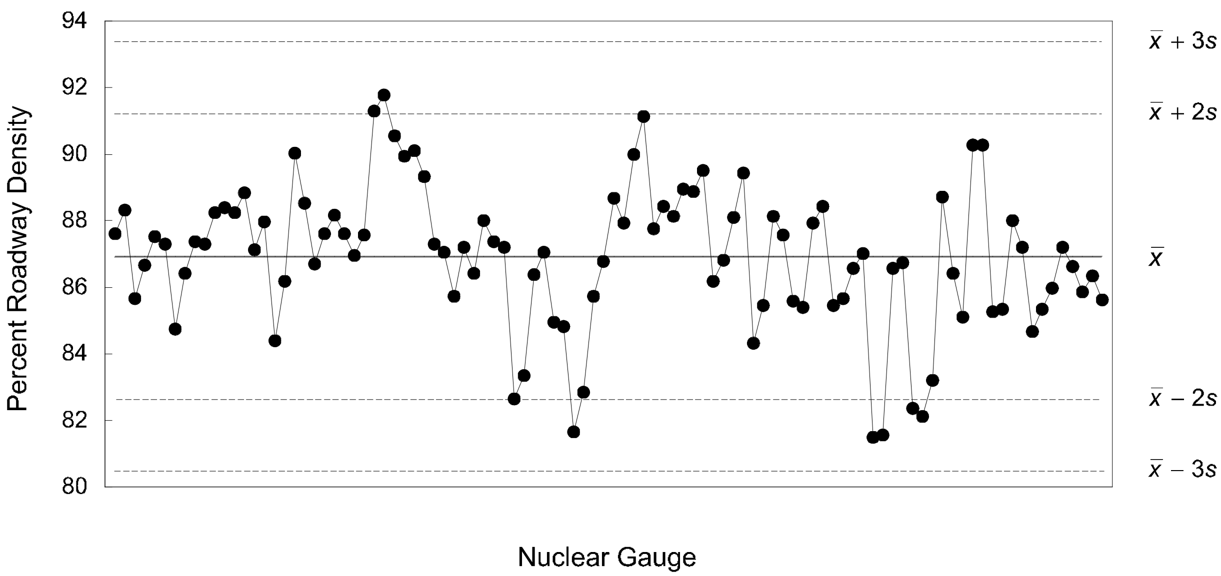


Figure H-9. Percent Roadway Density

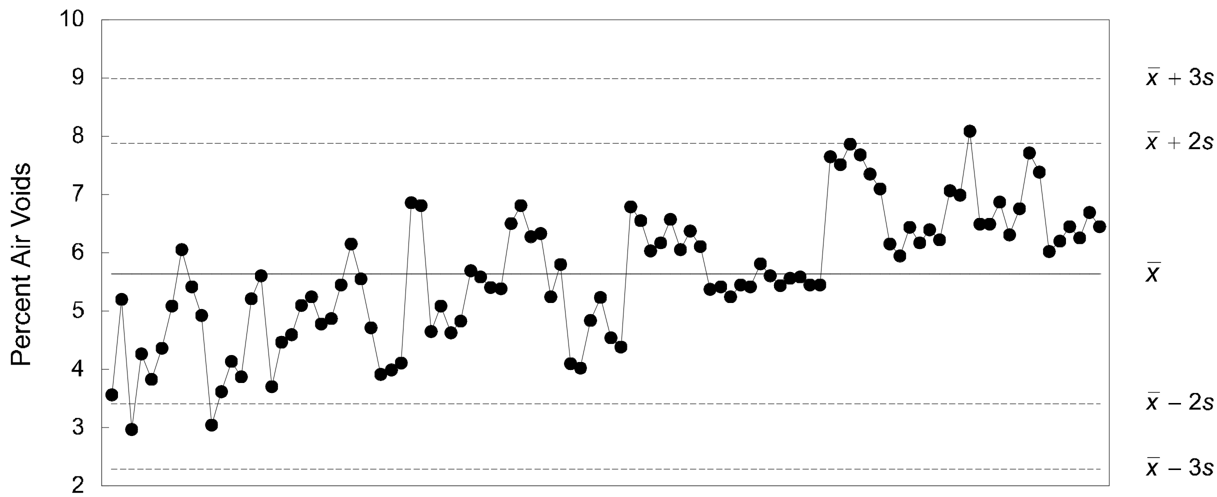


Figure H-10. Percent Air Voids

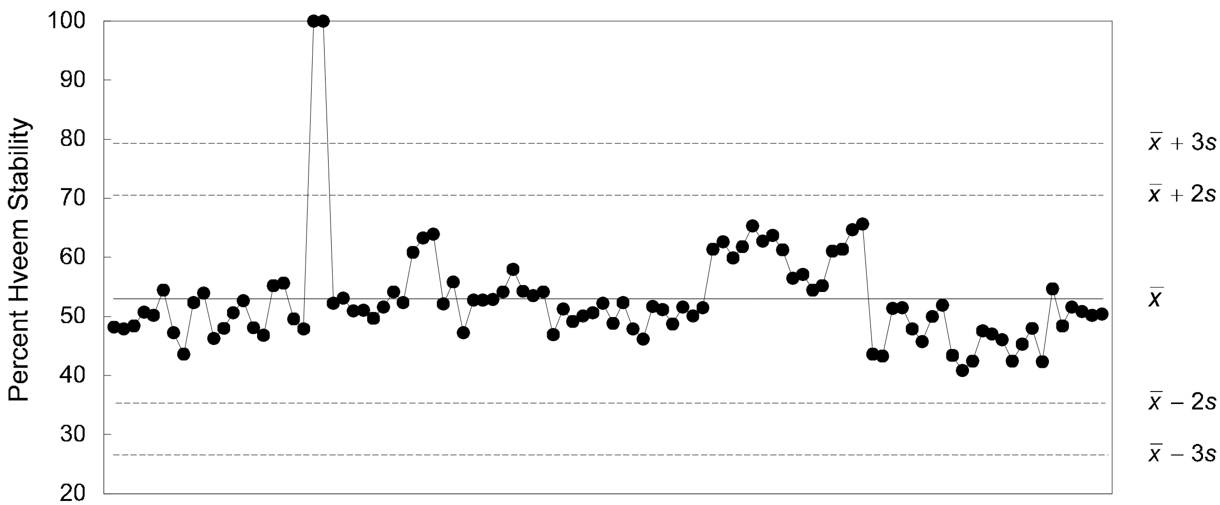
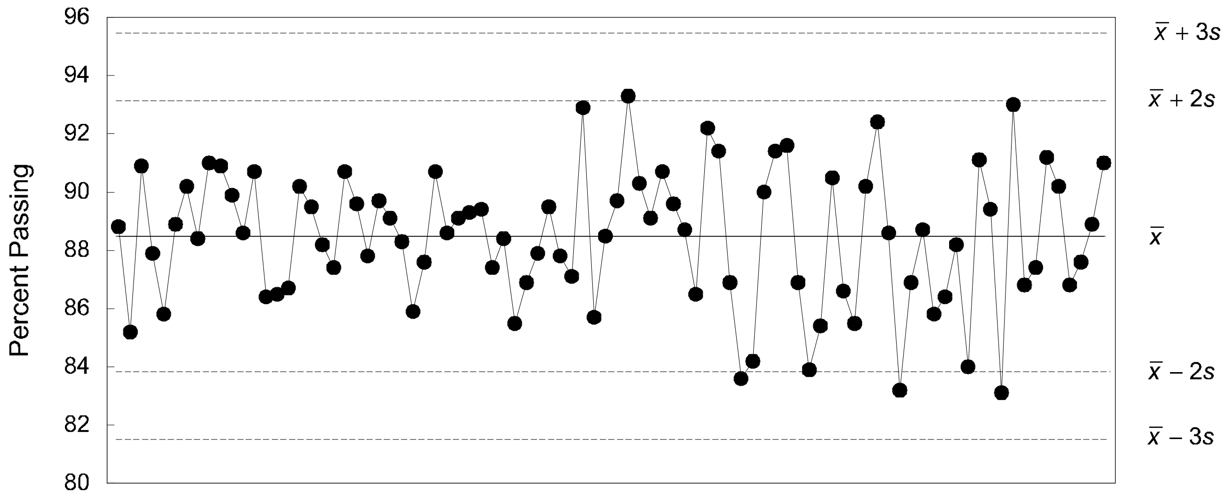


