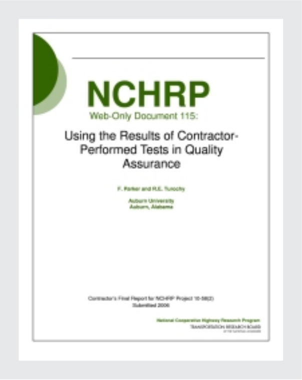
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Using the Results of Contractor-Performed Tests in Quality Assurance
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Auburn, Alabama

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CHAPTER 1: INTRODUCTION

PROBLEM STATEMENT AND RESEARCH OBJECTIVES

The results of extensive sampling and testing at the AASHO Road Test in the late 1950's and early 1960's revealed unexpectedly large variabilities in measured properties of highway construction materials and products. This has led to considerable changes in the way highway construction projects are managed.

The overall construction quality assurance process that has evolved includes three basic elements depicted in Figure 1. Process (quality) control, acceptance and independent assurance procedures are integral parts of the quality assurance process. In the traditional separation of responsibilities, contractors are responsible for their quality control and state DOTs are responsible for acceptance and independent assurance. However, with the enactment of the federal regulation 23 CFR 637B in 1995 (2), the roles of state DOTs and contractors have become less clear and distinct. Under certain conditions 23 CFR 637B permits the use of contractor tests for acceptance which results in a mixing and mingling of traditional responsibilities.

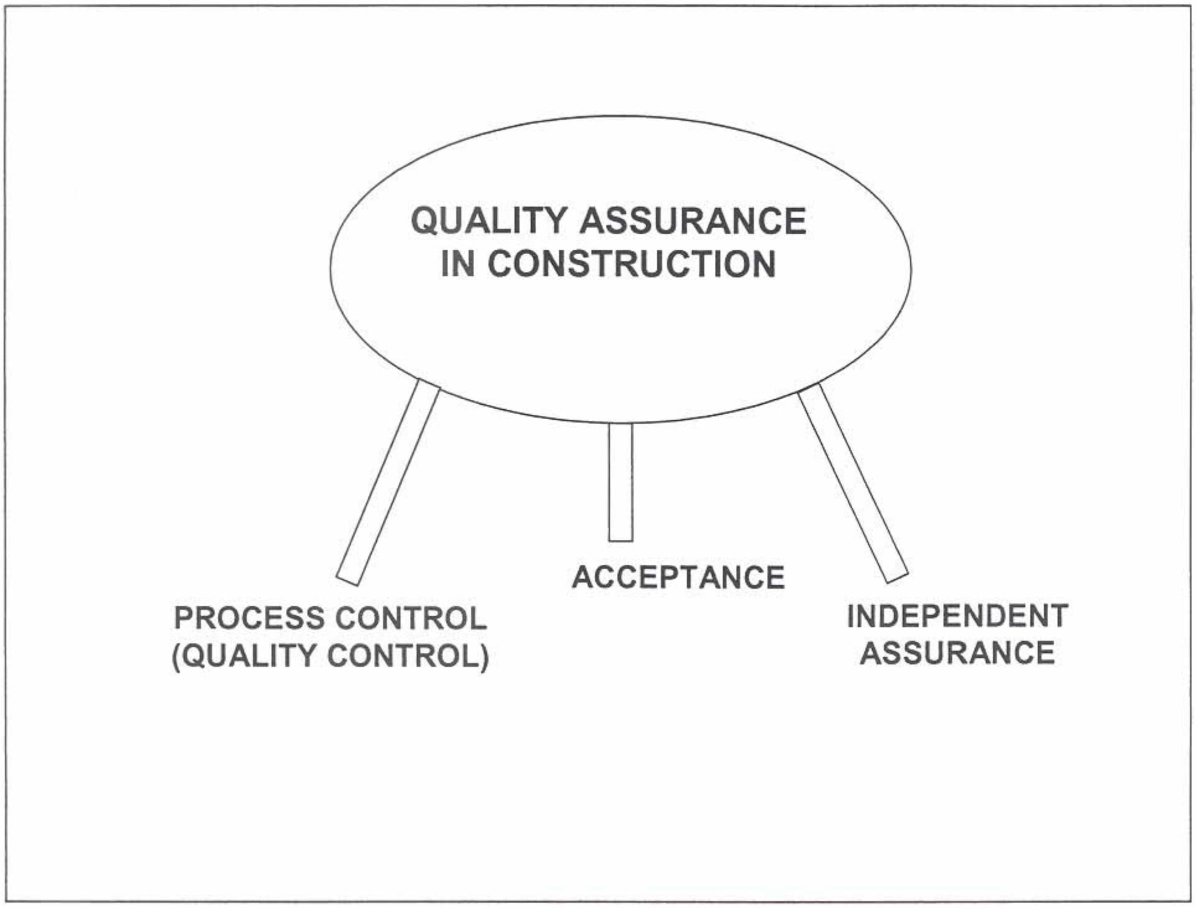


Figure 1. Elements of Quality Assurance (Ref. 1)

There seems to be general agreement, or at least no serious controversy, as to the value of contractor quality (process) control. Issues arise when contractor-performed tests are used in the acceptance process. This shift in responsibilities and associated risks has caused concern within some state DOTs. A particular concern is the viability of contractor-performed tests when used in the acceptance process. The results of surveys reported by Hancher, et al (3) indicated this was the primary concern of state DOTs. This concern is consistent with results of a survey reported by Burati et al (4) that ranked “procedures for verifying or validating contractor’s and agency’s test results” as the topic that most needs additional study and analysis for developing effective and efficient quality assurance specifications.

The objective of this research, as stated in the Research Project Statement, “…is to develop procedures to assist state DOTs in effectively using contractor-performed tests in the quality-assurance process.” To satisfy this objective requires a focus on the acceptance element of the overall quality-assurance process. More specifically, study and analysis of procedures for verifying contractor-performed tests are needed to address concerns as to the viability of these tests for determining acceptance of construction materials and products.

SCOPE

The study conducted to accomplish the research objectives included the following components:

- An investigation of the state-of-practice for using contractor-performed tests in the quality-assurance process for highway construction. This included a limited review of state specifications and practices.