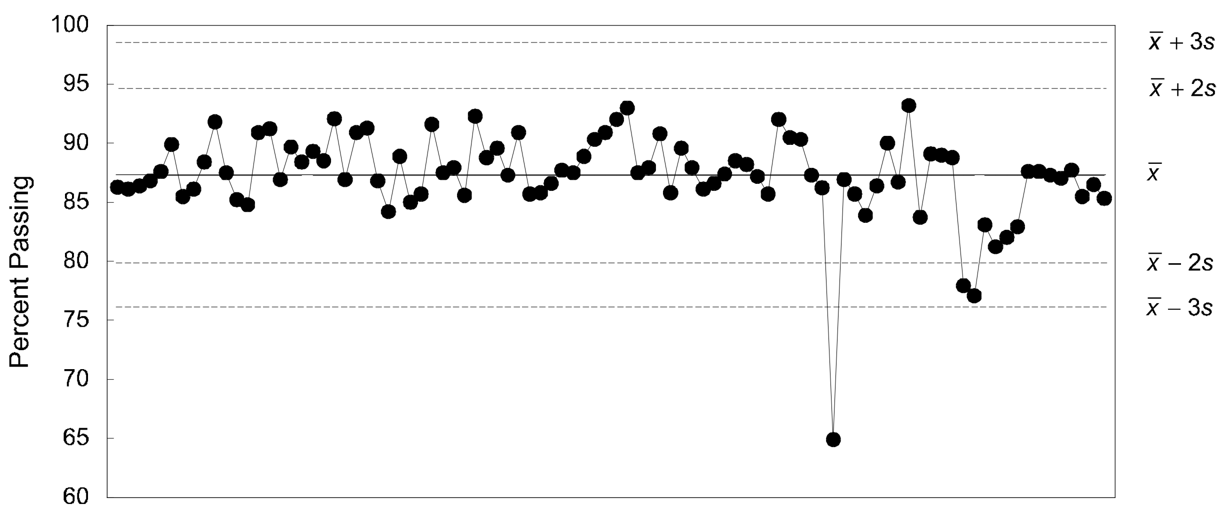
Figure H-11. Percent Hveem Stability

APPENDIX I

X-CHARTS OF QUALITY CHARACTERISTICS PROJECT 3, US-62

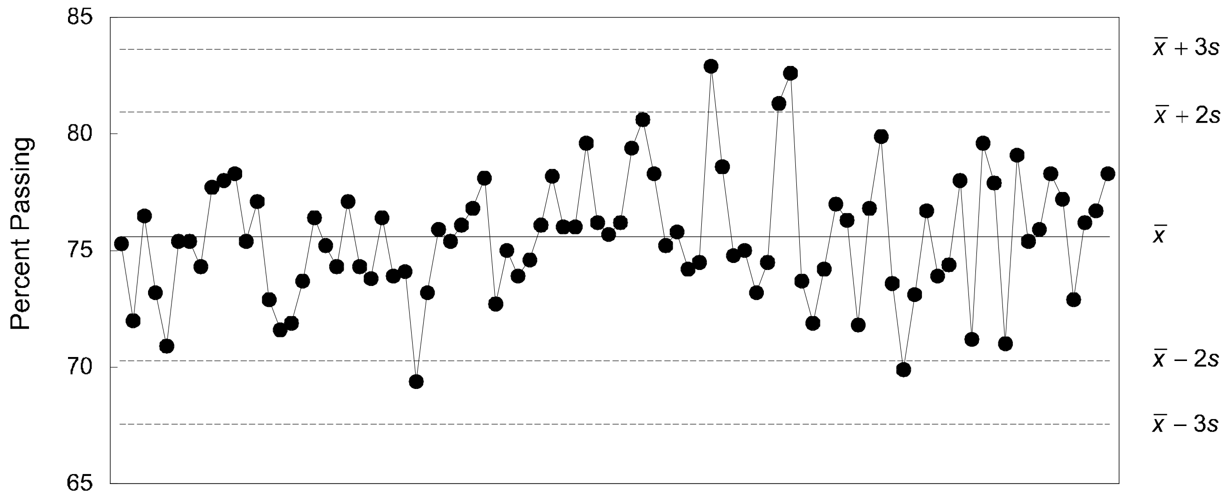


Mixture Analysis

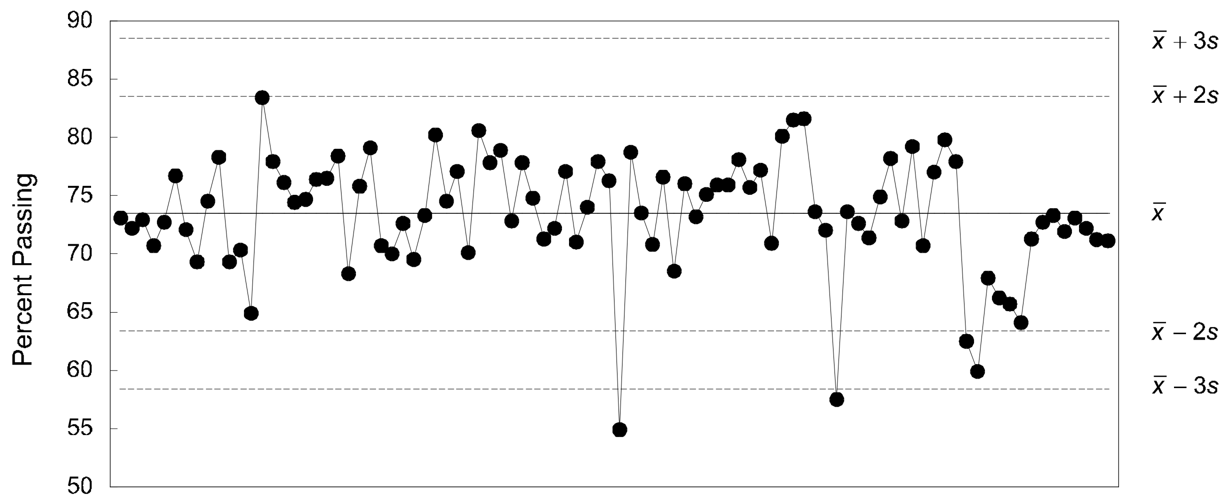


Cold Feed Analysis

Figure I-1. Percent Passing Sieve ½″

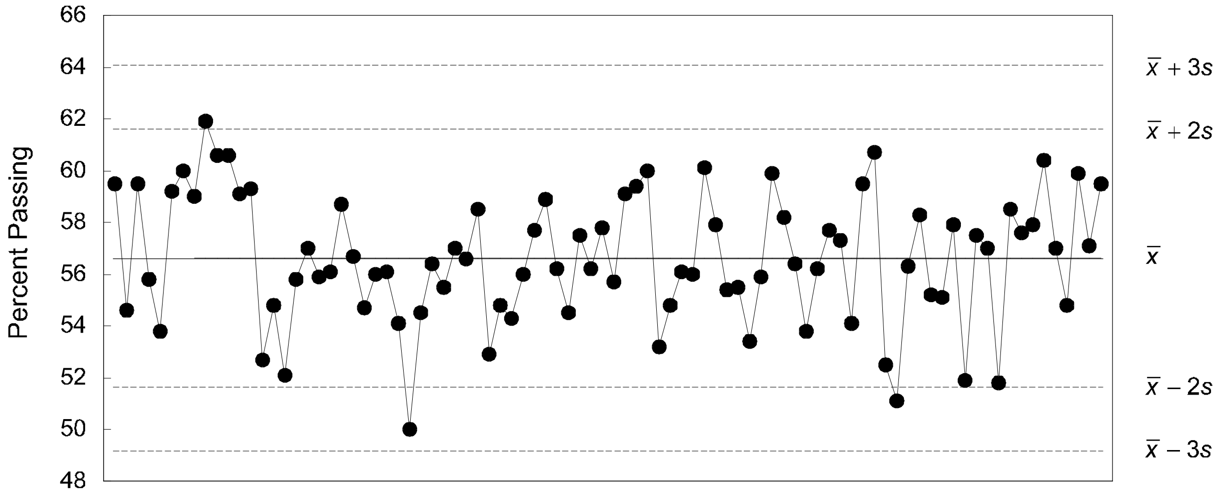


Mixture Analysis

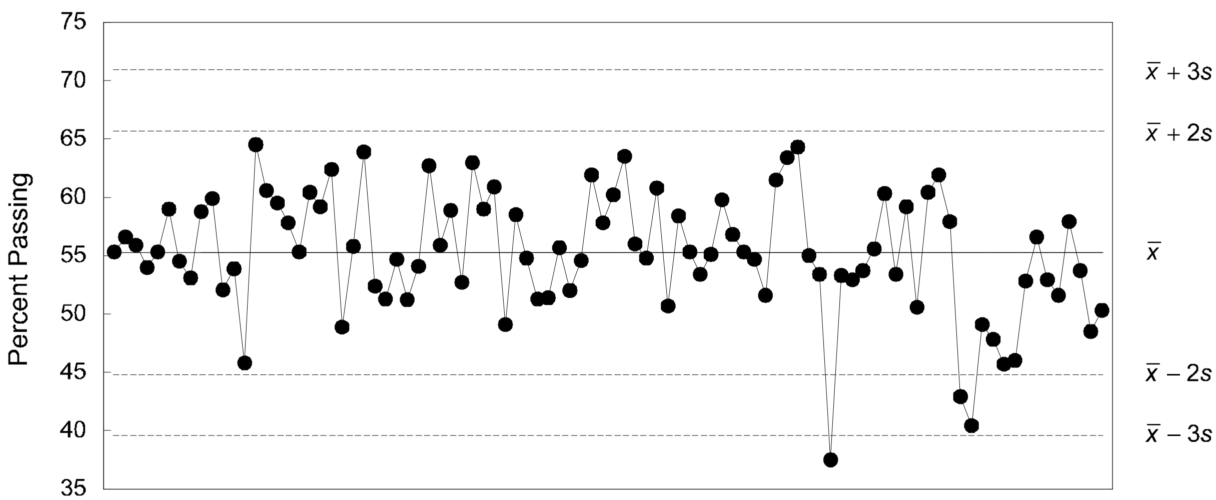


Cold Feed Analysis

Figure I-2. Percent Passing Sieve 3/8″

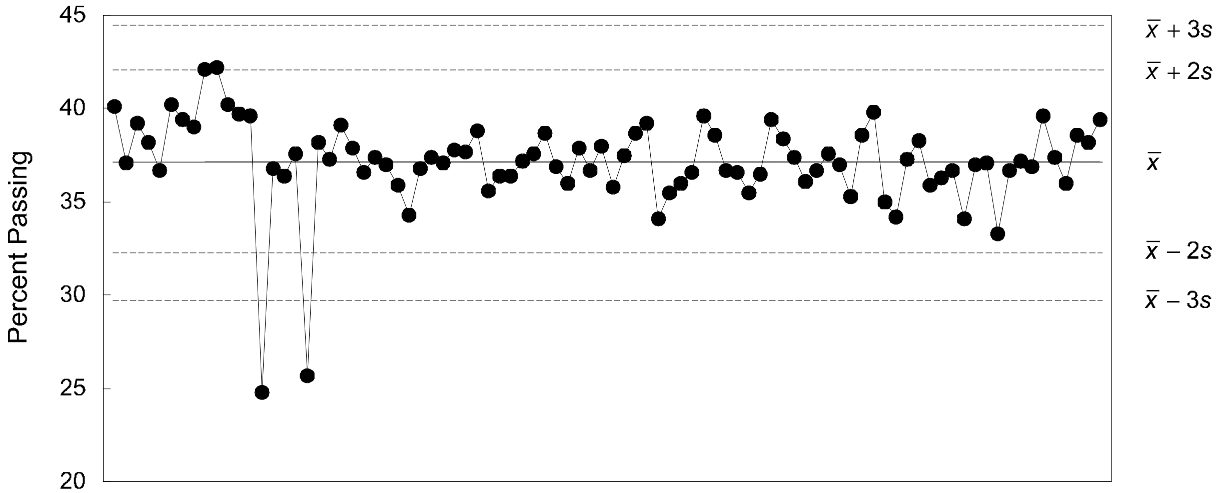


Mixture Analysis

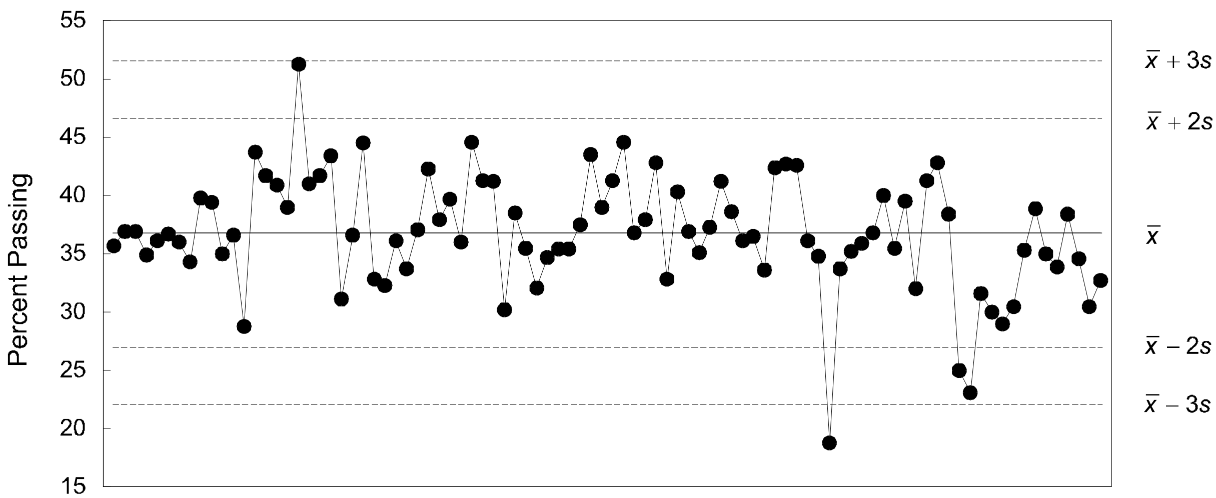


Cold Feed Analysis

Figure I-3. Percent Passing Sieve No. 4

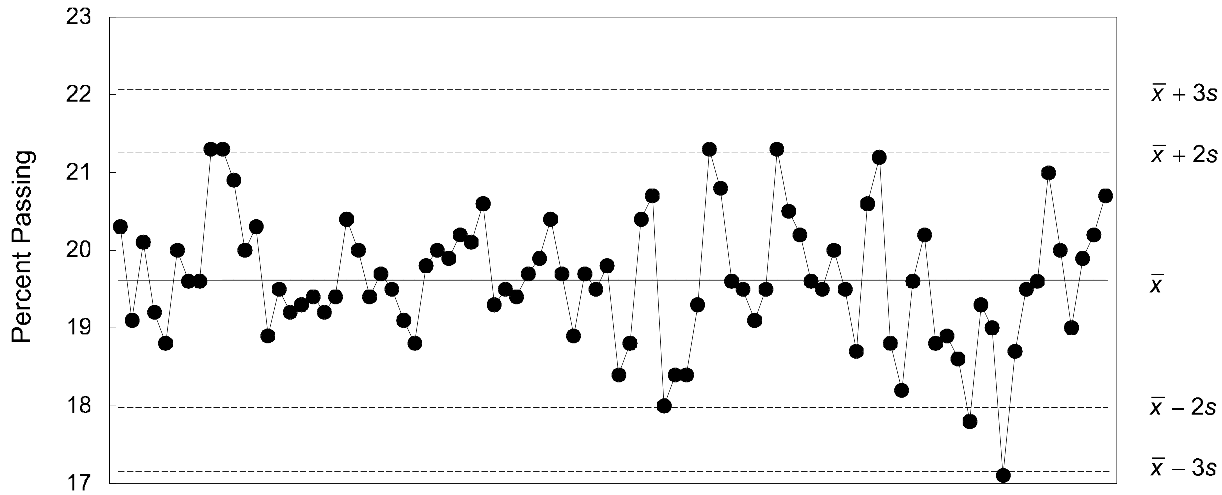


Mixture Analysis

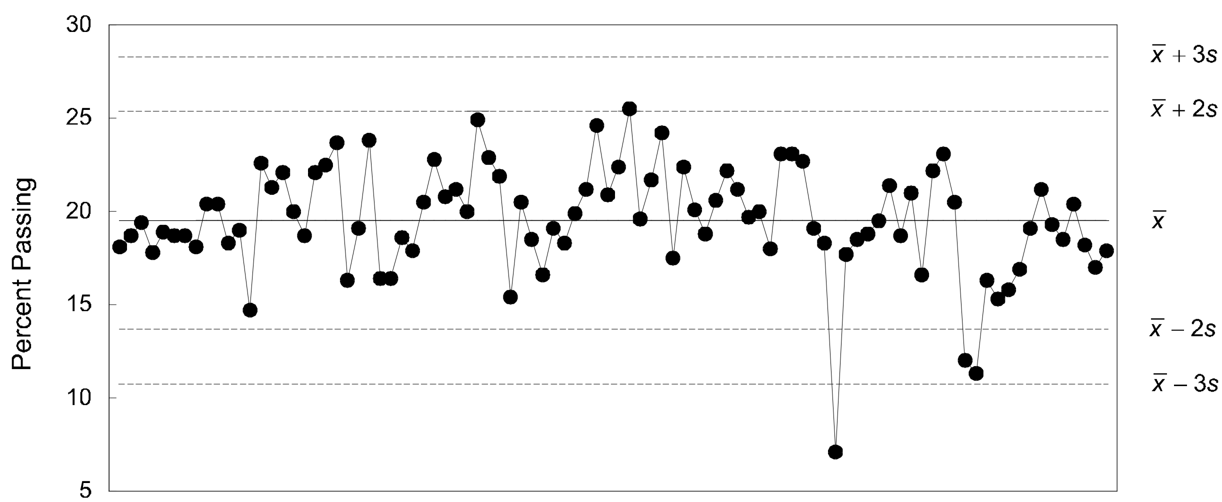


Cold Feed Analysis

Figure I-4. Percent Passing Sieve No. 10

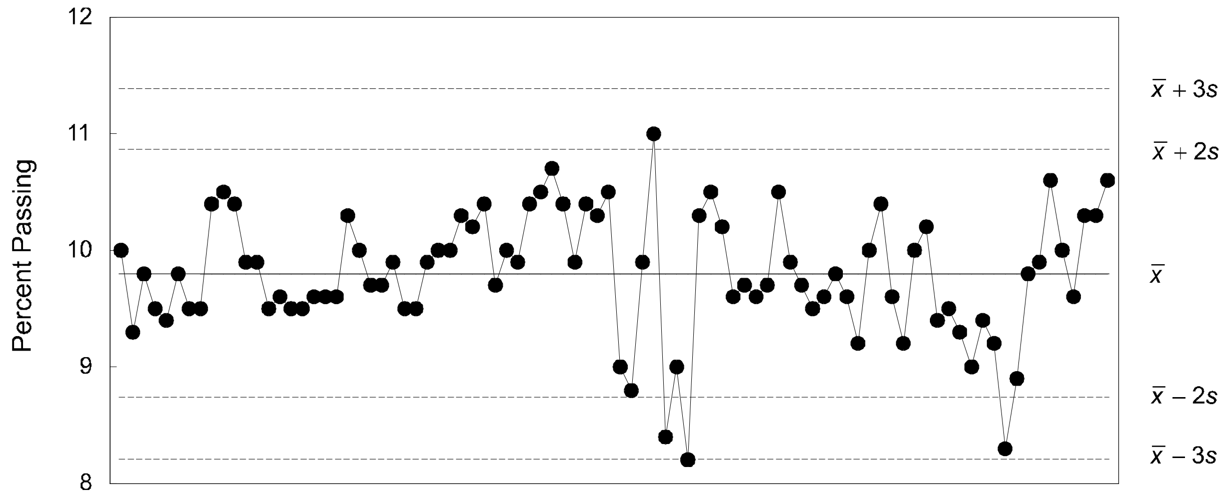


Mixture Analysis

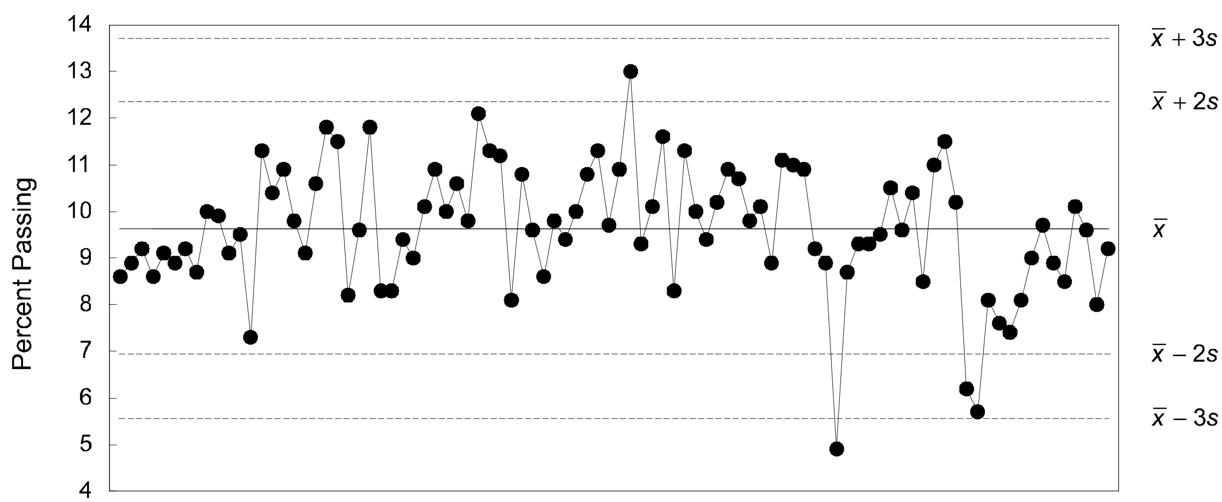


Cold Feed Analysis

Figure I-5. Percent Passing Sieve No. 40

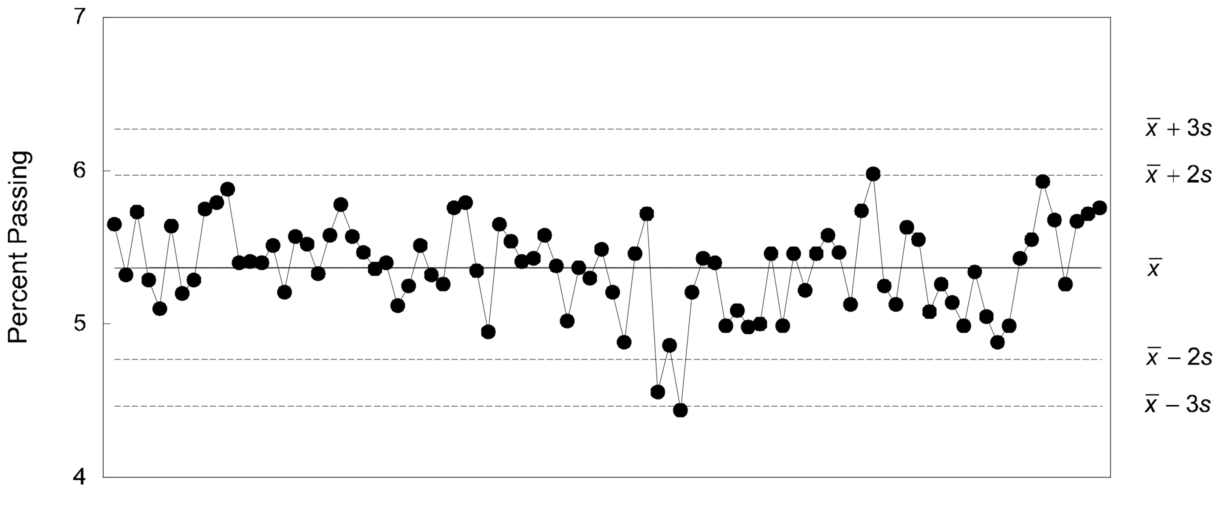


Mixture Analysis

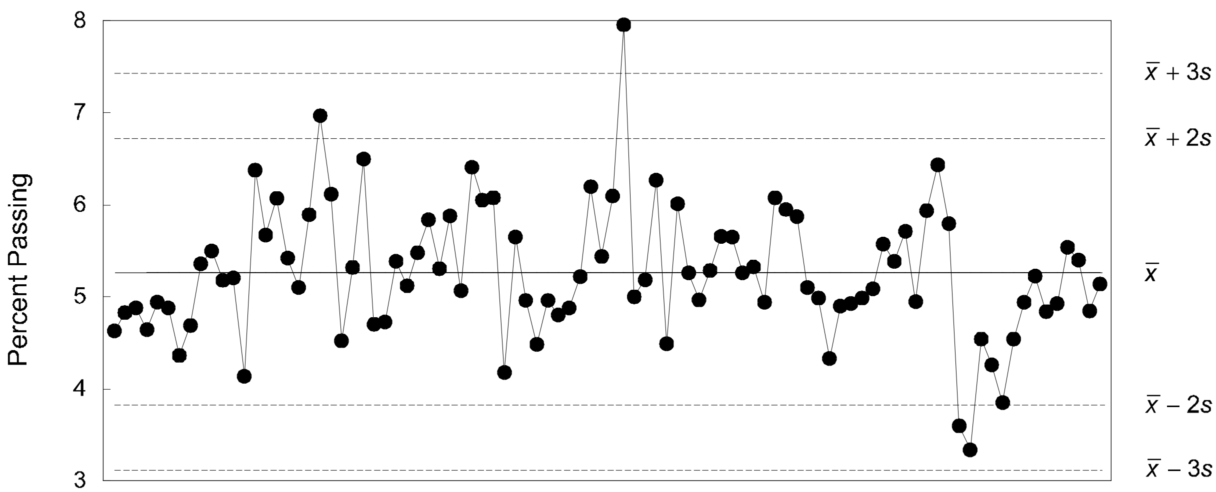


Cold Feed Analysis

Figure I-6. Percent Passing Sieve No. 80

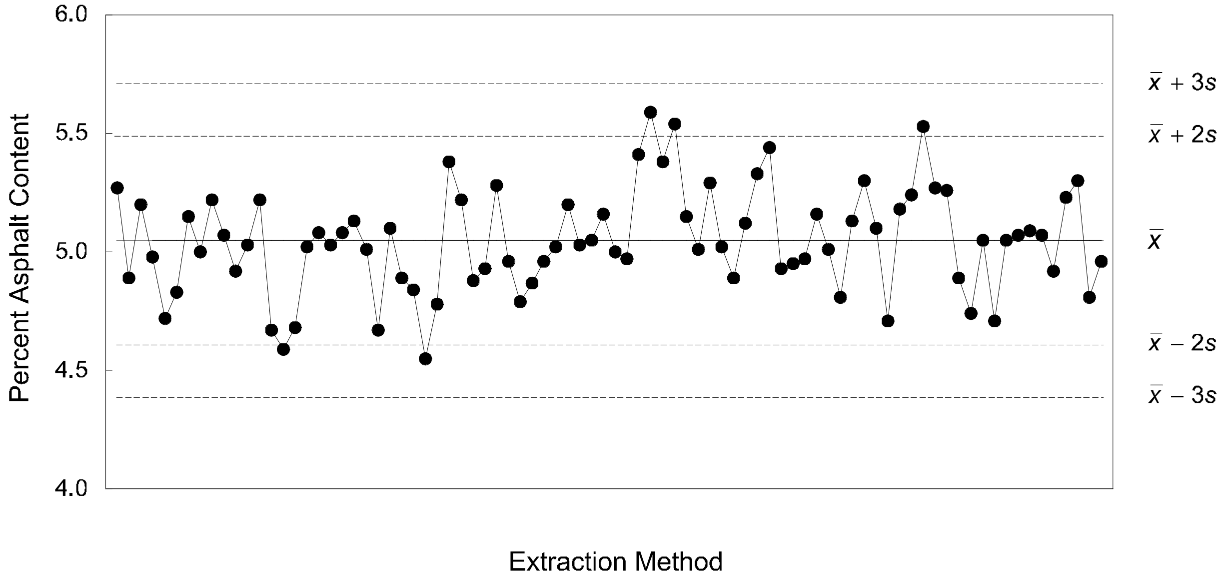


Mixture Analysis



Cold Feed Analysis

Figure I-7. Percent Passing Sieve No. 200



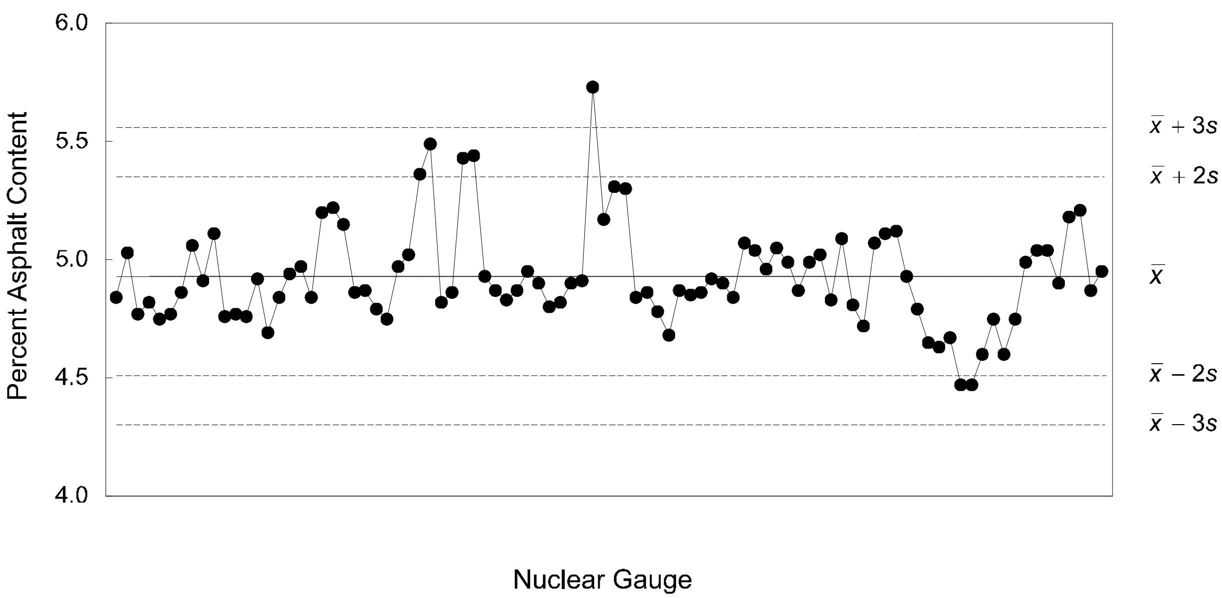
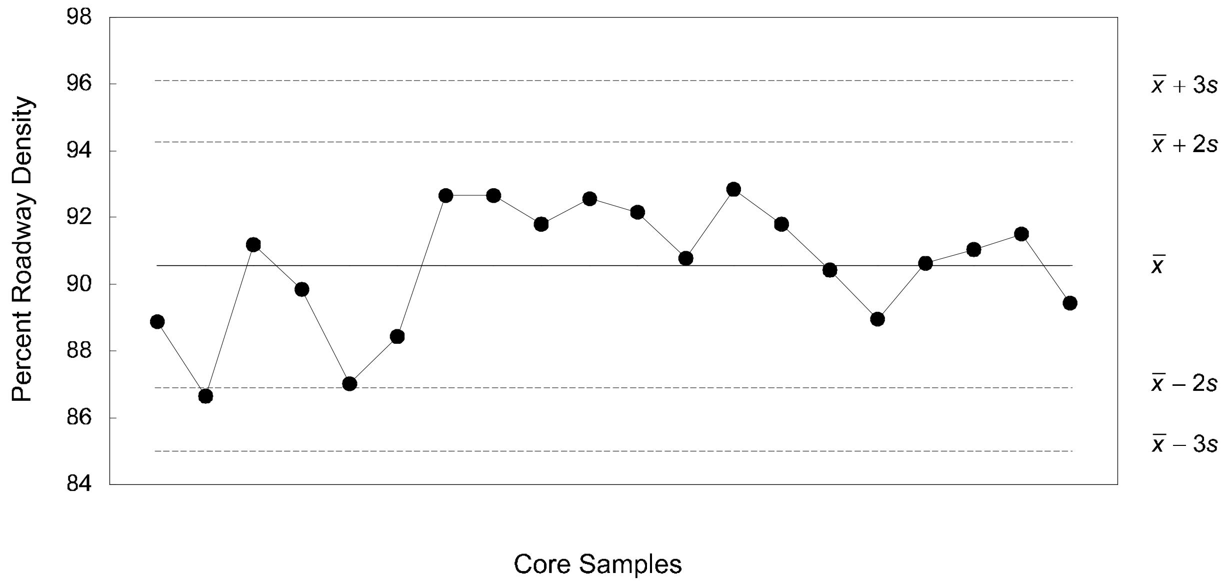


Figure I-8. Percent Asphalt Content



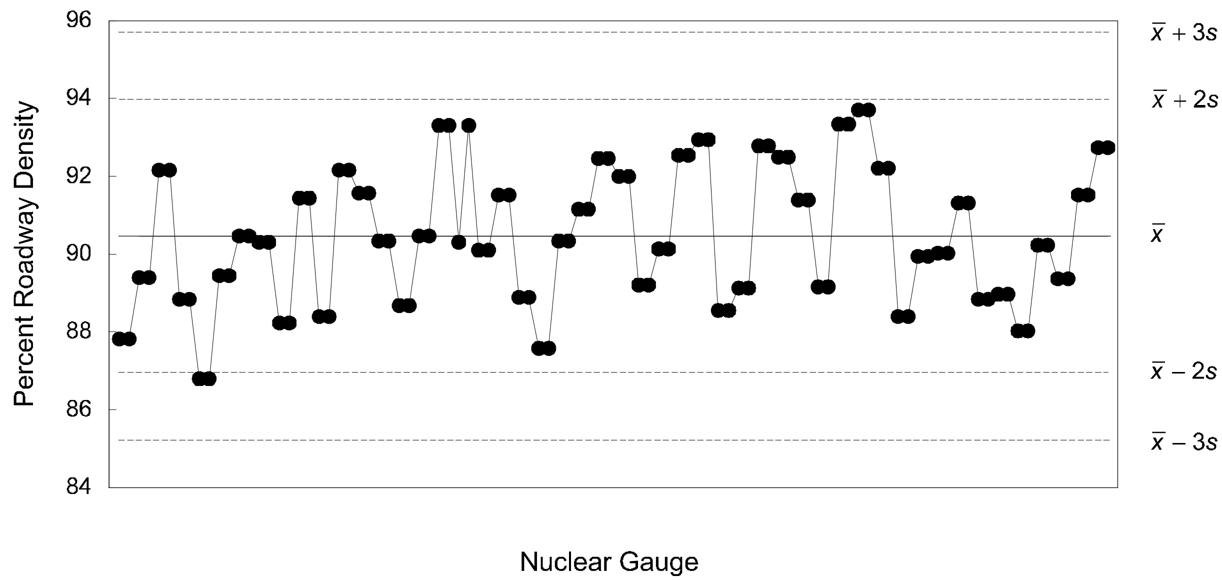


Figure I-9. Percent Roadway Density

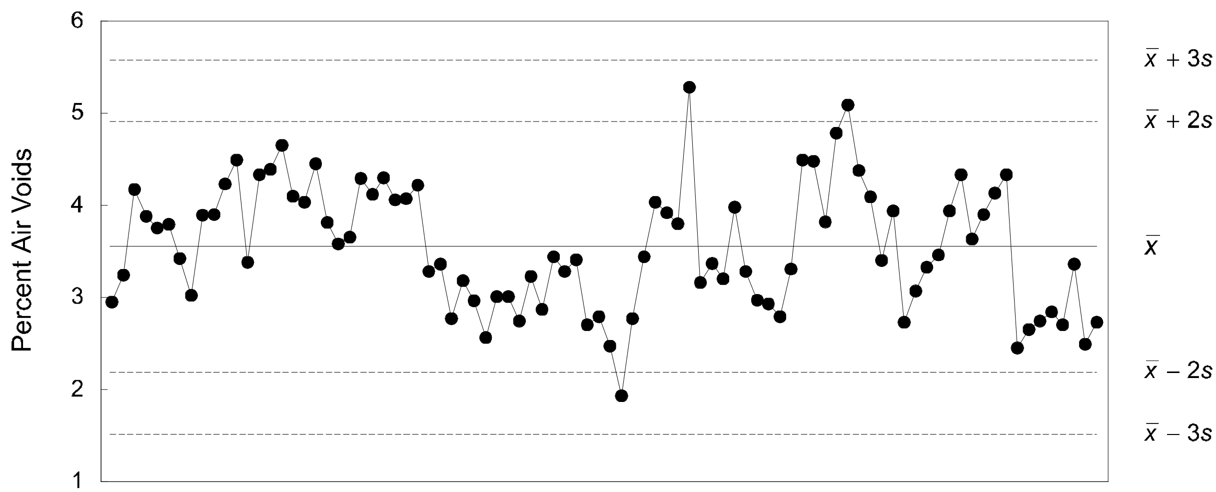


Figure I-10. Percent Air Voids

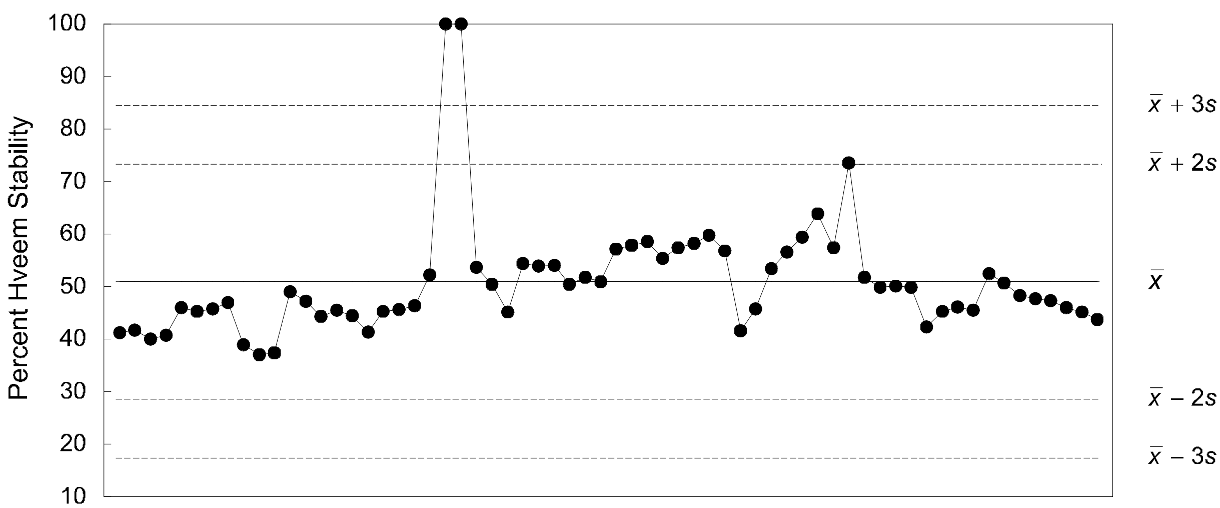
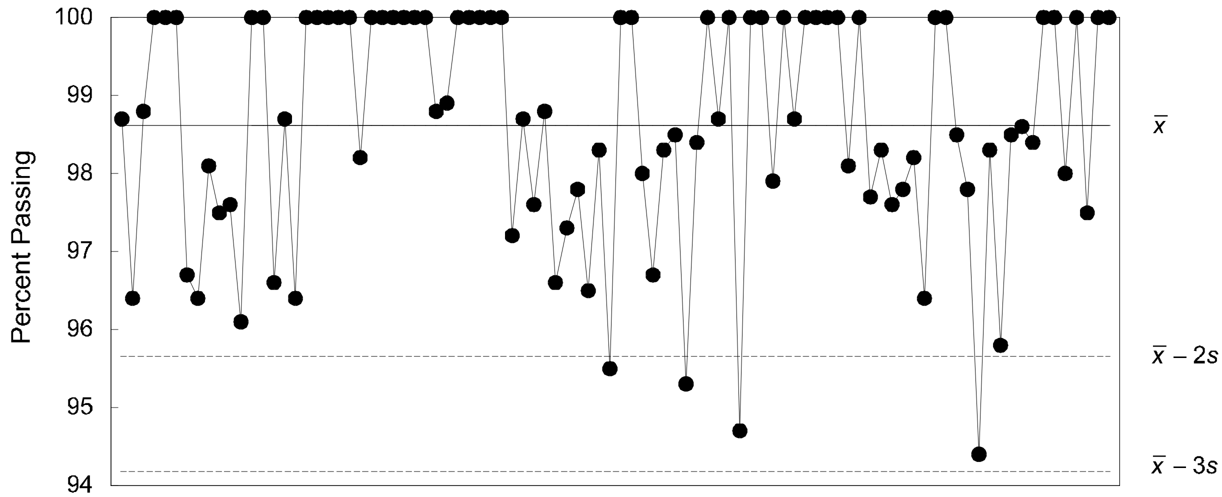