- Collection and comparisons of state DOT and contractor-performed tests for hot mix asphalt concrete (HMAC), portland cement concrete (PCC), and granular base course. Data were selected to allow evaluation of as many as possible of the quality-assurance variables that might affect comparisons.

- Analysis of the effects of differences in state DOT and contractor-performed tests on acceptance outcomes.

- Surveys of technicians to investigate potential reasons for observed differences in state DOT and contractor-performed tests.

- Conclusions and recommendations for using contractor-performed tests in the quality-assurance process for highway construction materials and products.

RESEARCH APPROACH

The basic premise for this research was that contractor-performed tests can be effectively used in the quality-assurance process if they provide the same results as state DOT-performed tests. Consistency between contractor-performed and state DOT-performed tests is important even if the tests are used for different purposes, i.e., contractor-performed tests for process (quality) control and state DOT-performed tests for acceptance. However, consistency becomes critical when contractor-performed tests are also used for acceptance. Legal issues are then added to technical and material or product quality issues.

Considerable effort was devoted to comparing state DOT and contractor-performed tests to determine if statistically significant ($\alpha = 0.01$) differences in variability and proximity to target or limiting values exists. In addition to statistical comparisons, the effects of differences in test results on acceptance outcomes were investigated. Measures of variability and proximity to target or limiting values were used in acceptance procedures to compute the probability of certain acceptance outcomes. Comparisons of these probabilities of acceptance outcomes provide a more practical assessment of differences than the statistical comparisons. Data provided by one state permitted comparison of contract payment levels that were computed with state DOT and contractor-performed tests.

The effects of quality assurance procedure variables on the above described comparisons were evaluated. Among the variables considered were contractor to state DOT sampling and testing ratios, LOT/subLOT size, verification method, utilization of contractor-performed tests (control or control and acceptance) and acceptance methodology.

In addition, surveys of contractor, consultant and state DOT asphalt technicians were conducted to assess potential causes for differences in test results between these three types of organization.

CHAPTER 2: STATE OF PRACTICE

HISTORICAL PERSPECTIVE

The AASHO Road Test, conducted during the late 1950's and early 1960's, is often credited with providing the impetus for developing statistically based quality assurance procedures for managing highway construction. Results of extensive sampling and testing at the AASHO Road Test documented unexpectedly large variabilities of measured material and product properties.

With the recognition that properties of highway construction materials and products may vary considerably from target values, a movement toward today's quality assurance procedures began. Statistical methods are the tools that allow quantification and consideration of variability. But significant changes in construction management philosophy have also occurred. The most important of these changes has been increased contractor involvement. The following are critical benchmarks in the evolutionary process that provide a basis for discussion:

- Recognition of material and product variability
- Application of statistical methods
- Method specifications
- End-result and performance-related specifications
- Quality assurance procedures/specifications
- Contractor-performed tests for acceptance (Federal Regulation 23 CFR 637B")
- Warranties and design-build procurement

After the true variability in properties of highway construction materials and products was recognized; the logical next step was to look for statistical methods to quantify and consider this variability in specification requirements. This led to the use of numerous statistical techniques in today’s specifications. Procedures to insure random samples and consideration of differences between split and independent samples are common. Numbers of samples and tolerances are related to both contractor and state DOT risks. Hypothesis testing and other comparative techniques are routinely used to determine the significance of differences between test results and specification criteria or differences between sets of test results. Pay adjustment schedules recognize and account for, at least theoretically, variations in performance that result from variations in as-constructed properties.

State DOTs have the dominant role in method specifications with minimal involvement of contractors. Materials and construction methods are specified and state DOT personnel control the production, placement and inspection processes. It has been said that with this type specification, contractors provide financing, equipment and manpower which is managed by state DOTs. An often noted pitfall of such a system is that it may be difficult to determine cause when the end product is deficient.

End-result and performance-related specifications share a very important common characteristic, i.e., the assumption that desirable properties of the as-constructed product can be identified and measured. This, from a construction management perspective, means the structure of these types of specification will be similar.

Differences in the two types of specifications are related to the identification of desirable properties. Performance related specifications presume that fundamental engineering properties directly related to performance can be identified and measured at time of construction. In addition, it is presumed that a quantifiable relationship exists between measured properties and performance and that these relationships can be used in the acceptance process. NCHRP Synthesis 212 (8), completed in 1995, concluded that no operational examples of performance-related specifications were identified and this has changed little in the intervening years.

Requirements for properties used in end-result specifications are not so rigorous. Identified properties are certainly related to end-product quality, but direct relationships with performance may not exist. Ease and convenience of sampling and testing are often key considerations when selecting properties. Acceptance and pay adjustment computation are based on the degree of compliance with specification requirements.

Many current state DOT end-result specifications for HMAC use both mix and in-place mat properties. Gradation and asphalt content are common acceptance parameters that are good indicators of construction quality but may not be directly relatable to pavement performance. As-constructed smoothness of surface layers is thought to be directly related to pavement performance and is a common acceptance parameter. However, a direct link between acceptance and quantifiable relationships between smoothness and pavement performance is not apparent in current pay adjustment schedules. Air void content is a second property similar to smoothness. Segregation is a property with a direct link to performance that is beginning to appear in specifications, although measurement remains difficult.

Quality assurance is defined as “all those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service" (1). As related to the construction process, the various elements are illustrated in Figure 1. Quality assurance specifications are defined as follows:

> "A combination of end-result specifications and materials and methods specifications. The contactor is responsible for QC (process control), and the highway agency is responsible for the acceptance of the product." (1)

This clear delineation of responsibilities has become distorted as some state DOTs, responding to provisions in federal regulation 23 CFR 637B (2), use contractor-performed tests in the acceptance process. No matter exactly how contractor-performed tests are used in the currently structured quality assurance process, i.e., process control or process control and acceptance, increased contractor involvement is obvious.

A final benchmark for discussion is warranties and design-build. These procurement practices represent the next step in the evolution of contractor participation in the control and management of highway construction. With their implementation, the transformation from practically total state DOT control to practically total contractor control will be complete.

REVIEWS AND SURVEYS

Beginning in 1971 with HRB Special Report 118 (6), there have been periodic reviews of quality assurance procedures and specifications. NCHRP syntheses were published in 1976 (5), 1979 (7), 1995 (8) and 2005 (9). These are general reviews of the overall quality-assurance process and most often employed surveys as the main source of information.