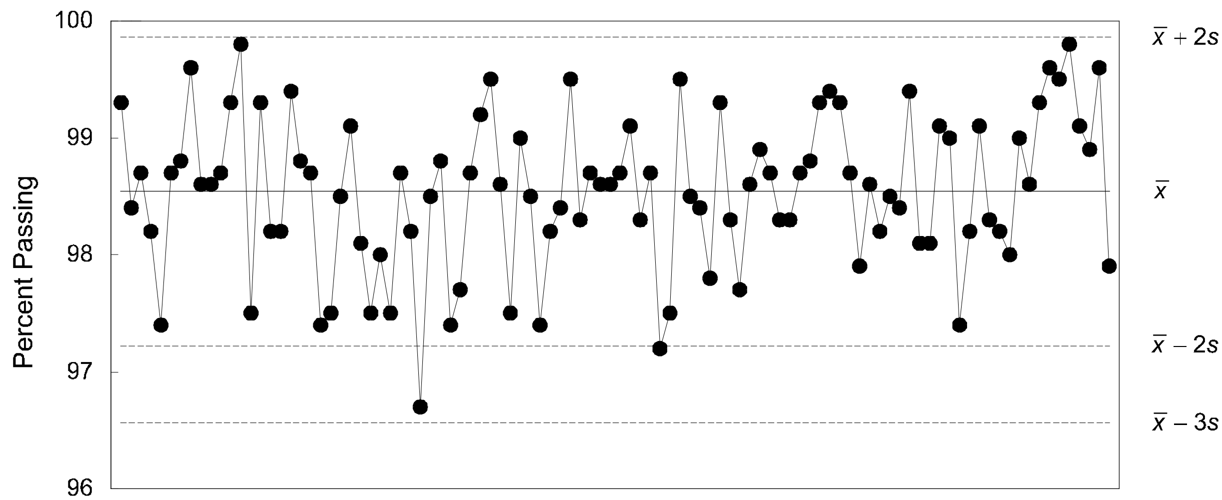
Figure I-11. Percent Hveem Stability

APPENDIX J

X-CHARTS OF QUALITY CHARACTERISTICS PROJECT 4, US-69

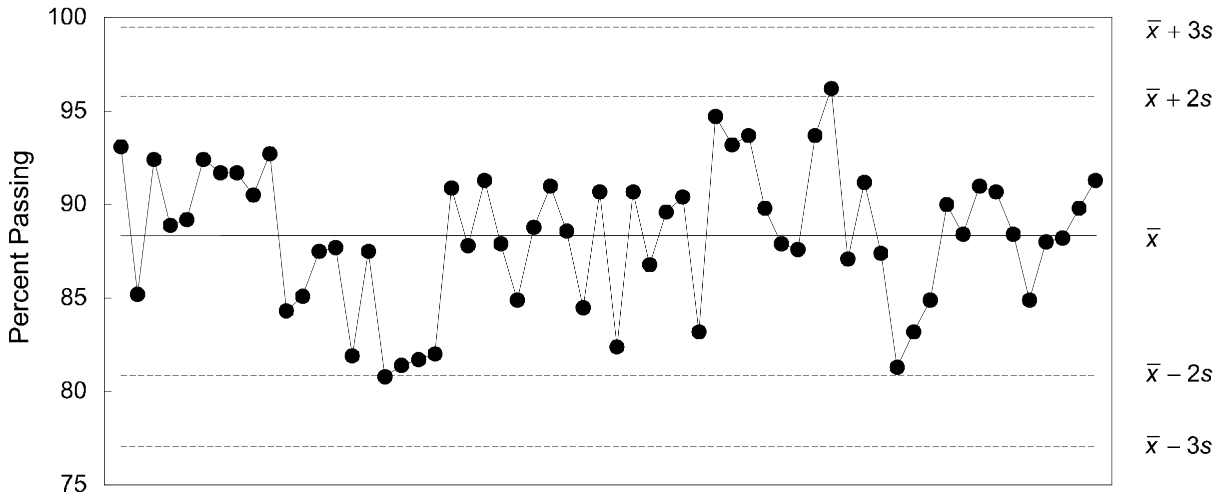


Mixture Analysis

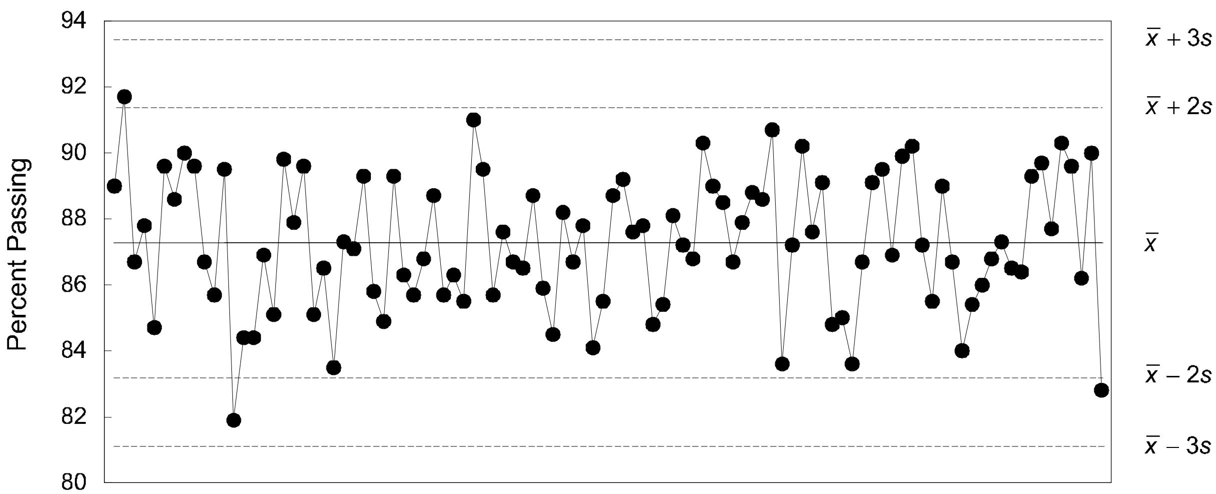


Cold Feed Analysis

Figure J-1. Percent Passing Sieve 1″

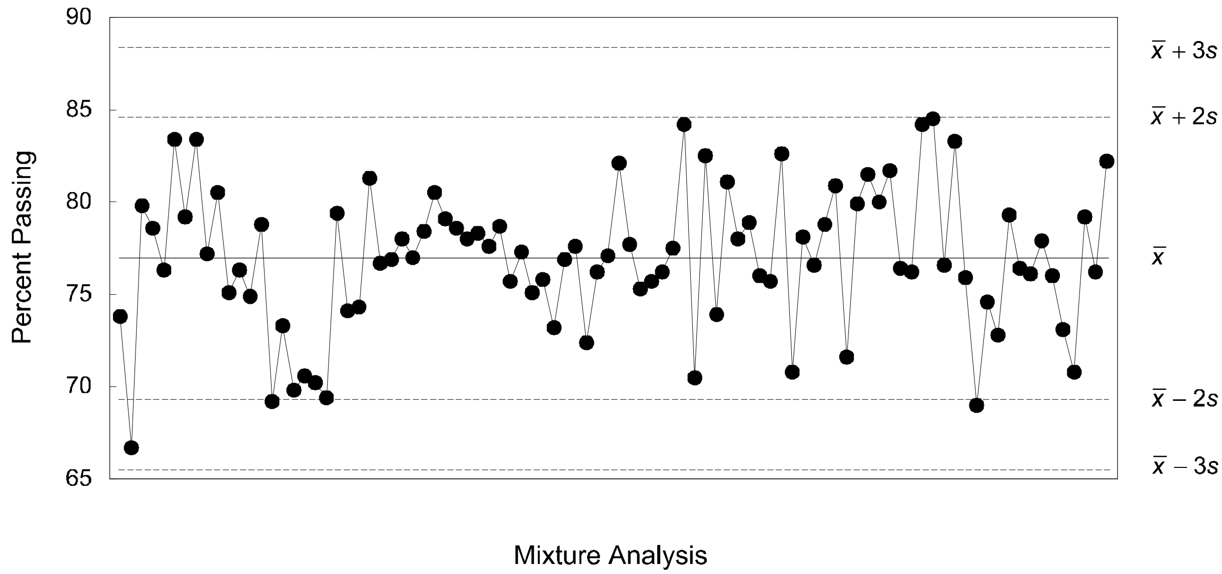


Mixture Analysis



Cold Feed Analysis

Figure J-2. Percent Passing Sieve ¾″



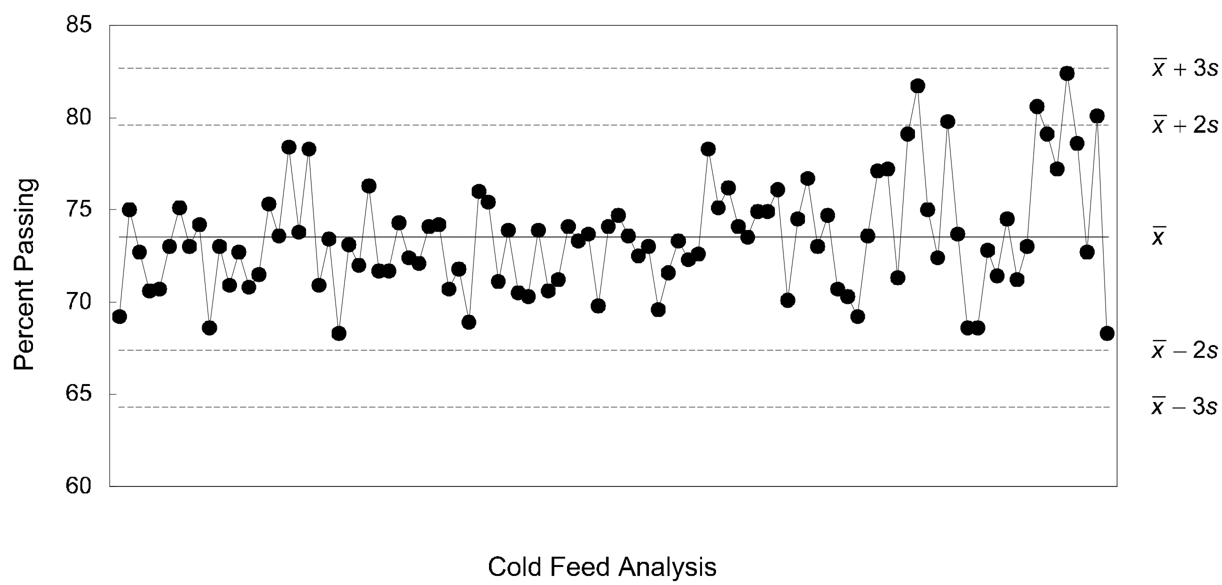
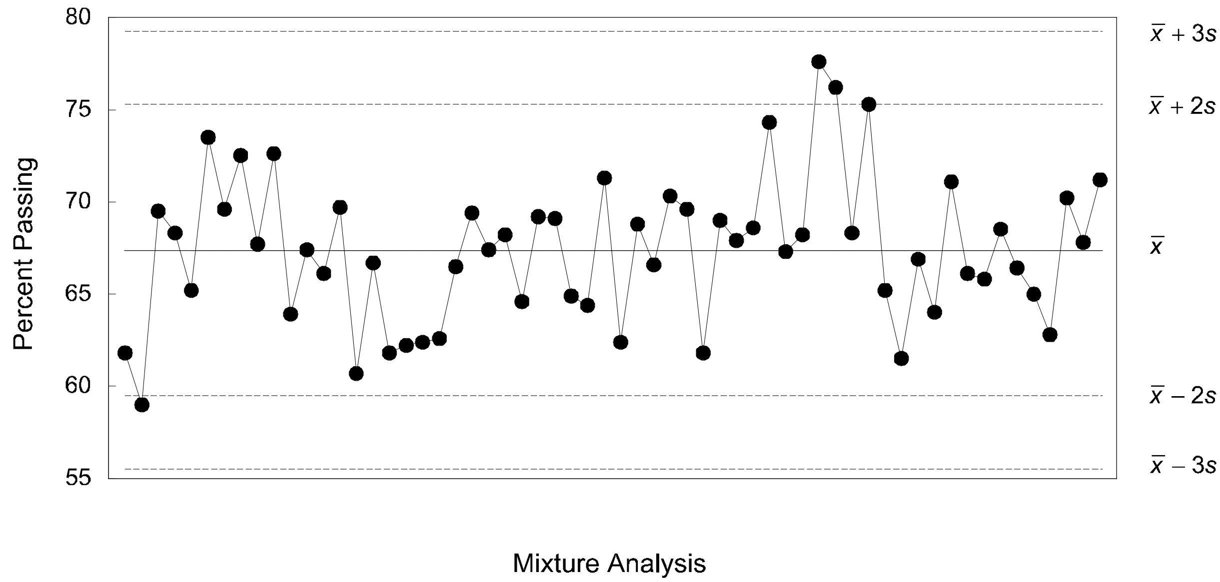


Figure J-3. Percent Passing Sieve ½″



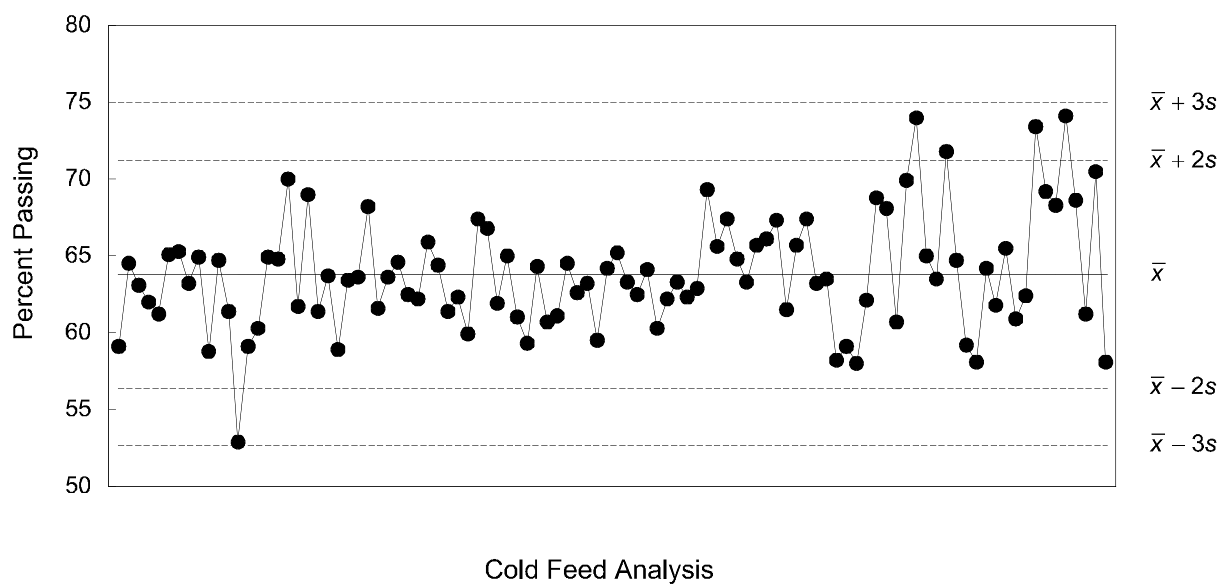
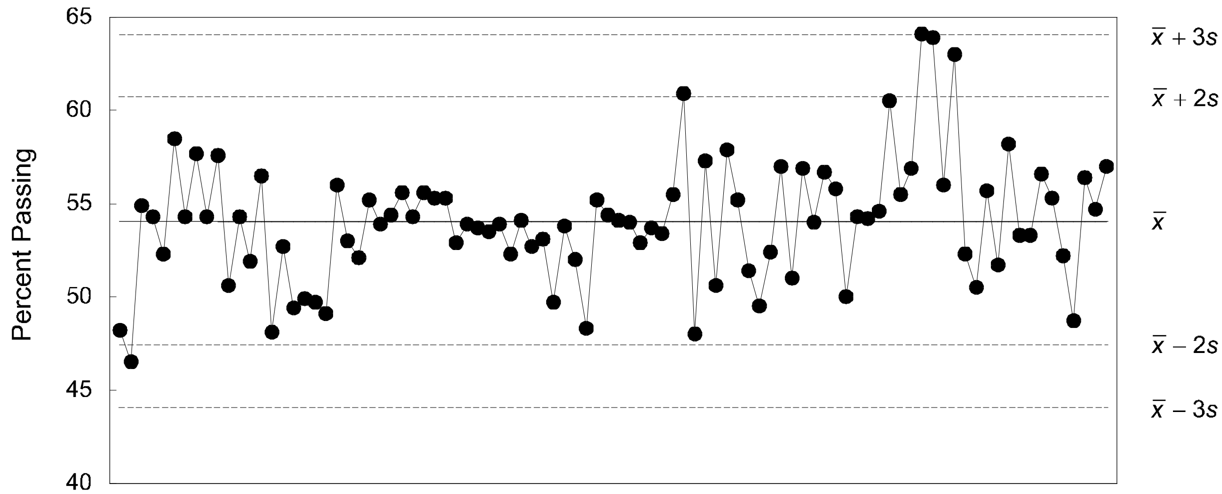
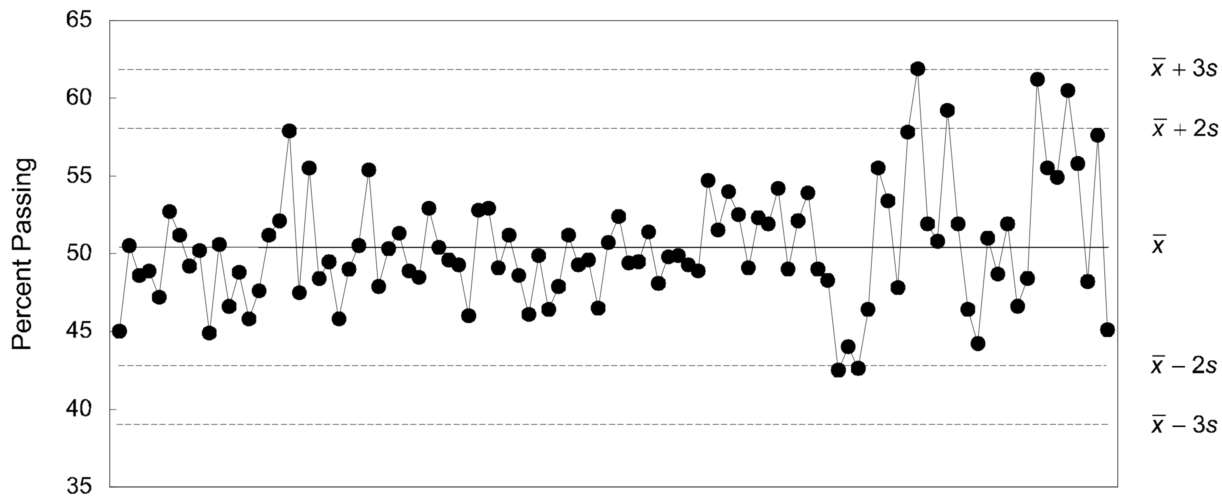


Figure J-4. Percent Passing Sieve 3/8″

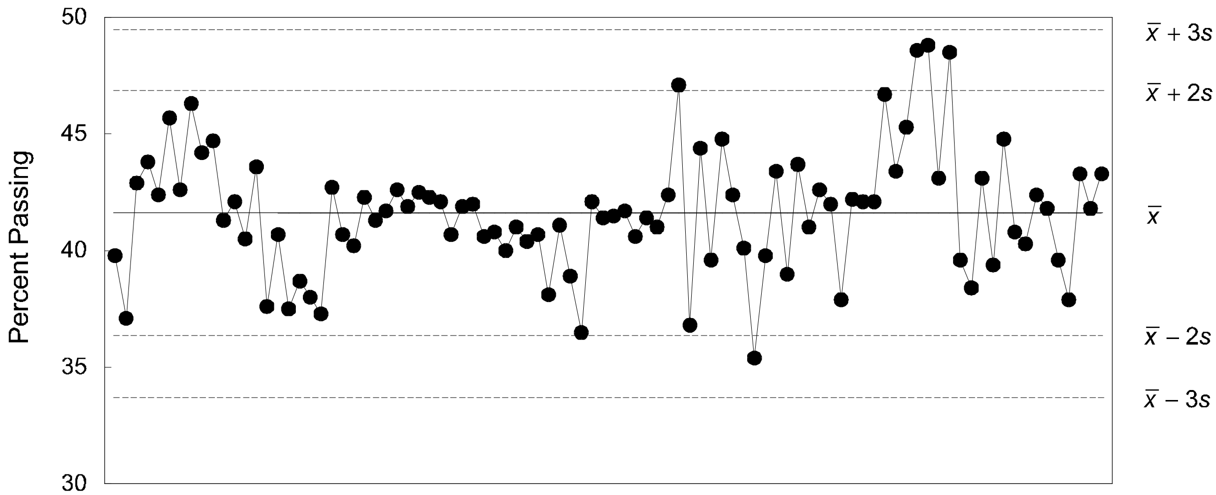


Mixture Analysis

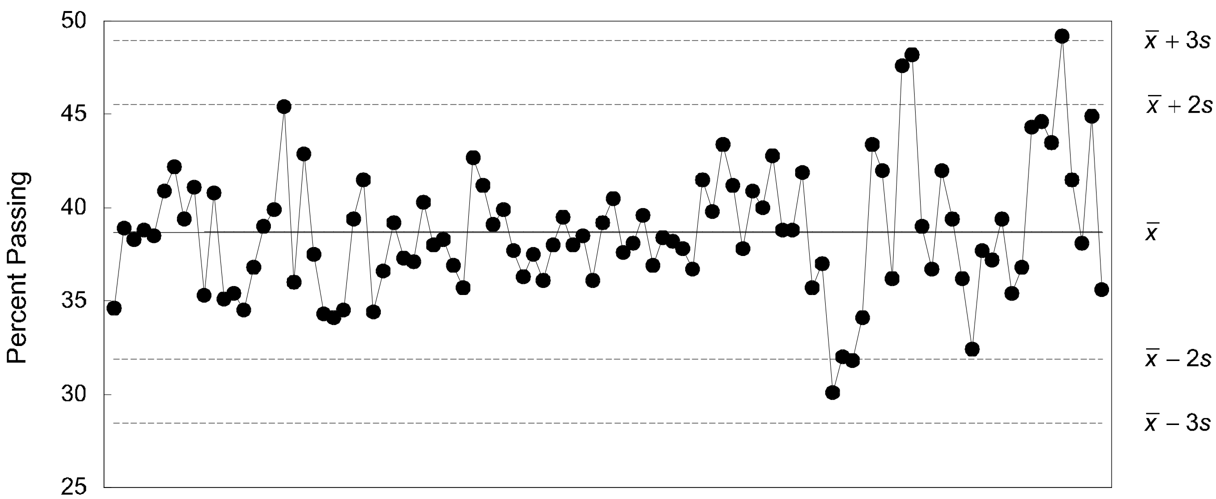


Cold Feed Analysis

Figure J-5. Percent Passing Sieve No. 4

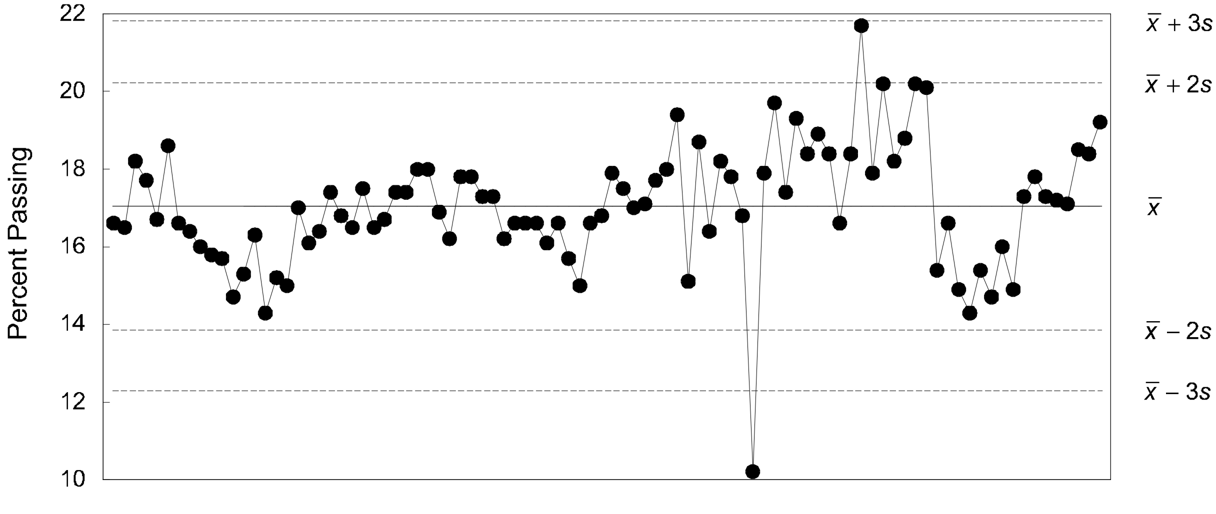


Mixture Analysis

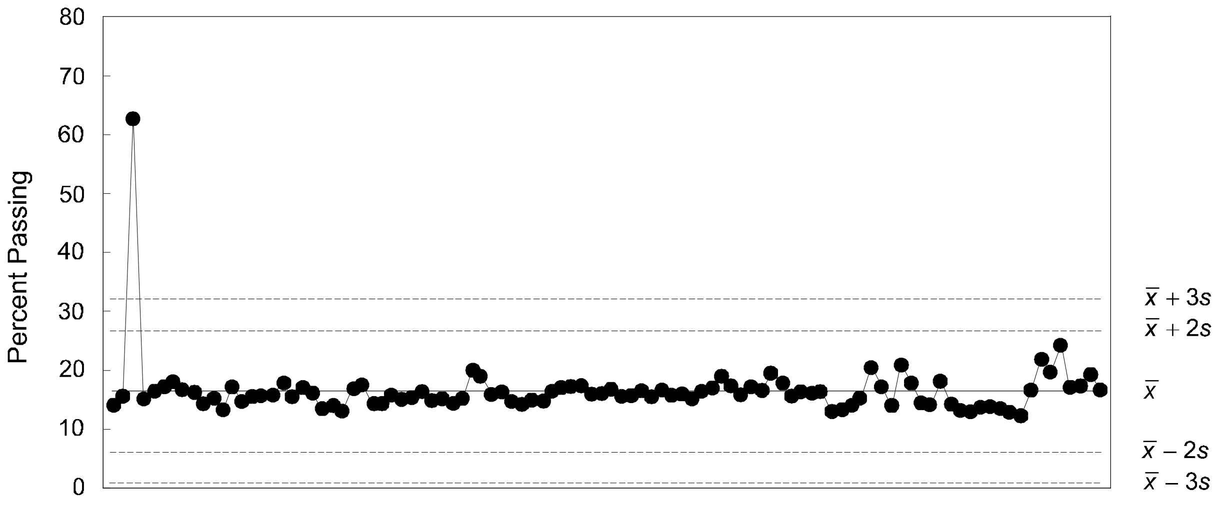


Cold Feed Analysis

Figure J-6. Percent Passing Sieve No. 10

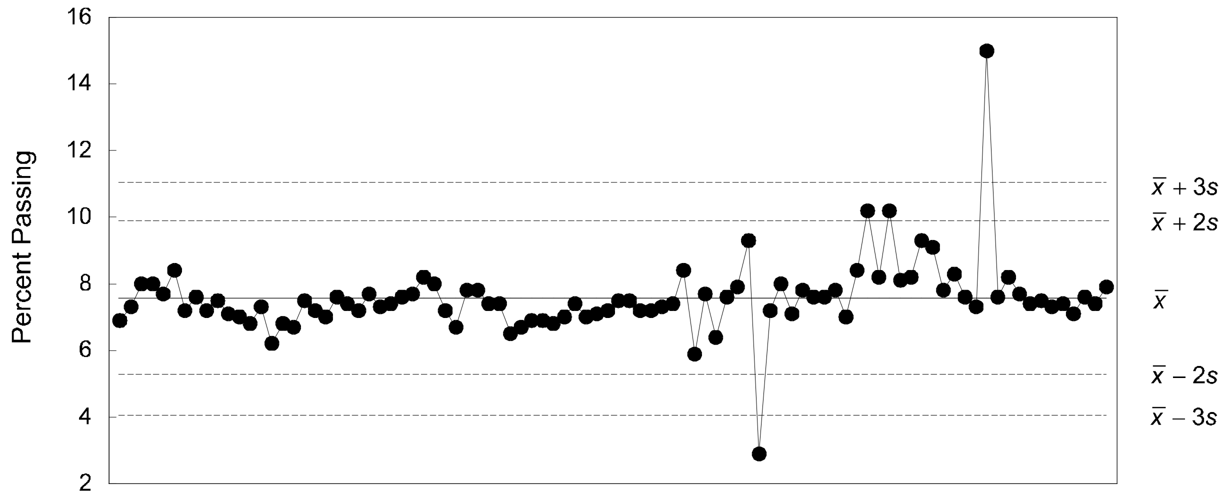


Mixture Analysis

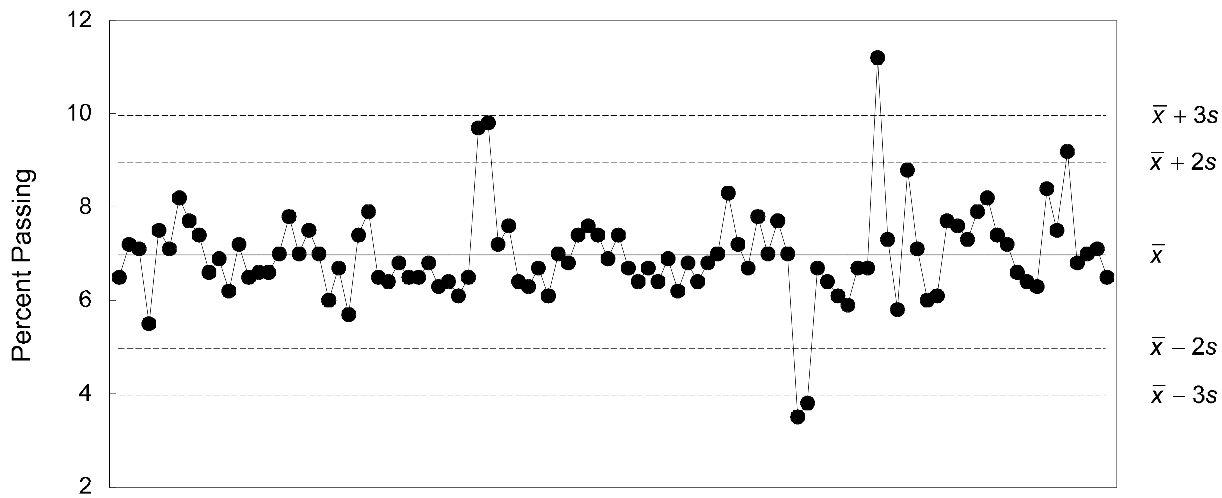


Cold Feed Analysis

Figure J-7. Percent Passing Sieve No. 40

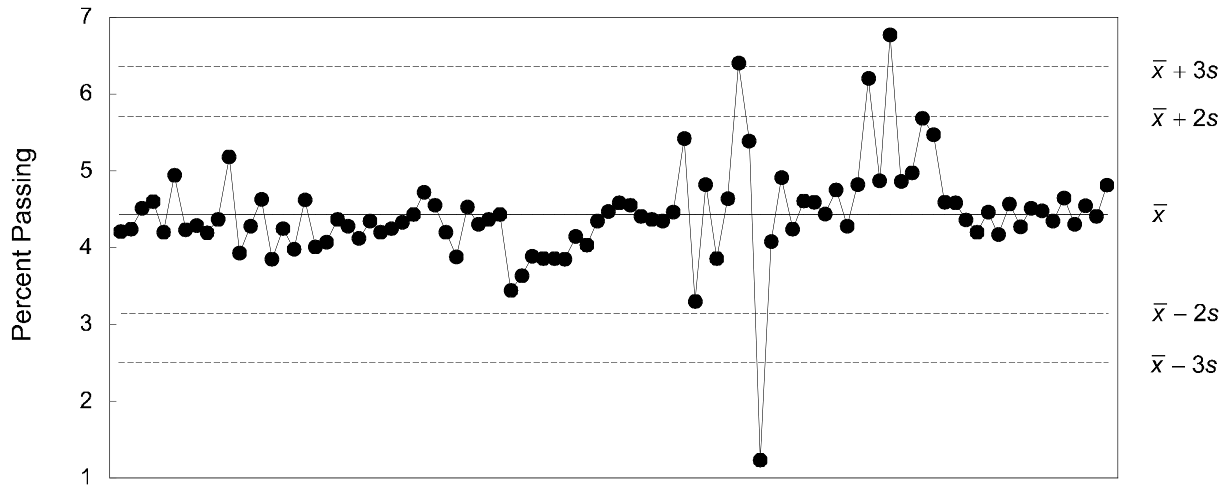


Mixture Analysis

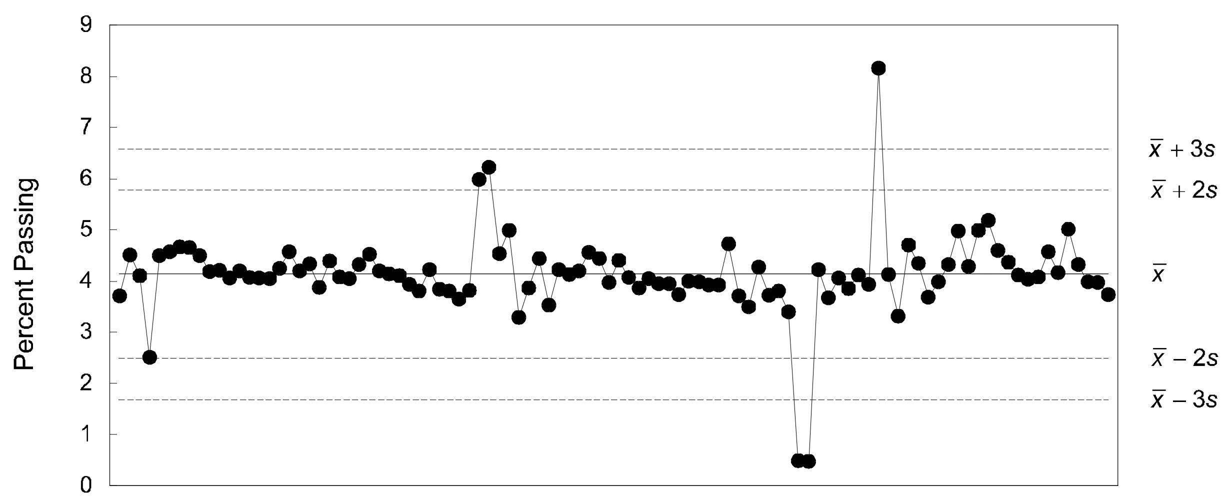


Cold Feed Analysis

Figure J-8. Percent Passing Sieve No. 80

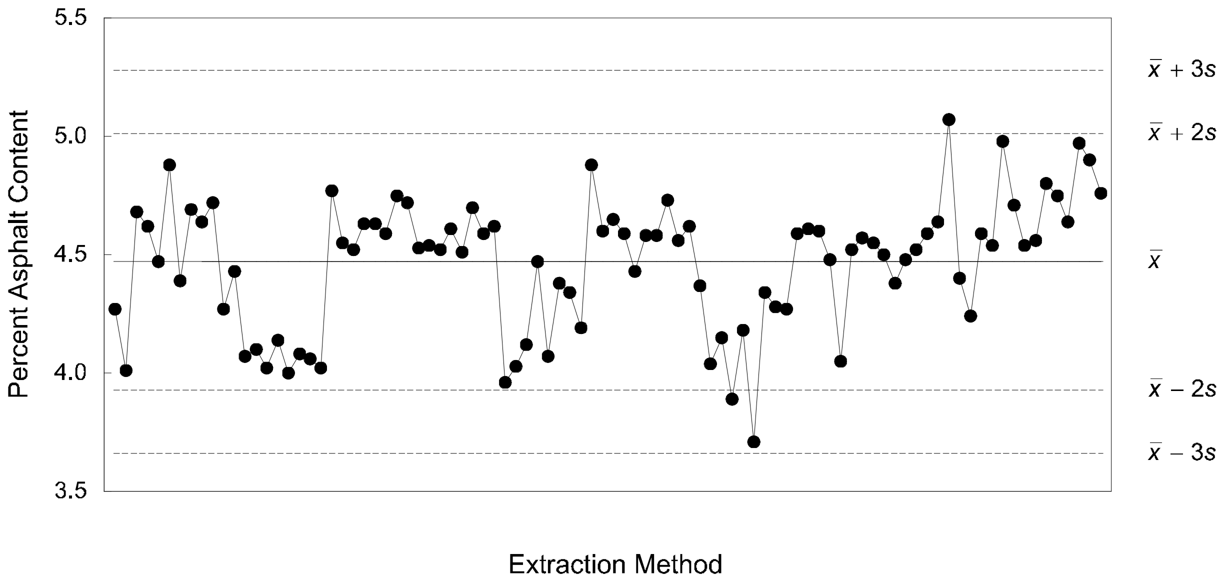


Mixture Analysis



Cold Feed Analysis

Figure J-9. Percent Passing Sieve No. 200



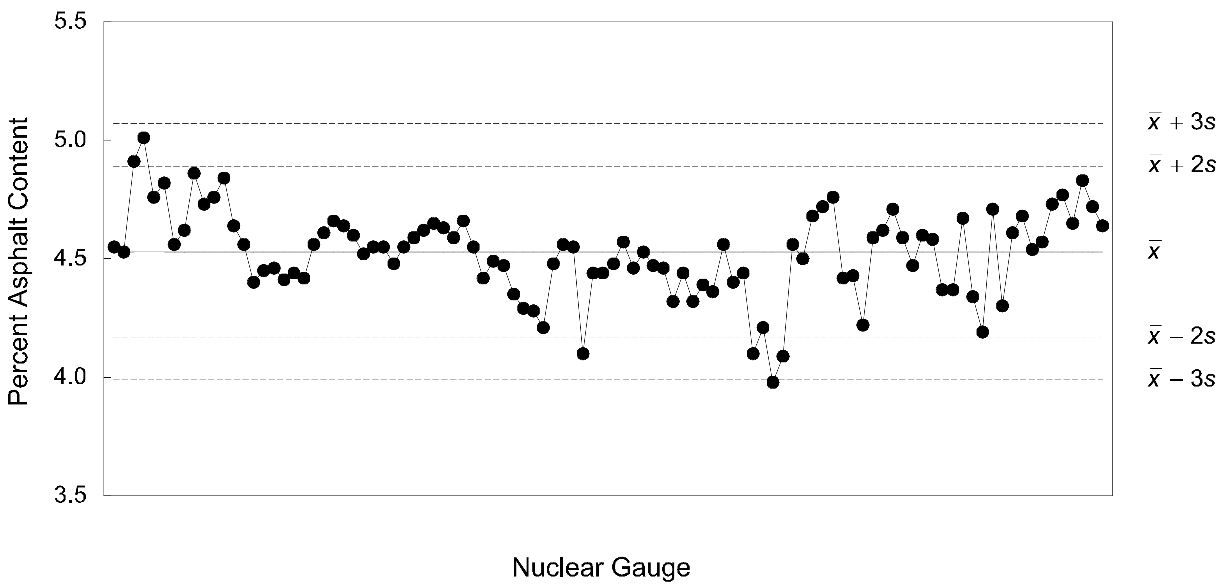
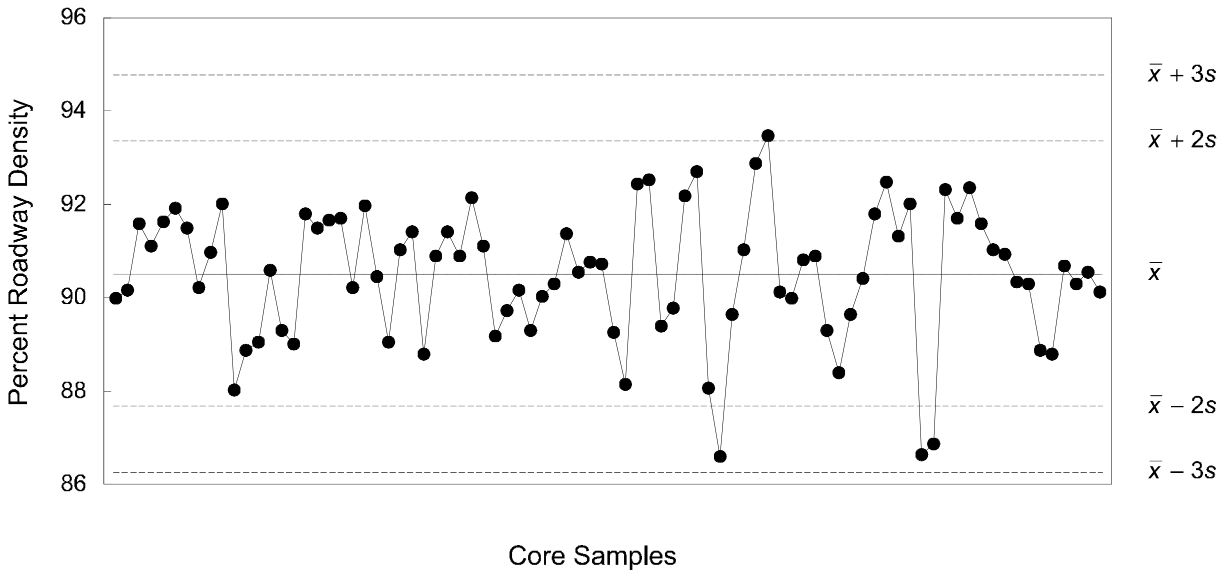