Limited reviews of specifications and practices for HMAC are provided by Benson (10) and Schmitt, et al (11). Benson reviewed specifications from 16 states with particular attention to common practices that could be adopted with some confidence. Schmitt, et al (11) conducted surveys of 42 state DOTs and 61 contractors to develop recommendations for modifying or developing quality control and quality assurance specifications. Key issues identified were (a) whether to use contractor or agency data for acceptance, (b) use of quantity or time for lots, and (c) testing frequency.

As part of this study, a limited review of specifications was conducted. Specifications for the 37 state DOTs shown in Figure 2 were reviewed on-line. Questionnaires were sent to 25 state DOTs and the FHWA-Western Federal Lands Highway Division (FHWA-WFLHD). Responses were received from 12 state DOTs and the FHWA-WFLHD.

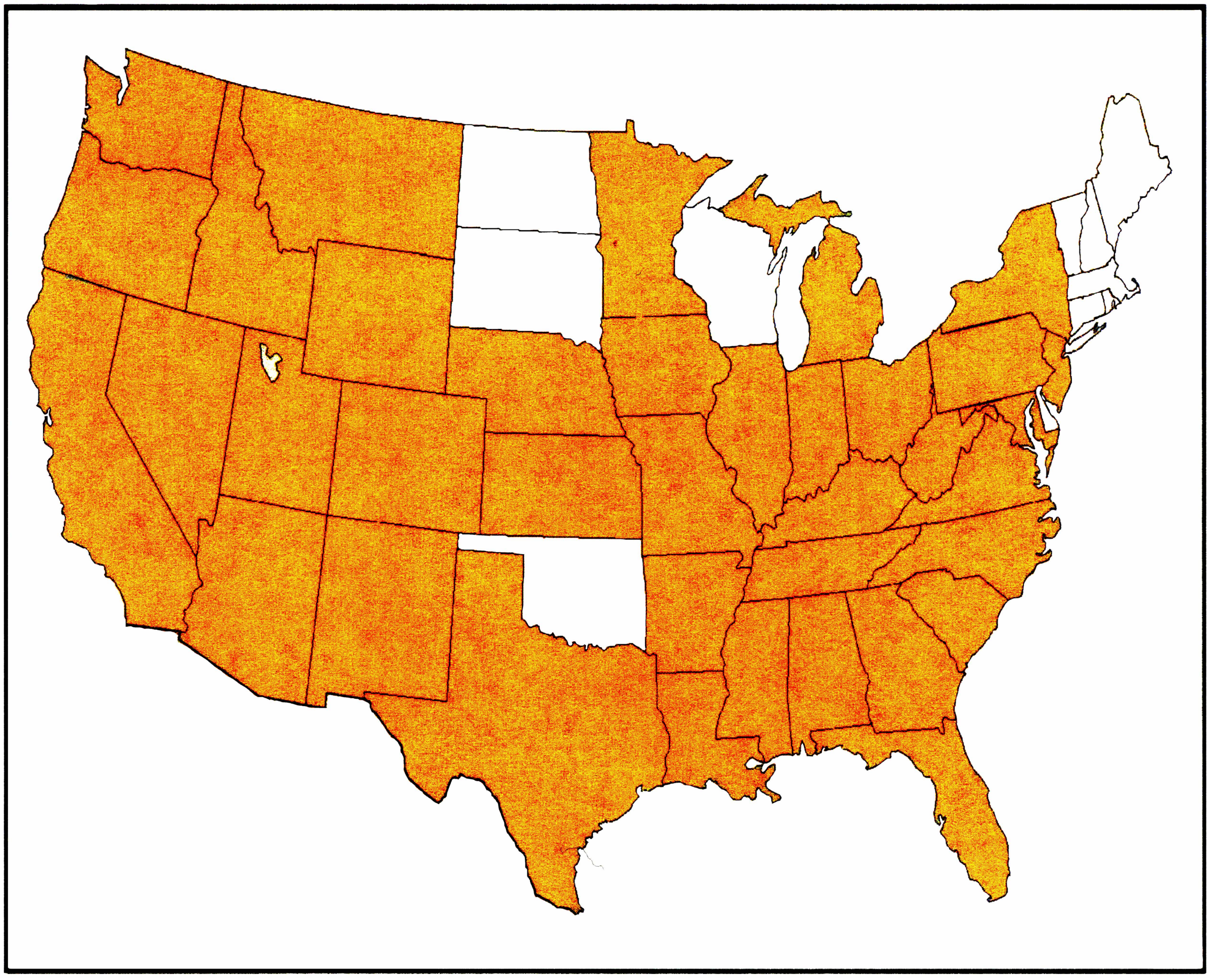


Figure 2. States Where Specifications Were Reviewed

Procedures for Using Contractor-Performed Tests

One of the overarching impressions developed from the review and survey was the extreme diversity in details of state DOT quality assurance processes. A reason is thought to be the variable progress state DOTs have made in moving from method to more end result oriented specifications. Reluctance to commit to required changes in construction management philosophy and uncertainty as to the best practices have certainly been impediments to progress. The result is a condition of flux in many state DOT quality assurance systems, particularly regarding the use of contractor-performed tests for acceptance.

A second overarching impression was a lack of consensus regarding critical definitions. This is expressed rather succinctly in the latest synthesis of practice (9) as follows:

> "One problem associated with QA programs and specifications since their inception has been differing interpretations of the specialized vocabulary used in these programs." (9)

One often finds terminology in various state DOT specifications that are unrelated to or possibly in conflict with those in TRB's, "Glossary of Highway Quality Assurance Terms" (1). A desire for clarity in this research effort leads to some consideration of definitions as related to project objectives.

There seems to be general agreement, or at least no serious controversy, as to the definition or meaning of quality assurance, quality (process) control, acceptance and independent assurance. As depicted in Figure 1, the latter three are part of an overall quality assurance process. In the traditional separation of responsibilities, contractors are responsible for quality control and state DOTs are responsible for acceptance and independent assurance. Issues arise when there is a mixing and mingling of responsibilities, particularly when contractor-performed tests are used for acceptance. In many instances, lack of clear delineation of responsibilities is the reason for confusing terminology.