Figure J-10.   Percent Asphalt Content



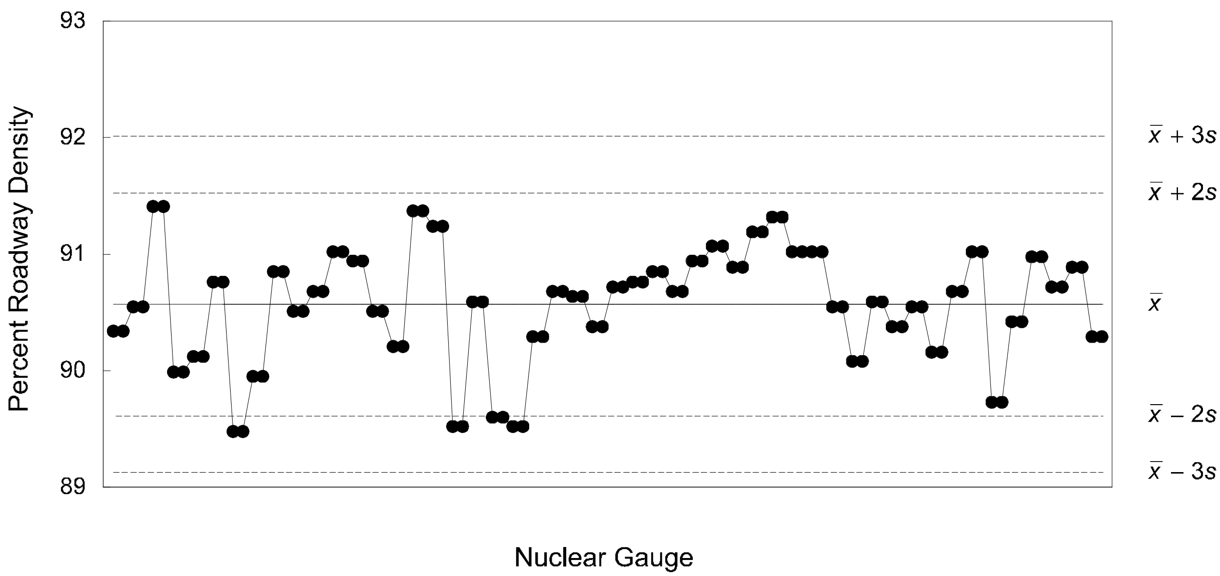


Figure J-11. Percent Roadway Density

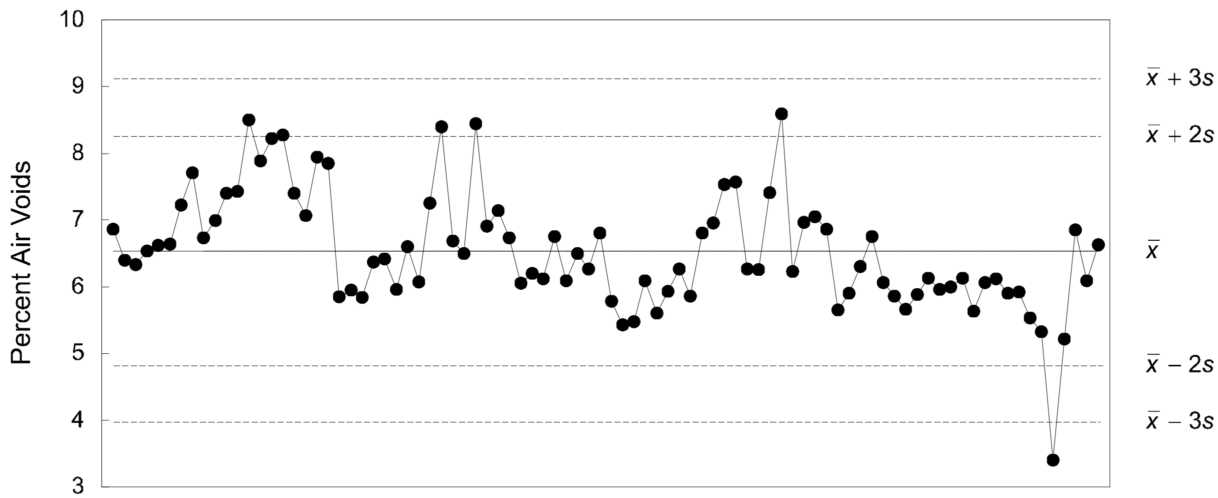


Figure J-12. Percent Air Voids

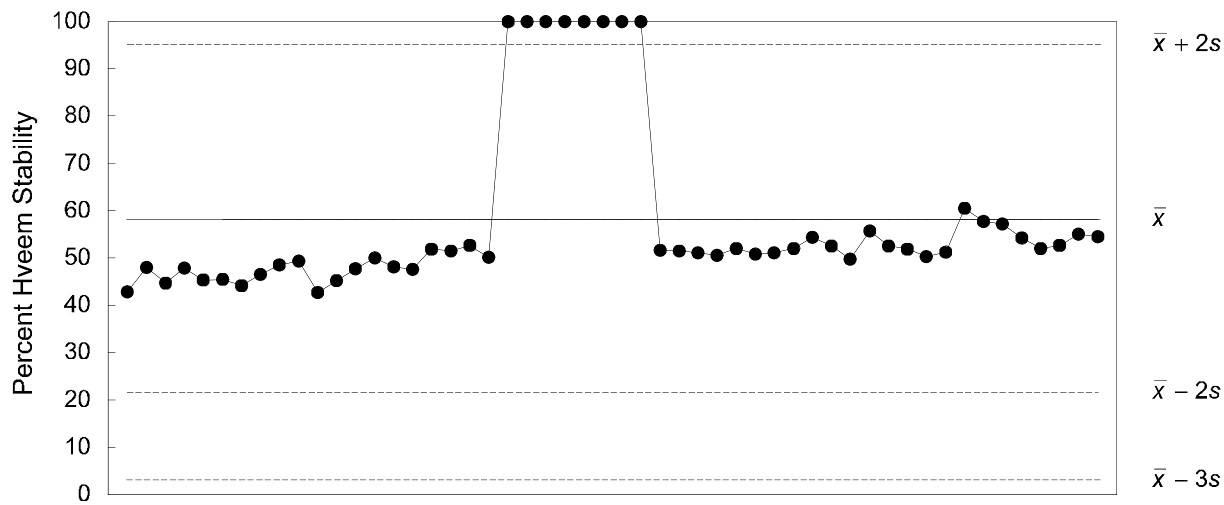


Figure J-13. Percent Hveem Stability

APPENDIX K

EXISTING QA SPECIFICATIONS FOR ASPHALT CONCRETE PAVEMENT

OKLAHOMA DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISIONS
FOR
QUALITY CONTROL AND ACCEPTANCE PROCEDURES
SECTION 411
PLANT MIX ASPHALT CONCRETE PAVEMENT

These Special provisions revise, amend, and where in conflict, supersede applicable Sections of the Standard Specifications for Highway Construction, Edition of 1988, and the Supplement thereto, Edition of 1991. These Special Provisions apply to all types of Asphalt Concrete Pavement.

411.01. DESCRIPTION. (Add the following:)

Contractor's Quality Control and Acceptance Procedures will apply to this work in accordance with the applicable requirements of Special Provisions 105-1QA; 106-1QA and as herein specified.

411.04. CONSTRUCTION METHODS. (Amend to include the following:)

1. **Contractor's Quality Control Testing and Inspection.** The Contractor shall provide quality control personnel as necessary to assure the production of quality products as specified. Such personnel shall include one or more Quality Control Technicians who either individually or collectively are fully qualified in the production, placement and testing of plant mix asphalt concrete.

The Contractor shall be responsible for the formulation of all mix designs. This may be accomplished by Contractor personnel, subcontractor such as independent laboratories, or upon written request, by the Engineer. Mix designs not formulated by the Engineer shall be subject to approval by the Engineer.

The Contractor shall perform or have performed all field sampling and testing necessary to ensure that materials and products are within the specified acceptable range. Control charts displaying results of these tests shall be maintained by the Contractor and displayed at the plant site. Copies of the Contractor's quality control tests shall be provided to the Engineer at time intervals acceptable to the Engineer. Certifications by the manufacturers may be used in lieu of field tests when such tests in the field are impracticable. Asphalt cement and additives are examples of materials in this category.

1.1. Contractor's Process Control. The Contractor shall be responsible for the process control of all materials during handling, blending, mixing and placing operations to produce an acceptable asphalt concrete.

At no time will the Engineer issue instructions to the Contractor or producer as to setting of dials, gauges, scales and meters. However, the Engineer may advise the Contractor against the continuance of any operations or sequence of operations which will result in non-compliance with Specification requirements.

1.2. Contractor's Testing. For the four characteristics subject to pay adjustments in this Special Provision, the Contractor's sampling and testing as a minimum shall comply with the schedule in paragraph (m)-5 "Contractor's Testing and Engineer's Acceptance Procedures". Additional sampling and testing to ensure compliance with Standard Specifications and other Special Provision requirements shall be in accordance with the Contractor's Quality Control Plan.

1.3. Contractor's Quality Control Plan. Prior to the initiation of work, the Contractor shall prepare a plan to ensure that acceptable quality can and will be obtained. The Plan, which is to be submitted to the Engineer at the prework conference, shall cover all of the items discussed in Sections 411 and 708 of the Standard Specifications. However, the Contractor must tailor the plan to meet specific needs of the project. Once accepted by the Engineer, the plan becomes a part of the Contract and shall be enforced accordingly. Subsequent changes to the plan may be required by the Engineer in order to adjust to changes in the process or to correct problems in meeting Specification requirements.

(m) <u>Acceptance</u>. While the Contractor shall be fully and exclusively responsible for producing an acceptable product, acceptance responsibility rests with the Engineer. The entire lot of asphalt, as defined in paragraph (m)-4 "Lot and Sublot Selection", will be accepted or rejected and paid for on the basis of acceptance test results.

1. Basis for Acceptance and Payment. The following characteristics will be considered when determining the acceptability and pay factors for Plant Mix Asphalt Concrete Pavement. However, all of the requirements of the Standard Specifications on materials and workmanship except those superseded by Special Provisions in this Contract, shall remain in effect.

- Asphalt Cement Content
- Gradation
- Air Voids
- Roadway Density

Several methods are available to test for the above characteristics. While only one method will be used, several tests may be made to measure each characteristic. The greater the number of tests conducted on each lot, the less average deviations will be allowed for full payment. The basis for acceptance and pay factors will be the average of the deviations from specified standards as indicated in Table I.

For the characteristics of asphalt cement content, gradation and air voids, signs of the deviations will be disregarded when computing averages, that is, deviations above target will be penalized the same as those below target. Signs of the deviations will be considered for roadway density. However, maximum as well as minimum density requirement must be adhered to. While pay adjustments relate only to those densities below target, densities above the absolute upper limits in Table I are unacceptable.

The pay factors in Table I that relate to gradation will be considered in a group with only the lowest pay factor for the individual sieves to be considered in determining payment. All sieves specified in Section 708.04 of the Standard Specifications or as modified by other Special Provisions must be run. The remaining applicable pay factors will be considered individually in determining payment. Pay factors for asphalt cement content, gradation (lowest), air voids, and roadway density will apply to all asphalt concrete placed.

Thus the total adjustment to payment (Combined Pay Factor) due to deviations from specified standards will be determined from the following formula:

$$CPF = \frac{3\,(AC + AV + D) + G}{10}$$

where:

CPF	=	Combined pay factor,
AC	=	Pay factor for asphalt cement content,
AV	=	Pay factor for air voids,
D	=	Pay factor for roadway density, and
G	=	Lowest pay factor for gradation.

2. **Conflicts Between Engineer's and Contractor's Test Results.** At the beginning and throughout the contract, the Engineer and the Contractor shall compare each other's test procedures and results. Should the Engineer determine that any of the Engineer's results are incorrect, such results will be discarded.

   If the Engineer further determines that the remaining correct results adequately represent the material being evaluated, the Engineer will use them for pay adjustment purposes. In doing so, the Engineer will take into account the increased allowable average deviations resulting from decrease in number of tests. If the Engineer determines that the remaining test results are too few to represent the material being evaluated, the Engineer may test additional sample or supplement them with appropriate Contractor test results.

   If the Engineer and the Contractor are unable to resolve their differences, the Contractor may request referee testing by representatives from the Department's Materials Division. The Contractor shall request referee testing in writing within 30 days after testing is complete for the lot. Such testing will be independent from any previous testing by either the Engineer or the Contractor and the results shall be considered final. Should the referee testing result in higher pay factors on the questioned lot(s), the additional testing costs will be absorbed by the Department. Otherwise, the entire cost (including administrative costs) shall be borne by the Contractor.

3. **Extreme Values (Outliers).** Test results apparently inconsistent with the results of the majority of tests will also be closely examined by the Engineer in order to determine their validity. The examination will cover the procedures used in sampling and testing and, if necessary, a mathematical analysis will be performed in accordance with ASTM E-178-80 using the upper 2.5% significance level. Test results thus determined by the Engineer to be non-representative of the material being evaluated will be discarded. The remaining test results will then be supplemented, if necessary, and treated in the manner indicated in paragraph (m)-2 above "Conflicts Between Engineer's and Contractor's Test Results".

4. **Lot and Sublot Selection.** The asphalt concrete will be randomly sampled and tested for all control test characteristics on a lot to lot basis in accordance with Special Provisions 106-1QA and the following requirements. However, any load of mixture which is visually unacceptable for reasons of being excessively segregated or aggregate improperly coated will be rejected for use in the work. Excessively high or low temperature will also be cause for rejection. Furthermore, sections of completed pavement which from visual observation or known

deficiencies appear to be seriously inadequate will be tested. The results of such tests will not be used for pay adjustment purposes but will be used to determine whether the section is totally unacceptable and must be removed. In the event that it is determined to be unacceptable, its removal and replacement shall be at no additional cost to the Department.

A standard size lot at the asphalt plant shall consist of four equal sublots of 1000 tons each. When the quantity represented is less than 4000 tons, the number of sublots in a lot will vary according to the following:

Quantity		Number of
Less Than	But Greater Than	Sublots
4000 Tons	3000 Tons	4
3000 Tons	2000 Tons	3
2000 Tons	1000 Tons	2
1000 Tons	250 Tons	1

Quantities of mixture less than 250 tons may be accepted by the Engineer upon visual inspection by which the Engineer has reason to believe that the materials are of acceptable quality. This quantity may be treated as a separate lot, combined with the previous lot, or combined with the following lot, as the case may warrant. On a multiple project contract, the lots of asphalt will carry over from project to project.

5. **Contractor's Testing and Engineer's Acceptance Procedures.** Once a lot has been defined, its identity will be maintained throughout the mixing and placement process. Pay factors, determined from random sampling and testing the lot at appropriate locations, will be used in computing its payment adjustment.

   The Contractor is required as a minimum to comply with the following schedule for sampling and testing. Depending upon the available time and the Engineer's confidence in the Contractor's Process Control, the Engineer may elect to perform more or less sampling and testing.

   Asphalt Cement Content and Gradation - 1 specimen and/or test randomly selected for each characteristic per sublot. Air Voids and Roadway Density - 3 specimens and/or tests per sublot randomly selected, averaged, and considered as one test in Table I.