In order to use quality control sampling and testing results as part of the acceptance decision, 23 CFR 637B (2) requires that "The quality of the material has been validated by the verification samplication and testing." As used herein, verification will refer to a procedure intended to determine if contractor and state DOT performed tests provide measures of material or product properties that are comparable, i.e., when compared they are acceptably close. Verification is critical to using contractor-performed tests in the acceptance process. The viability of contractor-performed tests is a primary concern of state DOTs (3), and procedures for verifying contractor-performed tests have been identified as a topic needing additional study (4).

Table 1 groups state DOT specifications for various materials and products according to requirements for contractor-performed testing, requirements for comparing contractor test results with state DOT test results, and the use of contractor-performed test results for acceptance. Included are specifications from the 37 states illustrated in Figure 2. The materials and products are limited to those that require both contractor and state DOT-performed test results. Exceptions in Group B are HMAC in Illinois and Washington and PCC in Nevada and Montana. These materials in these four states were included because they have end result type specifications that use statistical principles for acceptance but require no contractor-performed testing.

Table 1. Classification of Testing, Verification and Acceptance Procedures

Group A: Both State DOT and Contractor Testing Required

Subgroup A-1-a: State DOT Test Results for Acceptance and Comparisons Required

1. HMA properties and mat density- Colorado*
2. PCC pavement mix and slab properties- Colorado*

Subgroup A-1-b: State DOT Test Results for Acceptance and No Comparison Required

1. HMA mix properties and mat density- Indiana*, New Jersey, Utah, Arizona
2. HMA mix properties- Mississippi, Tennessee, Louisiana, Nevada, Texas
3. HMA mat density- West Virginia*, Idaho*, Montana
4. PCC properties- Arizona
5. PCC strength- Michigan
6. PCC pavement mix and slab properties- Indiana*
7. Base density- New Mexico

Subgroup A-2-a: Contractor Test Results for Acceptance and Comparisons Required

1. HMA mix properties and mat density- Florida*, South Carolina*, Maryland, Wyoming, Minnesota, Iowa, Missouri, Oregon, Kansas
2. HMA mix properties- Alabama*, Georgia*, North Carolina*, West Virginia*, Ohio, New York*, Kentucky, Nebraska
3. PCC- Florida*, Utah
4. PCC pavement- Missouri, Oregon, Texas, Kansas
5. Aggregate base- Florida*, Arkansas, Missouri
6. Earthwork- Florida, Arkansas

Subgroup A-2-b: Contractor Test Results for Acceptance and No Comparison Required

1. HMA mix properties- Idaho*
2. HMA mat density – Virginia*, New York* (series 70), Nebraska
3. PCC plastic properties – Michigan, Kansas (pavement)

Subgroup A-3-a: Combined Test Results for Acceptance and Comparisons Required

1. HMA mix properties and mat density- New Mexico, California
2. HMA mix properties- Virginia*, Michigan, Arkansas*
3. PCC pavement- Arkansas*
4. Base- New Mexico

Subgroup A-3-b: Combined Test Results for Acceptance and No Comparisons Required

1. HMA mix properties- Pennsylvania

Group B: Only State DOT Testing Required for Acceptance

1. HMA mix properties and mat density – Illinois, Washington
2. HMA mix properties- Montana
3. HMA mat density- Alabama*, Georgia*, Mississippi, Tennessee, Kentucky, Pennsylvania, Ohio, Michigan, Louisiana, New York* (series 50 and 60), Texas, Nevada
4. PCC- Nevada, Montana

* States that responded to survey.

The combination of materials and state DOTs in Group A are those where specifications require both contractor and state DOT sampling and testing. Subgroup A-1-b represents the traditional separation of contractor (quality control) and state DOT (acceptance) responsibilities. Subgroups A-2-a and A-3-a represent typical use of contractor-performed test results for acceptance when they are verified. Subgroups A-2-b and A-3-b indicate use of contractor-performed test results without verification, but in all cases other properties are involved in final acceptance.

The combinations of materials and state DOTs in Group B are those where specifications require only state DOT sampling and testing for acceptance. Certainly there are many other combinations which have state DOT dominated quality control and acceptance procedures that could have been included. However, as noted previously, combinations included in Group B are combinations with basically end-result specifications that use statistical principles for acceptance. HMAC mat density is included in Group B for twelve states. For these same states, mix properties are included in Group A where both contractor and state DOT-performed tests are required.

The complexity of Table 1 is indicative of the diversity in the use of contractor-performed test results in the quality assurance process. In the following sections, details of verification and acceptance procedures for HMAC and PCC are presented and discussed.

Procedures for Hot Mix Asphalt Concrete

The use of contractor-performed test results in the quality assurance process is most widespread for HMAC. This was apparent from the review of specifications and is also reported by Hughes (9). It reflects considerable movement from method to end result specifications with increased contractor involvement. Contractors are given responsibility for mix design, contractors are required to develop and implement quality control programs, and, ultimately, contractor-performed test results are used for acceptance.

The properties for HMAC may be separated into material and (in-place) mat properties. Material properties include gradation, asphalt content, voids in total mix (VTM), voids in mineral aggregate (VMA), and, occasionally, voids filled with asphalt (VFA), tensile strength ratio (TSR), moisture content, stability, and dust to asphalt ratio. Some material properties are used for process control and some are used for both process control and acceptance. In-place mat properties include in-place density, smoothness (surface courses), and, occasionally, layer thickness. In-place density is always used as both a control and acceptance property and was the only mat property considered for analysis.

Smoothness and layer thickness were not considered for analysis because only one set of measurements is normally made by either the contractor or state DOT. For smoothness, there are occasionally different tests used for control and acceptance. For example straight edge measurements are made for quality control and profilograph (PI) or inertial profiler (IRI) measurements for acceptance. Cores are measured for layer thickness and two sets of length measurements with a ruler or a caliper seems somewhat redundant.

Table 2 summarizes details of procedures for HMAC for the 37 state DOT specifications reviewed. The presentation is in the form of questions and responses based on the procedures. The diversity encountered required, on occasion, creative reasoning to categorize some procedure details.

Responses to question 1 indicate that, when required, contractor-performed test results are more likely than not used in the acceptance process. The responses also indicated that contractor-performed tests of mix properties are used more than contractor-performed tests of mat density. Among the state DOTs responding to the survey, nine use contractor performed test results for mix acceptance but their own test results for mat density acceptance. Final pay adjustments are most often based on combinations of pay adjustments for mix properties and mat density. In 11 states, contractor test results are used only for quality control.

Questions 2 and 3 provide insight into sampling and testing frequencies. For a majority of situations, the ratio of contractor to state DOT testing frequencies is 4 to 1 or less, with 4 to 1, by far, the most common.

Questions 4 through 9 are applicable when contractor test results are used for acceptance. In 16 of the 23 states that use contractor-performed test results for acceptance, verification is achieved by one to one comparisons. This verification procedure has been referred to as “statistically weak”. Its widespread use is believed due to consideration of practical and reasonable numbers of tests and LOT size for acceptance. An often expressed reason or justification for using contractor-performed test results for acceptance is shrinking state DOT work forces for construction management.

Table 2. Practices When Using Contractor- Performed Tests for HMAC

1. Are contractor- performed test results used in the acceptance process?
    - Yes- 23[2]
    - No- 13[3]

2. What are the ratios of contractor to state DOT testing frequencies for mix properties?
    - 4 to 1 or less - 21
    - 5 to 1 to 9 to 1 - 3
    - 10 to 1 or greater - 6
    - Other - 2

3. What are the ratios of contractor to state DOT testing frequencies for mat density?
    - 4 to 1 or less - 10
    - 5 to 1 to 9 to 1 - 5
    - 10 to 1 or greater - 3
    - Other - 1

4. What are methods for verifying (comparing with state DOT) contractor-performed test results when used in the acceptance process?
    - 1 state DOT to 1 contractor - 16
    - 1 state DOT to contractor average - 1
    - F and t test - 4
    - Other - 2

5. What acceptance method is used?
    - Pass/ Fail - 2[4]
    - Pay adjustment - 22[4]

6. What are LOT sizes for acceptance?
    - Days production - 9
    - Project production - 2
    - Tonnage (>1000 tons) - 9
    - Other - 3

7. How are contractor-performed test results used in making acceptance decisions?
    - Alone - 18[2]
    - Combined with state DOT - 5

8. How are contractor- performed test results related to specification requirements for making acceptance decisions?
    - Deviation from target -10
    - Absolute deviation from target - 4
    - Percent within limits - 9

9. How are pay adjustments for individual properties used to determine LOT pay adjustments ?[5]
    - Lowest - 8[4]
    - Weighted average - 11
    - Cumulative - 4

Notes

1. Review of Maryland DOT specifications is not included.
2. In Alabama, Georgia, Kentucky, West Virginia, Pennsylvania, Ohio, New York, Michigan, and Idaho contractor-performed test results are used for mix properties but DOT-performed test results are used for mat density.
3. Includes Illinois and Washington even though no contractor sampling and testing required.
4. The Iowa DOT has a pass/fail system for mix properties and adjusts pay for mat density.
5. Surface smoothness is commonly used acceptance property, but it is almost always applied independently of mix and mat properties and is almost always based on one set of measurements, i.e., state DOT or contractor.

that are practical. From a contractors' perspective, timely acceptance decisions should reasonably be expected. These factors limit the number of state-DOT tests for verification.

Four state DOTs use more statistically robust F and t tests. This method, however, is not without application problems. Minimum sample sizes are required before valid comparisons can be made but contractors want timely acceptance decisions. Table 3 illustrates how these four state DOTs use F and t tests to verify contractor-performed tests. The most common method to overcome the problem of minimum sample size is to designate the entire project production as a LOT for acceptance. Table 3 also illustrates differences in what constitutes comparable test results, i.e., mean only or mean and variability. The significance level used to determine statistically significant differences in all four states is 1%.

When contractor-performed test results are used in the acceptance process, they are most likely used for the computation of pay adjustments to bid prices. A pass/fail procedure is used in only two states. Included in the 22 procedures where pay adjustments are computed are several that compute pay reductions as a last resort in what is basically a pass/fail system. These acceptance procedures are somewhat flexible and contain remnants of method specifications. Both contractor and state DOT sampling and testing are required, and re-sampling and retesting may be allowed. Unfavorable comparisons or unacceptable test results first lead to investigations or additional sampling and testing before definitive decisions are made regarding acceptance and pay factor determination.

Table 3. Differences in Application Procedures for F and t tests

State	LOT Size	Testing Procedure	Verification Procedure
Kansas	Day (mat density) 3000 tons (mix)	F & t for last 5 LOTs F to decide t or mod. t	t indicates same $\overline{X}$
New Mexico	Total Project Production	F & t cumulatively	F and t indicate same s^2 and $\overline{X}$
California	Total Project Production	t cumulatively Assume equal s^2	t indicates same $\overline{X}$
Idaho	Days Production	F & t cumulatively F to decide t or mod. t	t indicates same $\overline{X}$

On the other hand, some specifications have more rigid acceptance procedures. In these there is a stronger commitment to a statistically based procedure and significant movement toward end results. These acceptance procedures are characterized by definite sampling and testing requirements, specific verification procedures (if contractor-performed tests are used for acceptance) and definite consequences based on comparisons of test results and comparisons of test results with acceptance criteria.

LOT sizes for acceptance are most often a day’s production (9 states) or a discrete tonnage greater than 1000 tons (9 states). Two states delineate the entire project production of a material or product as a LOT for acceptance. These are western states that use the F and t test for verification. Larger quantities eliminate the impediment of minimum required numbers of test results for application of F and t tests as noted above.

Questions 7-9 are related to computation and application of pay adjustments. Eighteen of 23 states use verified contractor-performed test results alone to compute pay adjustments. Five states combine their test results with contractor test results.

To compute pay adjustments, ten states compare deviation from target values with numerical criteria. Deviations may be positive or negative. Four states use similar procedures but the basis is absolute deviation from target values. Nine states use the percent within limits (PWL) method or some derivative. PWL methods use LOT means and standard deviations to compute pay adjustments.

Finally, pay adjustments for individual properties are used to compute LOT pay adjustments. The most common method (11 states) is a weighted average LOT pay adjustment computed with individual property pay adjustments. The lowest property pay adjustment is applied in 8 states and cumulative adjustments for several properties are applied in 4 states. Smoothness is a mat property that is commonly included for asphalt concrete surface courses. The pay adjustments for smoothness are, however, most often treated independently of material properties and mat density.