(n) **<u>Plant Startup Requirements</u>** - Prior to beginning production of asphalt for the mainline, the Contractor shall provide a quality control system in accordance with paragraph "a" of Special Provision 106-1QA. The system shall include the fully equipped laboratory and the full complement of quality control personnel that are to perform the quality control functions for the remainder of the project.

Plant startup production shall be limited to that necessary to calibrate the plant and the testing equipment and procedures using the mix design approved for mainline construction. The asphalt concrete thus produced shall be sampled and tested by both the Contractor and Engineer for VMA, Hveem Stability and all of the characteristics in Table I except roadway density. The Contractor's test results shall then be reconciled with those from the Engineer.

No asphalt concrete from the startup operation shall be placed on the mainline or the control strip. Instead, adjustments shall continue to be made until all of the requirements are met. Asphalt concrete from the plant startup operation may be utilized and paid for in the construction temporary facilities or if no temporary facilities are available they shall become the property of the Contractor and will not be paid for. Costs associated with startup operations will not be measured separately for payment but will be included in the payment for Contractor's Quality Control.

(o) **Control Strip Requirements** - After fulfilling the plant startup requirements, one or more control strips shall be constructed on the shoulder or detour for the purpose of verifying the required production mix characteristics and establishing rolling patterns to obtain target requirements. The initial placement of asphalt concrete shall be limited to approximately 500 tons. This material shall then be sampled and tested by the Contractor and the Engineer for VMA, Hveem Stability and all of the characteristics in Table I. No additional asphalt concrete shall be placed until all the results are evaluated and necessary adjustments in production and placement procedures are made. No pay adjustments will be made for deviations from target on the approximately 500 ton placement.

After necessary adjustments are made, the above process shall be repeated for the next approximately 500 tons of asphalt concrete placed. Pay adjustments for deviations from target on this second placement will be made at the rate of one half those specified. If required, additional control strips shall be made on the shoulder until an acceptable product (i.e., within the 1.00 pay factor range of Table I) is produced. Pay adjustments for deviations from target on all asphalt mixture in excess of the first approximately 1000 tons will be made at the full rate as specified in Subsection 411.04(m)-1. Control strips will not be measured separately for payment. Work and materials associated with control strips will be paid for at the contract unit price (as adjusted) for the appropriate type of asphalt concrete.

Table I. Acceptance Schedule

Characteristics	Pay Factor	Number of Tests 1	2	3	4
		Average of Deviations from Target (Without Regard to Signs)			
Asphalt Cement Content	1.00	0.00 - 0.70	0.00 - 0.50	0.00 - 0.40	0.00 - 0.30
(Extraction or Nuclear)	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 - 0.40
	0.80	0.91 - 1.00	0.65 - 0.71	0.53 - 0.58	0.46 - 0.50
Target: JMF (%)	Unacceptable (2)	Over 1.00	Over 0.71	Over 0.58	Over 0.50
		Average of Deviations from Target (Without Regard to Signs)			
Asphalt Cement Content	1.00	0.00 - 0.30	0.00 - 0.21	0.00 - 0.17	0.00 - 0.10
(Digital Print-out)	0.95	0.31 - 0.35	0.22 - 0.25	0.18 - 0.20	0.16 - 0.10
	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 (%)	Unacceptable (2)	Over 0.46	Over 0.33	Over 0.27	Over 0.23
		Average of Deviations from Target (Without Regard to Signs)			
Gradation: No.4 & Larger	1.00	0.00 - 8.00	0.00 - 5.66	0.00 - 4.62	0.00 - 4.00
Sieve (3)	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 (%)	Unacceptable (2)	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	1.00	0.00 - 6.50	0.00 - 4.60	0.00 - 3.75	0.00 - 3.25
100 Sieve (3)	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 (%)	Unacceptable (2)	Over 15.50	Over 10.96	Over 8.95	Over 7.75
		Average of Deviations from Target (Without Regard to Signs)			
Gradation: No.200	1.00	0.00 - 3.00	0.00 - 2.12	0.00 - 1.73	0.00 - 1.50
Sieve (3)	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 (%)	Unacceptable (2)	Over 6.60	Over 4.67	Over 3.81	Over 3.30

Table I (continued). Acceptance Schedule

Characteristics	Pay Factor	Number of Tests			
		1	2	3	4
		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 (2)	Over 3.00	Over 2.12	Over 1.73	Over 1.50
		Average of Deviations from Target (Considering Signs)			
Roadway Density (4) (Core or Nuclear)	1.00	(+)4.00 - (-)2.00	(+)2.83 - (-)1.41	(+)2.31 - (-)1.15	(+)2.00 - (-)1.00
	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 Theoretical Density	Unacceptable (2)	Over (-)8.00 Over (+)4.00	Over (-)5.66 Over (+)2.83	Over (-)4.62 Over (+)2.31	Over (-)4.00 Over (+)2.00

FOOTNOTES:

1. 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.

2. Unless otherwise directed by the Engineer, products testing in this range are unacceptable and shall be removed and replaced at no additional 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.

3. Only the smallest of the gradation pay factors shall be considered in determining adjustment in pat for each lot.

4. 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 I. Acceptance Schedule

Characteristics	Pay Factor	Number of Tests 1	2	3	4
		Average of Deviations from Target (Without Regard to Signs)			
Asphalt Cement Content	1.00	0.00 - 0.70	0.00 - 0.50	0.00 - 0.40	0.00 - 0.30
(Extraction or Nuclear)	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 - 0.40
	0.80	0.91 - 1.00	0.65 - 0.71	0.53 - 0.58	0.46 - 0.50
Target: JMF (%)	Unacceptable [2]	Over 1.00	Over 0.71	Over 0.58	Over 0.50
		Average of Deviations from Target (Without Regard to Signs)			
Asphalt Cement Content	1.00	0.00 - 0.30	0.00 - 0.21	0.00 - 0.17	0.00 - 0.10
(Digital Print-out)	0.95	0.31 - 0.35	0.22 - 0.25	0.18 - 0.20	0.16 - 0.10
	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 (%)	Unacceptable [2]	Over 0.46	Over 0.33	Over 0.27	Over 0.23
		Average of Deviations from Target (Without Regard to Signs)			
Gradation: No.4 & Larger	1.00	0.00 - 8.00	0.00 - 5.66	0.00 - 4.62	0.00 - 4.00
Sieve [3]	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 (%)	Unacceptable [2]	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	1.00	0.00 - 6.50	0.00 - 4.60	0.00 - 3.75	0.00 - 3.25
100 Sieve [3]	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 (%)	Unacceptable [2]	Over 15.50	Over 10.96	Over 8.95	Over 7.75

Table I (continued). Acceptance Schedule

Characteristics	Pay Factor	Number of Tests: 1	2	3	4
		Average of Deviations from Target (Without Regard to Signs)			
Gradation: No.200 Sieve (3)	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 (%)	Unacceptable (2)	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 (2)	Over 3.00	Over 2.12	Over 1.73	Over 1.50

Table I (continued). Acceptance Schedule

Characteristics	Pay Factor	Number of Tests 1	2	3	4
		Average of Deviations from Target (Considering Signs)			
Roadway Density [4] (Core or Nuclear)	1.00	(+)4.00 - (–)2.00	(+)2.83 -(–)1.41	(+)2.31 - (–)1.15	(+)2.00 - (–)1.00
	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: 94.00% of Maximum Theoretical Density	0.50	(–)7.41 - (–)8.00	(–)5.24 - (–)5.66	(–)4.28 - (–)4.62	(–)3.71 - (–)4.00
	Unacceptable [2]	Over (–)8.00 Over (+)4.00	Over (–)5.66 Over (+)2.83	Over (–)4.62 Over (+)2.31	Over (–)4.00 Over (+)2.00

<u>FOOTNOTES</u>:

1. 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.

2. Unless otherwise directed by the Engineer, products testing in this range are unacceptable and shall be removed and replaced at no additional 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.

3. Only the smallest of the gradation pay factors shall be considered in determining adjustment in pat for each lot.

4. 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.

APPENDIX L

PROPOSED QA SPECIFICATIONS FOR ASPHALT CONCRETE PAVEMENT

OKLAHOMA DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISIONS
FOR
QUALITY CONTROL AND ACCEPTANCE PROCEDURES
SECTION 411
PLANT MIX ASPHALT CONCRETE PAVEMENT

These Special provisions revise, amend, and where in conflict, supersede applicable Sections of the Standard Specifications for Highway Construction, Edition of 1988, and the Supplement thereto, Edition of 1991. These Special Provisions apply to all types of Asphalt Concrete Pavement.

The Contractor is responsible for the quality of the materials and construction, whereas the Department will be responsible for determining the acceptability of such materials and construction.

It is the intent of these Special Provisions that materials and construction of acceptable quality shall receive an average pay factor of 100 percent; that materials and construction of truly superior quality shall be awarded a bonus payment; and that materials and construction of deficient quality will receive a reduced payment or be removed and replaced.

411.01. DESCRIPTION. (Add the following:)

Contractor's Quality Control and Acceptance Procedures will apply to this work in accordance with the applicable requirements of Special Provisions 105-1QA; 106-1QA and as herein specified.

411.04. CONSTRUCTION METHODS. (Amend to include the following:)

1. Contractor's Quality Control Testing and Inspection. The Contractor shall provide quality control personnel and testing equipment as necessary to assure the production of quality products as specified. Such personnel shall include one or more Quality Control Technicians who either individually or collectively are fully qualified in the production, placement and testing of plant mix asphalt concrete. The Contractor shall provide a fully equipped laboratory at the plant. To assure precision and accuracy of testing, the laboratory equipment shall be checked every six months and calibrated to the required standards by qualified individuals at the Contractor's expense. Personnel shall be proficient in conducting the required tests.

The Contractor shall be responsible for the formulation of all mix designs. This may be accomplished by Contractor personnel, subcontractor such as independent laboratories, or upon written request, by the Engineer. Mix designs not formulated by the Engineer shall be subject to approval by the Engineer.

The Contractor shall perform or have performed all field sampling and testing necessary to ensure that materials and products are within the specified acceptable range. Certifications by the manufacturers may be used in lieu of field tests when such tests in the field are impracticable. Asphalt cement and additives are examples of materials in this category.

1.1. Contractor's Process Control. The Contractor shall be responsible for the process control of all materials during handling, blending, mixing and placing operations to produce an acceptable asphalt concrete pavement

At no time will the Engineer issue instructions to the Contractor or producer as to setting of dials, gauges, scales and meters. However, the Engineer may advise the Contractor against the continuance of any operations or sequence of operations which will result in non-compliance with Specification requirements.

1.2. Contractor's Testing. As a minimum, the Contractor's sampling and testing shall comply with the following schedule:

Property	Sampling and Testing Frequency
Gradation	1 per 1000 tons
Asphalt Content	1 per 1000 tons
Air Voids	1 per 1000 tons
Roadway Density	1 per 1000 tons
Thickness	As needed to control operations
Smoothness	As needed to control operations

Additional sampling and testing to ensure compliance with Standard Specifications and other Special Provision requirements shall be in accordance with the Contractor's Quality Control Plan.

1.3. Contractor's Quality Control Plan. Prior to the initiation of work, the Contractor shall prepare a Quality Control Plan to ensure that acceptable quality can and will be obtained. The Plan, which is to be submitted to the Engineer at the preconstruction conference, shall cover all of the items discussed in Sections 411 and 708 of the Standard Specifications. However, the Plan must be tailored to meet specific needs of the project. Once accepted by the Engineer, the Plan becomes a part of the Contract and shall be enforced accordingly. Subsequent changes to the Plan may be required by the Engineer in order to adjust to changes in the process or to correct problems in meeting Specification requirements.

1.4. Control Charts. Control charts covering as a minimum the characteristics of gradation, asphalt content, air voids, roadway density, and thickness shall be maintained by the Contractor and displayed at the plant or job site. The charts shall identify the project number, the contract item number, the characteristics, the date, the lot and sublot numbers, the applicable upper and/or lower specification limits, the Contractor's test results and any other data needed to facilitate control of the process and identify problems before they become serious. Copies of the Contractor's quality control tests shall be provided to the Engineer at time intervals acceptable to the Engineer.

(m) <u>Acceptance</u>. While the Contractor shall be fully and exclusively responsible for producing an acceptable product, acceptance responsibility rests with the Engineer. The entire lot of asphalt, as defined in Subsection (m)-1.1, will be accepted or rejected and paid for on the basis of acceptance test results. The Engineer may choose to use the Contractor's tests for acceptance after the Contractor's test results have demonstrated to be consistent with tests taken by the Department and that they adequately represent the material being evaluated.

1. **Basis for Acceptance and Payment.** The following characteristics will be considered in evaluating materials and construction for acceptance and payment. However, all of the requirements of the Standard Specifications on materials and workmanship, except those superseded by Special Provisions in the Contract, shall remain in effect.

   - Asphalt Cement Content
   - Gradation
   - Air Voids
   - Roadway Density
   - Pavement Surface Smoothness (as provided in Special Provision 430-11QA)

1.1. Lot and Sublot Definition

Except for pavement smoothness, acceptance and pay adjustments will be made on a lot-by-lot basis. Each lot of asphalt concrete will be sampled at random and tested for all the quality characteristics described in (m)-1.1, in accordance with the following requirements.

The standard lot size shall consist of five equal sublots of 1000 tons each. Each sublot will be sampled at random to obtain one or more test specimens as follows:

a) Gradation and asphalt cement content determination: one specimen and one test for each characteristic per sublot.

b) Air voids determination: three specimens per sublot averaged and considered as one individual test.

c) Roadway density determination: three cores and/or three nuclear gauge test determinations per sublot with additional sampling and testing made as necessary. The average of the density measurements is considered as one individual test.

In the event that operational conditions cause work to be interrupted before the standard lot size has been achieved, the lot size my be redefined by the Engineer. However, the number of test determinations required to evaluate each lot will be at least four. Each partial lot will be divided into at least four equal sublots, and each sublot will be sampled at random to obtain the required number of test specimens.

Quantities of mixture less than 250 tons may be accepted by the Engineer upon visual inspection by which the Engineer has reason to believe that the materials and construction are of acceptable quality. At the Engineer’s option, this quantity may be treated as a separate lot, combined with the previous lot or combined with the following lot, as the case may warrant. On a multiple project contract, the lots of the asphalt will carry over from project to project.

1.2. Smoothness Acceptance and Pay Adjustments

For smoothness determination and pay adjustment purposes, the pavement surface will be tested on an extent-to-extent basis in accordance with Special Provisions 430-11QA. Acceptance and pay adjustment determinations made under Special Provisions 430-11QA will be completely independent of those made under this Provision.

1.3. Criteria for Lot Acceptance and Payment

Except for surface smoothness, conformance with the specifications will be judged on the basis of the following two criteria:

a) The estimated lot percent defective with respect to gradation, asphalt cement content, air voids, and roadway density. The lot percent defective with respect to a particular quality characteristic is the amount of materials and construction which falls outside the specified limit(s) listed in following table:

Quality Characteristic	Lower Limit (L)	Upper Limit (U)
Gradation:		
Sieves # 4 and larger	Target – 6.0%	Target + 6.0%
Sieves # 10 through # 80	Target – 4.5%	Target + 4.5%
Sieve #200	Target – 2.0%	Target + 2.0%
Asphalt Cement Content	Target – 0.5%	Target + 0.5%
Air Voids (LMS)	Target – 1.5%	Target + 1.5%
Roadway Density	92%	98%

b) Any load of asphalt mixture that is excessively segregated or having aggregate improperly coated will be rejected for use in the work. Excessively high or low temperature will also be cause for rejection. Furthermore, sections of completed pavement which from visual observation or known deficiencies appear to be seriously inadequate will be extensively tested. The results of such tests will not be used for pay adjustment purposes, but will be used to determine whether the section is totally unacceptable and must be removed. In the event that a section is determined to be unacceptable, its removal and replacement shall be at no additional cost to the Department.

1.4. Acceptable Quality Level

A lot shall be considered of acceptable quality with respect to a particular characteristic if the percent defective, as defined in Subsection (m)-1.3(a) is no more than 10 percent. The Contractor shall perform the necessary quality control sampling and testing to ensure that acceptable quality level requirements are met.

1.5. Determination of Lot Percent Defective

The lot percent defective with respect to each of the characteristics of gradation, asphalt content, air voids, and roadway density, will be determined as follows:

1. Compute the sample mean ($\overline{X}$) and the standard deviation (S) of the N = 5 test results (X_i):

$$\overline{X} = \frac{\sum X_i}{N} \qquad S = \sqrt{\frac{\sum (X_i - \overline{X})^2}{N-1}}$$

2. Compute the upper quality index (Q_U) and/or the lower quality index (Q_L) corresponding to the upper and/or lower limits listed in Subsection (m)-1.3(a):

$$Q_U = \frac{U - \overline{X}}{S} \qquad Q_L = \frac{\overline{X} - L}{S}$$

3. Using Table-1 (for sample size N = 5), determine the percentage of materials and construction falling outside the specification limits PD_U and/or PD_L associated with Q_U and/or Q_L, respectively. Add these two values to obtain the lot percent defective:

$$PD = PD_U + PD_L$$

1.6. Pay Factors for Lot Quality Characteristics.

Except for pavement smoothness, the pay factor (PF) for each quality characteristic will be determined as follows:

1. If *PD* is less than 50 percent, proceed to Step 4.
2. If *PD* is greater than or equal to 50 percent but less than 60 percent, the Engineer may elect to reevaluate the lot with additional test specimens as described in Step 2b.
   a) If no additional test specimens are taken, proceed to Step 4.
   b) If the Engineer elects to reevaluate the lot, five additional test specimens will be taken at new random locations. Using the five new test results, estimate the total percent defective *PD* as explained in Subsection (m)-1.6. The final *PD* value for the lot will be the average the *PD* values determined using the two sets of test specimens.
3. If *PD* is greater than or equal to 60 percent, the Engineer may require the removal and replacement of the defective lot at the Contractor's expense. If this option is not exercised, the Contractor may elect to replace the lot or leave it in place subject to a pay factor of PF = 0%.
4. Compute the percent payment for the lot using the equation:

$$PF = 102 - 0.04(PD) - 0.016(PD)^2$$

1.7. Pay Adjustment for Lots

Once a lot has been defined, its identity will be maintained throughout the mixing and placement process. When the lot is completed, the individual pay factors determined in Subsection (m)-1.6 for gradation, asphalt content, air voids, and roadway density will be used to calculate a composite pay factor (*CPF*) and a pay adjustment (*PA*) for the subject lot as follows:

$$CPF = \frac{3(PF_A + PF_V + PF_D) + PF_G}{10}$$

where:

PF_A = Pay factor for asphalt content,
PF_V = Pay factor for air voids,
PF_D = Pay factor for roadway density, and
PF_G = Pay factor for gradation -- the smallest of the individual pay factors for the sieves listed in Subsection (m)-1.3(a)

The pay adjustment for the completed lot will be determined in accordance with the following formula:

$$PA_{Lot} = (CPF - 1)(CUP)(Q_{Lot})$$

where:

PA_{Lot} = Pay adjustment for the lot,
CPF = Composite pay factor,
CUP = Contract unit price ($/Ton), and
Q_{Lot} = Quantity of concrete in the lot (Tons)

1.8. Pay Adjustments Not Covered in Special Provisions 411-1QA

Adjustments in pay, for deviations from specified standards of characteristics other than those described in these Special Provisions (if any) will be made in accordance with General Provision 105.03.

1.9. Total Pay Adjustment for Entire Project

The total adjustment in pay for the entire project is the sum of: (1) the pay adjustments for individual lots per Subsection (m)-1.7; plus (2) the pay adjustments for smoothness per Special Provision 430-11QA; plus (3) other pay adjustments, if appropriate, per Subsection (m)-1.10.

2. Conflicts Between Engineer's and Contractor's Test Results

At the beginning and throughout the contract, the Engineer and the Contractor shall compare each other's test procedures and results. The comparison should be based on the methods described in Appendix-F of the "AASHTO Implementation Manual for Quality Assurance, 1995".

Should the Engineer determine from the comparison or for any other reason that any of the acceptance test results are incorrect, such results will be discarded. In this case, additional acceptance sampling and testing will be performed to supplement the remaining, valid test results.

If the Engineer and the Contractor are unable to resolve their differences, the Contractor may request referee testing by an independent testing laboratory accredited by AASHTO. Such laboratory must be acceptable to both the Department and the Contractor.

The request for referee testing shall be submitted in writing by the Contractor to the Engineer within 15 days after completion of the lot. Referee testing will be independent from any previous testing by either the Engineer or the Contractor and the results of such referee testing shall be considered final. Should the referee testing result in higher pay factors for the lot(s) in question, the cost of referee testing will be paid by the Department. Otherwise, the entire cost of referee testing shall be borne by the Contractor.

3. Extreme Values (Outliers)

Test results apparently inconsistent with the results of the majority of tests will also be closely examined by the Engineer in order to determine their validity. The examination will cover the procedures used in sampling and testing and, if necessary, a mathematical analysis will be performed in accordance with ASTM E-178-80 using the upper 2.5% significance level. Test results thus determined by the Engineer to be non-representative of the material being evaluated will be discarded. In this case, additional acceptance sampling and testing will be performed to supplement the remaining, valid test results.

(n) **Plant Startup Requirements** - Prior to beginning production of asphalt for the mainline, the Contractor shall provide a quality control system in accordance with paragraph “a” of Special Provision 106-1QA. The system shall include the fully equipped laboratory and the full complement of quality control personnel that are to perform the quality control functions for the remainder of the project.

Plant startup production shall be limited to that necessary to calibrate the plant and the testing equipment and procedures using the mix design approved for mainline construction. The asphalt concrete thus produced shall be sampled and tested by both the Contractor and Engineer for VMA, Hveem Stability and all of the characteristics in Table I except roadway density. The Contractor’s test results shall then be reconciled with those from the Engineer.

No asphalt concrete from the startup operation shall be placed on the mainline or the control strip. Instead, adjustments shall continue to be made until all of the requirements are met. Asphalt concrete from the plant startup operation may be utilized and paid for in the construction temporary facilities or if no temporary facilities are available they shall become the property of the Contractor and will not be paid for. Costs associated with startup operations will not be measured separately for payment but will be included in the payment for Contractor’s Quality Control.

(o) **Control Strip Requirements** - After fulfilling the plant startup requirements, one or more control strips shall be constructed on the shoulder or detour for the purpose of verifying the required production mix characteristics and establishing rolling patterns to obtain target requirements. The initial placement of asphalt concrete shall be limited to approximately 500 tons. This material shall then be sampled and tested by the Contractor and the Engineer for VMA, Hveem Stability and all of the characteristics in Subsection (m)1.1. No additional asphalt concrete shall be placed until all the results are evaluated and necessary adjustments in production and placement procedures are made. No pay adjustments will be made for defective product (i.e., having percent defective more than 10 percent) produced on the approximately 500 ton placement.

After necessary adjustments are made, the above process shall be repeated for the next approximately 500 tons of asphalt concrete placed. Pay adjustments for deviations from target on this second placement will be made at the rate of one half those specified. If required, additional control strips shall be made on the shoulder until an acceptable product (i.e., percent defective of no more than 10 percent) is produced. Pay adjustments will be applied to all asphalt mixture in excess of the first approximately 1000 tons as described in Subsection 411.04(m)1.7. Control strips will not be measured separately for payment. Work and materials associated with control strips will be paid for at the contract unit price (as adjusted) for the appropriate type of asphalt concrete.

Table 1. Estimation of Lot Percent Defective

Variability-Unknown Procedure **Standard Deviation Method**

Sample Size N = 4

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.67	49.33	49.00	48.67	48.33	48.00	47.67	47.33	47.80
0.1	46.67	46.33	46.00	45.67	45.33	45.00	44.67	44.33	44.00	43.67
0.2	43.33	43.00	42.67	42.33	42.00	41.67	41.33	41.00	40.67	40.33
0.3	40.00	39.67	39.33	39.00	38.67	38.33	38.00	37.67	37.33	37.00
0.4	36.67	36.33	36.00	35.67	35.33	35.00	34.67	34.33	34.00	33.67
0.5	33.33	33.00	32.67	32.33	32.00	31.67	31.33	31.00	30.67	30.33
0.6	30.00	29.67	29.33	29.00	28.67	28.33	28.00	27.67	27.33	27.00
0.7	26.67	26.33	26.00	25.67	25.33	25.00	24.67	24.33	24.00	23.67
0.8	23.33	23.00	22.67	22.33	22.00	21.67	21.33	21.00	20.67	20.33
0.9	20.00	19.67	19.33	19.00	18.67	18.33	18.00	17.67	17.33	17.00
1.0	16.67	16.33	16.00	15.67	15.33	15.00	14.67	14.33	14.00	13.67
1.1	13.33	13.00	12.67	12.33	12.00	11.67	11.33	11.00	10.67	10.33
1.2	10.00	9.67	9.33	9.00	8.67	8.33	8.00	7.67	7.33	7.00
1.3	6.67	6.33	6.00	5.67	5.33	5.00	4.67	4.33	4.00	3.67
1.4	3.33	3.00	2.67	2.33	2.00	1.67	1.33	1.00	0.67	0.33
1.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Values in the body of this table are estimates of the lot percent defective corresponding to specific values of Q, the quality index. For values of Q greater than or equal to zero, the estimate of percent defective is read directly from the table. For negative values of Q, the values read from the table must be subtracted from 100.

Table 1 (continued). Estimation of Lot Percent Defective

Variability-Unknown Procedure **Standard Deviation Method**

Sample Size N = 5

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.64	49.29	48.93	48.58	48.22	47.87	47.51	47.15	46.80
0.1	46.44	46.09	45.73	45.38	45.02	44.67	44.31	43.96	43.61	43.25
0.2	42.90	42.54	42.19	41.84	41.48	41.13	40.78	40.43	40.08	39.72
0.3	39.37	39.02	38.67	38.32	37.97	37.62	37.28	36.93	36.58	36.23
0.4	35.88	35.54	35.19	34.85	34.50	34.16	33.81	33.47	33.13	32.78
0.5	32.44	32.10	31.76	31.42	31.08	30.74	30.40	30.06	29.73	29.39
0.6	29.05	28.72	28.39	28.05	27.72	27.39	27.06	26.73	26.40	26.07
0.7	25.74	25.41	25.09	24.76	24.44	24.11	23.79	23.47	23.15	22.83
0.8	22.51	22.19	21.87	21.56	21.24	20.93	20.62	20.31	20.00	19.69
0.9	19.38	19.07	18.77	18.46	18.16	17.86	17.55	17.26	16.96	16.66
1.0	16.36	16.07	15.78	15.48	15.19	14.91	14.62	14.33	14.05	13.76
1.1	13.48	13.20	12.93	12.65	12.37	12.10	11.83	11.56	11.29	11.02
1.2	10.76	10.50	10.23	9.97	9.72	9.46	9.21	8.96	8.71	8.46
1.3	8.21	7.97	7.73	7.49	7.25	7.02	6.79	6.56	6.33	6.10
1.4	5.88	5.66	5.44	5.23	5.02	4.81	4.60	4.39	4.19	3.99
1.5	3.80	3.61	3.42	3.23	3.05	2.87	2.69	2.52	2.35	2.19
1.6	2.03	1.87	1.72	1.57	1.42	1.28	1.15	1.02	0.89	0.77
1.7	0.66	0.55	0.45	0.36	0.27	0.19	0.12	0.06	0.02	0.00

Values in the body of this table are estimates of the lot percent defective corresponding to specific values of Q, the quality index. For values of Q greater than or equal to zero, the estimate of percent defective is read directly from the table. For negative values of Q, the values read from the table must be subtracted from 100.

Table 1 (continued). Estimation of Lot Percent Defective

Variability-Unknown Procedure **Standard Deviation Method**

Sample Size N = 6

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.63	49.27	48.90	48.53	48.16	47.80	47.43	47.06	46.70
0.1	46.33	45.96	45.60	45.23	44.86	44.50	44.13	43.77	43.40	43.04
0.2	42.68	42.31	41.95	41.59	41.22	40.86	40.50	40.14	39.78	39.42
0.3	39.06	38.70	38.34	37.98	37.62	37.27	36.91	36.55	36.20	35.84
0.4	35.49	35.14	34.79	34.43	34.08	33.73	33.38	33.04	32.69	32.34
0.5	32.00	31.65	31.31	30.96	30.62	30.28	29.94	29.60	29.26	28.93
0.6	28.59	28.25	27.92	27.59	27.26	26.92	26.60	26.27	25.94	25.61
0.7	25.29	24.96	24.64	24.32	24.00	23.68	23.37	23.05	22.74	22.42
0.8	22.11	21.80	21.49	21.18	20.88	20.57	20.27	19.97	19.67	19.37
0.9	19.07	18.78	18.49	18.19	17.90	17.61	17.33	17.04	16.76	16.48
1.0	16.20	15.92	15.64	15.37	15.09	14.82	14.55	14.29	14.02	13.76
1.1	13.50	13.24	12.98	12.72	12.47	12.22	11.97	11.72	11.47	11.23
1.2	10.99	10.75	10.51	10.28	10.04	9.81	9.58	9.36	9.13	8.91
1.3	8.69	8.48	8.26	8.05	7.84	7.63	7.42	7.22	7.02	6.82
1.4	6.63	6.43	6.24	6.05	5.87	5.68	5.50	5.33	5.15	4.98
1.5	4.81	4.64	4.47	4.31	4.15	4.00	3.84	3.69	3.54	3.40
1.6	3.25	3.11	2.97	2.84	2.71	2.58	2.45	2.33	2.21	2.09
1.7	1.98	1.87	1.76	1.66	1.55	1.45	1.36	1.27	1.18	1.09
1.8	1.01	0.93	0.85	0.78	0.71	0.64	0.57	0.51	0.46	0.40
1.9	0.35	0.30	0.26	0.22	0.18	0.15	0.12	0.09	0.07	0.05
2.0	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Values in the body of this table are estimates of the lot percent defective corresponding to specific values of Q, the quality index. For values of Q greater than or equal to zero, the estimate of percent defective is read directly from the table. For negative values of Q, the values read from the table must be subtracted from 100.

Table 1 (continued). Estimation of Lot Percent Defective

Variability-Unknown Procedure **Standard Deviation Method**

Sample Size N = 7

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.63	49.25	48.88	48.50	48.13	47.76	47.38	47.01	46.63
0.1	46.26	45.89	45.51	45.14	44.77	44.40	44.03	43.65	43.28	42.91
0.2	42.54	42.17	41.80	41.44	41.07	40.70	40.33	39.97	39.60	39.23
0.3	38.87	38.50	38.14	37.78	37.42	37.06	36.69	36.33	35.98	35.62
0.4	35.26	34.90	34.55	34.19	33.84	33.49	33.13	32.78	32.43	32.08
0.5	31.74	31.39	31.04	30.70	30.36	30.01	29.67	29.33	28.99	28.66
0.6	28.32	27.98	27.65	27.32	26.99	26.66	26.33	26.00	25.68	25.35
0.7	25.03	24.71	24.39	24.07	23.75	23.44	23.12	22.81	22.50	22.19
0.8	21.88	21.58	21.27	20.97	20.67	20.37	20.07	19.78	19.48	19.19
0.9	18.90	18.61	18.33	18.04	17.76	17.48	17.20	16.92	16.65	16.37
1.0	16.10	15.83	15.56	15.30	15.03	14.77	14.51	14.26	14.00	13.75
1.1	13.49	13.25	13.00	12.75	12.51	12.27	12.03	11.79	11.56	11.33
1.2	11.10	10.87	10.65	10.42	10.20	9.98	9.77	9.55	9.34	9.13
1.3	8.93	8.72	8.52	8.32	8.12	7.92	7.73	7.54	7.35	7.17
1.4	6.98	6.80	6.62	6.45	6.27	6.10	5.93	5.77	5.60	5.44
1.5	5.28	5.13	4.97	4.82	4.67	4.52	4.38	4.24	4.10	3.96
1.6	3.83	3.69	3.57	3.44	3.31	3.19	3.07	2.95	2.84	2.73
1.7	2.62	2.51	2.41	2.30	2.20	2.11	2.01	1.92	1.83	1.74
1.8	1.65	1.57	1.49	1.41	1.34	1.26	1.19	1.12	1.06	0.99
1.9	0.93	0.87	0.81	0.76	0.70	0.65	0.60	0.56	0.51	0.47
2.0	0.43	0.39	0.36	0.32	0.29	0.26	0.23	0.21	0.18	0.16
2.1	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.03	0.02
2.2	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Values in the body of this table are estimates of the lot percent defective corresponding to specific values of Q, the quality index. For values of Q greater than or equal to zero, the estimate of percent defective is read directly from the table. For negative values of Q, the values read from the table must be subtracted from 100.

Table 1 (continued). Estimation of Lot Percent Defective

Variability-Unknown Procedure **Standard Deviation Method**

Sample Size N = 8

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.62	49.24	48.86	48.49	48.11	47.73	47.35	46.97	46.59
0.1	46.22	45.84	45.46	45.08	44.71	44.33	43.96	43.58	43.21	42.83
0.2	42.46	42.08	41.71	41.34	40.97	40.59	40.22	39.85	39.48	39.11
0.3	38.75	38.38	38.01	37.65	37.28	36.92	36.55	36.19	35.83	35.47
0.4	35.11	34.75	34.39	34.04	33.68	33.33	32.97	32.62	32.27	31.92
0.5	31.57	31.22	30.87	30.53	30.18	29.84	29.50	29.16	28.82	28.48
0.6	28.15	27.81	27.48	27.15	26.82	26.49	26.16	25.83	25.51	25.19
0.7	24.86	24.54	24.23	23.91	23.59	23.28	22.97	22.66	22.35	22.04
0.8	21.74	21.44	21.14	20.84	20.54	20.24	19.95	19.66	19.37	19.08
0.9	18.79	18.51	18.23	17.95	17.67	17.39	17.12	16.85	16.57	16.31
1.0	16.04	15.78	15.51	15.25	15.00	14.74	14.49	14.24	13.99	13.74
1.1	13.49	13.25	13.01	12.77	12.54	12.30	12.07	11.84	11.61	11.39
1.2	11.17	10.94	10.73	10.51	10.30	10.09	9.88	9.67	9.47	9.26
1.3	9.06	8.87	8.67	8.48	8.29	8.10	7.91	7.73	7.55	7.37
1.4	7.19	7.02	6.85	6.68	6.51	6.35	6.19	6.03	5.87	5.71
1.5	5.56	5.41	5.26	5.12	4.97	4.83	4.69	4.56	4.42	4.29
1.6	4.16	4.03	3.91	3.79	3.67	3.55	3.43	3.32	3.21	3.10
1.7	2.99	2.89	2.79	2.69	2.59	2.49	2.40	2.31	2.22	2.13
1.8	2.04	1.96	1.88	1.80	1.73	1.65	1.58	1.51	1.44	1.37
1.9	1.31	1.24	1.18	1.12	1.07	1.01	0.96	0.91	0.86	0.81
2.0	0.76	0.72	0.67	0.63	0.59	0.55	0.52	0.48	0.45	0.42
2.1	0.39	0.36	0.33	0.30	0.28	0.26	0.23	0.21	0.19	0.17
2.2	0.16	0.14	0.13	0.11	0.10	0.09	0.08	0.07	0.06	0.05
2.3	0.04	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.00

Values in the body of this table are estimates of the lot percent defective corresponding to specific values of Q, the quality index. For values of Q greater than or equal to zero, the estimate of percent defective is read directly from the table. For negative values of Q, the values read from the table must be subtracted from 100.

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