Procedures for Portland Cement Concrete

The shift in the responsibility for acceptance testing from state DOTs to contractors is not as advanced or pronounced for PCC products as with hot-mix asphalt concrete. Several factors may explain the relatively sparse use of contractor-performed tests for acceptance purposes. One of these is the fact that PCC is typically not produced by the contractor, but rather by a producer or supplier who sells the product to the contractor. A second factor is that a wide variety of PCC applications exist (while HMA is used solely for pavements); lot sizes, testing frequencies, etc. typically vary among these applications, further complicating change from the traditional division of sampling and testing responsibilities. Finally, the most important property of PCC is strength. This can only be determined after some curing time (usually 28 days) which makes timely final acceptance decisions difficult.

Properties of PCC can be grouped into two categories: plastic properties, and hardened, or in-place, properties. Some states that require contractor testing for acceptance have done so only for in-place properties (compressive strength, flexural strength, and pavement thickness), while other states have done so with both hardened and plastic properties (slump and air content).

Pavement smoothness is not considered in this analysis since typically only one measurement is made, rather than both the contractor and the agency measuring smoothness and then comparing the findings. In some states, the contractor is responsible for collecting the data while the state DOT then reviews and interprets the results.

Table 4 presents a summary of how contractor-performed tests are used for acceptance and pay adjustments; there is little consensus among the states using contractor-performed tests. Item 1 in the table clearly shows that most state DOTs still control acceptance testing; only eight of those whose specifications were reviewed use contractor-performed tests for acceptance. In many other states, the contractor carries no testing responsibilities whatsoever. The remaining items in Table 3 apply only to the eight states noted in Item 1 (Arkansas, Colorado, Florida, Kansas, Missouri, Texas, Utah, and West Virginia).

It can be seen in Item 2 that a wide variety of approaches are used to compare results of tests conducted by contractors and state DOTs. At one extreme, one state uses the statistical approach of t-tests and F-tests to compare means and variances of test results from each party. While this approach may be more conceptually complex than others, it also maximizes the probability that the product is characterized correctly by the test results. However, this approach cannot be applied until some minimum sample size of test results are available (most commonly three test results per party as found in the review of hot-mix asphalt acceptance procedures).

Table 4. Practices When Using Contractor-Performed Tests for PCC

1. Are contractor-performed tests used in the acceptance process?[1]
    Yes: 8
    No: 29

2. What methods are used for verification (comparison) of contractor-performed test results when used in the acceptance process?[2]
    One DOT to one contractor: 2
    DOT average to contractor average: 1
    F- and t-tests: 1
    One DOT to contractor average: 4
    No direct comparison made: 1

3. What is the methodology of the acceptance process?[3]
    Pass/Fail: 2
    Pay adjustment: 7

4. What are lot sizes for acceptance?[4]
    Project production: 2
    One day production: 4
    Area/volume: 2

5. How are contractor-performed test results used in the acceptance process?
    Alone: 4
    Combined with DOT: 4

6. How are contractor-performed test results related to specification requirements for making acceptance decisions?
    Deviation from target value: 1
    Variability/standard deviation: 2
    Percent within limits: 2
    As yet undetermined: 3

7. How are pay adjustments for individual properties used to determine lot pay adjustments?
    Weighted average: 5
    Other: 2

Notes:

1. The eight states (22% of those states studied) are: Arkansas, Colorado, Florida, Kansas, Missouri, Texas, Utah, West Virginia. One of these states (Colorado) has two acceptance processes for PCC products: “flexural strength criteria” in which contractor-performed tests are used for acceptance, and “compressive strength criteria” in which only agency-performed tests are used for acceptance.
2. One state (Florida) compares an individual agency test result to an individual contractor-performed test result for slump, air content, compressive strength, and flexural strength, *and* compares the average of agency test results to the average of contractor test results for both strength properties.
3. One state (Texas) uses a pass/fail approach to acceptance for slump, air content, and flexural strength but applies a pay adjustment based on the results of pavement thickness tests.
4. One state (Colorado) that uses project production as the lot size allows for a new lot to begin when a “process change” occurs. Process changes include changes in mix design, material source, design pavement thickness, or construction method. The other state (West Virginia) that uses project production as the lot size applies this lot definition to each lane of pavement (each lane constitutes a lot).

At the other extreme, two states use the simple and relatively inexpensive, but statistically weak, approach of comparing one state DOT result to the corresponding contractor test result. This approach, while appealing from a resource perspective, may not effectively compare contractor and state DOT tests. Other comparison procedures include comparison of one state DOT-performed test to an average of contractor-performed test results, and comparing averages of test results from both parties. Interestingly, although four states use this approach, they do not take advantage of the fact that such a data set can also be the basis for statistical testing.

Regarding acceptance and pay adjustment processes, all but one of the eight state DOTs that use contractor-performed tests for acceptance apply pay adjustments based on some or all of the properties tested, rather than simply accepting products on a pass/fail basis. While all of these states use contractor-generated results in the acceptance and pay adjustment processes, half of them use contractor data alone, while half use contractor and DOT-generated results in some combination.

For acceptance purposes, LOT size varies widely. Two states use the entire project quantity as the basis for acceptance and pay adjustment; two other states an area or volume based quantity. Four states define a LOT as one day of production (or smaller subsets if production exceeds a specified amount). Pay adjustments are typically applied using weighted averages of the various factors for which pay adjustments are possible, except in two states, in one of which only one property is used for pay adjustment purposes.

A variety of practices are used to relate the results of contractor-performed tests to specification requirements. Two state DOTs use the percent within limits concept.

One state uses deviations from specified targets, while two others use measures of variability. The processes used in three states were not evident from the specifications review.

Confidence in Contractor-Performed Tests

The limited survey described earlier asked state DOTs how confident they were that contractor-performed tests provided the same measure of material quality as their tests. The state DOTs were asked to rank (5 “confident” to 1 “not confident”) their level of confidence. The composite ranking for 12 state DOTs was 4.1 for HMAC and for 10 state DOTs was 4.8 for PCC. These rankings are contrary to the results of surveys reported by Hancher, et al (3) where viability of contractor-performed tests was of primary concern to state DOTs. However, in the surveys reported by Hancher, et al (3), both state DOTs and contractors indicated the major advantage of contractor-performed quality control was contractor responsibility for their products. This implies that the concern of state DOTs is related to use of contractor-performed tests for acceptance.

A second question asked state DOTs was how satisfied they were with their quality assurance programs. The composite ranking, on a scale of 1 to 5, for 12 state DOTs was 3.8 for HMAC and for 10 state DOTs was 4.0 for PCC. These are not as high as the rankings related to confidence in test results but do indicate a relatively high satisfaction level.

COMPARISONS OF CONTRACTOR AND STATE DOT-PERFORMED TESTS

Several studies that compared contractor and state DOT performed test results were found in the literature. These studies include statistical comparisons of means and variability of contractor and state DOT test results. In addition, indications of possible bias were examined. Several of the studies (17-21) were of data collected during the development and implementation of statistically based quality assurance procedures for HMAC by the Alabama DOT. A recently published study (3) compared contractor and Kentucky Transportation Cabinet test results for HMAC and both paving and structural PCC. An unpublished study analyzed data collected during the trial implementation of a statistically based quality assurance procedure for structural PCC by the Alabama DOT.

Alabama DOT Hot Mix Asphalt Concrete Tests

Parker and Hossain (12) compared asphalt content and air voids measurements for HMAC (Marshall mix design) collected during implementation of a statistically based quality assurance procedure by the Alabama DOT. Table 5 contains the results of statistical comparisons (5% significance level) of asphalt content measurements for three mix types and combined data from three construction seasons. The variable used in the analyses was the difference between measured and target values ($\Delta = X - X_T$). Data used in the comparisons are illustrated in Figures 3 and 4. The statistical comparisons provide no strong indications of significant differences or similarities between means or variabilities of contractor and Alabama DOT asphalt

Table 5. Summary of Statistical Analyses of Differences Between AHD and Contractor Asphalt Content for Combined Mix Data (Ref. 12)

Year	Mix Type	Significantly Different Variability	Higher Variability	Significantly Different Mean Deviation	Higher Mean Deviation
1	414	Yes	AHD	No	…
9	416	Yes	AHD	Yes	AHD
9	417	No	…	No	…
2	Combined	Yes	AHD	Yes	AHD
1	414	No	…	Yes	Contractor
9	416	No	…	Yes	AHD
9	417	No	…	No	…
1	Combined	No	…	Yes	Contractor
1	414	Yes	AHD	No	…
9	416	No	…	No	…
9	417	No	…	Yes	Contractor
0	Combined	Yes	AHD	Yes	AHD

AHD – Alabama Highway Department (now Alabama Department of Transportation)

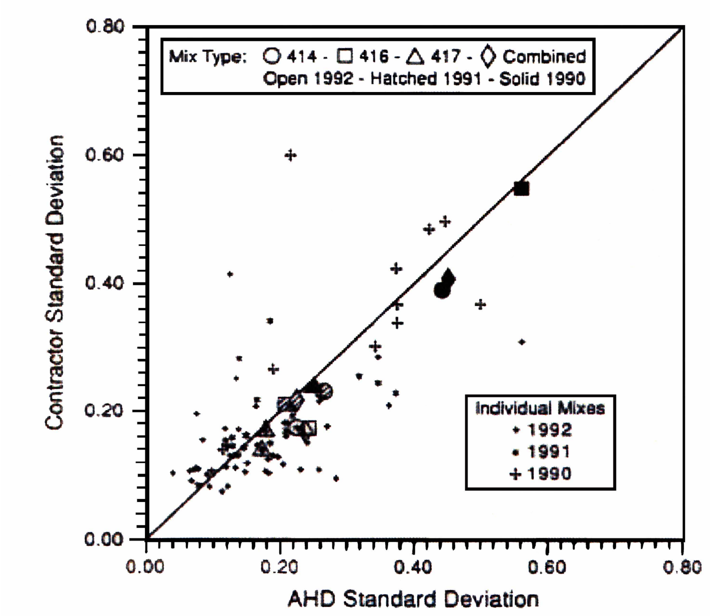


Figure 3. Summary of AHD and Contractor Asphalt Content Standard Deviation (Ref.17)

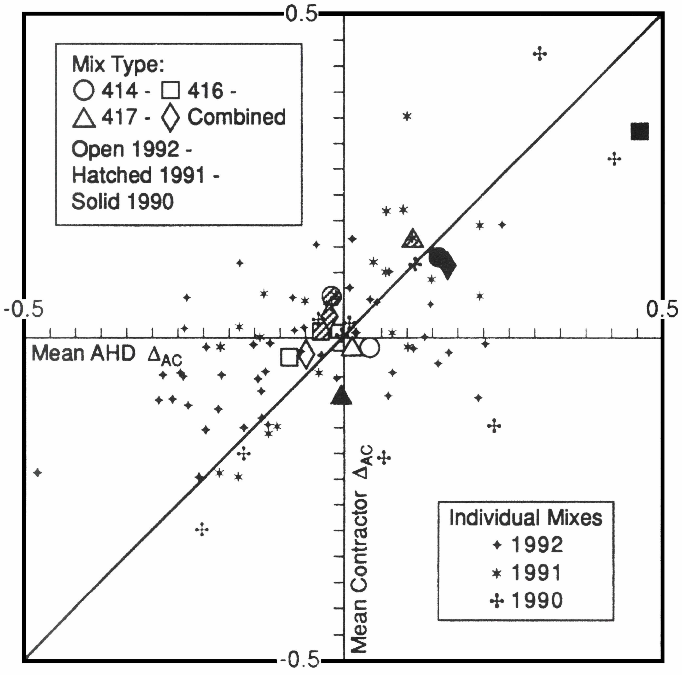


Figure 4. Summary of AHD and Contractor Asphalt Content Mean Deviation (Ref. 12)

content measurements. The statistical comparisons and Figure 3 do, however, show that the variability of Alabama DOT asphalt content measurements is likely larger than the variability of contractor measurements.

Table 6 and Figures 5 and 6 show results of similar analyses for air voids. The statistical comparisons in Table 6 and Figure 6 suggest no significant differences in means of contractor and Alabama DOT air voids measurements. As to variability, the statistical comparisons provide no strong indication of differences or similarities. However, similar to asphalt content, the statistical comparison and Figure 5 suggests that the variability of Alabama DOT air voids measurements is likely larger than the variability of contractor measurements.

Parker and Hossain (13) compare mat density measurements (with a nuclear gauge) collected during the above mentioned implementation by the Alabama DOT.

Table 7 contains results of statistical comparisons (5% significance level). No results are shown for 1991 because during this construction season the Alabama DOT only measured mat density with cores. Data used in the comparison are depicted graphically in Figures 7 and 8. The statistical comparisons in Table 7 indicate significant differences in means and variability of contractor and Alabama DOT measurements. Larger variability and larger deviation from target density (94% of theoretical maximum mix density) for Alabama DOT measurements are illustrated in Figures 7 and 8.

Figure 7 also strongly indicates that measured mat densities are consistently lower than the target mat density ($\Delta = X - 94$). It should be noted that the 94% target is more rigorous than the more common target of 92%. Implications of the consistent inability to achieve target compaction are meaningful for the acceptance

Table 6. Summary of Statistical Analyses of Differences Between AHD and Contractor Air Void Content for Combined Mix Data (Ref. 12)

Year	Mix Type	Significantly Different Variability	Higher Variability	Significantly Different Mean Deviation	Higher Mean Deviation
1	414	No	…	No	…
9	416	Yes	AHD	No	…
9	417	No	…	No	…
2	Combined	Yes	AHD	No	…
1	414	Yes	AHD	No	…
9	416	Yes	AHD	No	…
9	417	No	…	No	…
1	Combined	Yes	AHD	No	…
1	414	Yes	AHD	No	…
9	416	No	…	No	…
9	417	Yes	Contractor	Yes	AHD
0	Combined	No	…	No	…

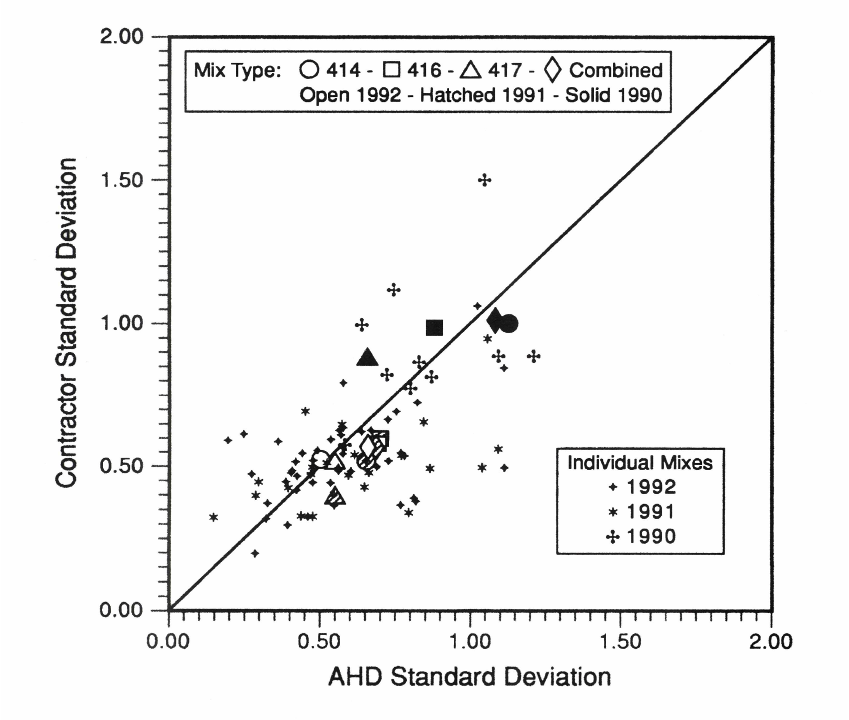


Figure 5. Summary of AHD and Contractor Air Void Content Standard Deviation (Ref. 12)

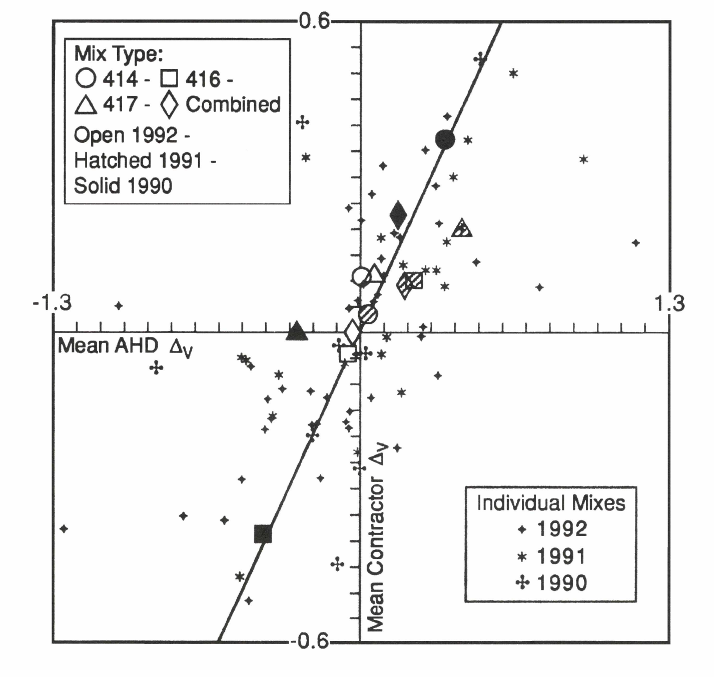


Figure 6. Summary of AHD and Contractor Air Void Content Mean Deviation (Ref. 12)

Table 7 Summary of Statistical Analyses of Differences Between AHD and Contractor Mat Density (Nuclear Gage) Measurements for Combined Mix Data (Ref. 13)

Year	Mix Type	Significantly Different Variability	Numerically Higher Variability	Significantly Different Mean Deviation	Numerically Higher Mean Deviation
1993	414	Yes	AHD	Yes	AHD
	416	Yes	AHD	Yes	AHD
	417	Yes	AHD	Yes	…
	Combined	Yes	AHD	Yes	AHD
1992	414	Yes	AHD	Yes	AHD
	416	Yes	AHD	Yes	AHD
	417	Yes	AHD	No	…
	Combined	Yes	AHD	Yes	AHD
1990	414	Yes	AHD	Yes	AHD
	416	Yes	AHD	Yes	AHD
	417	Yes	Contractor	Yes	AHD
	Combined	Yes	AHD	Yes	AHD

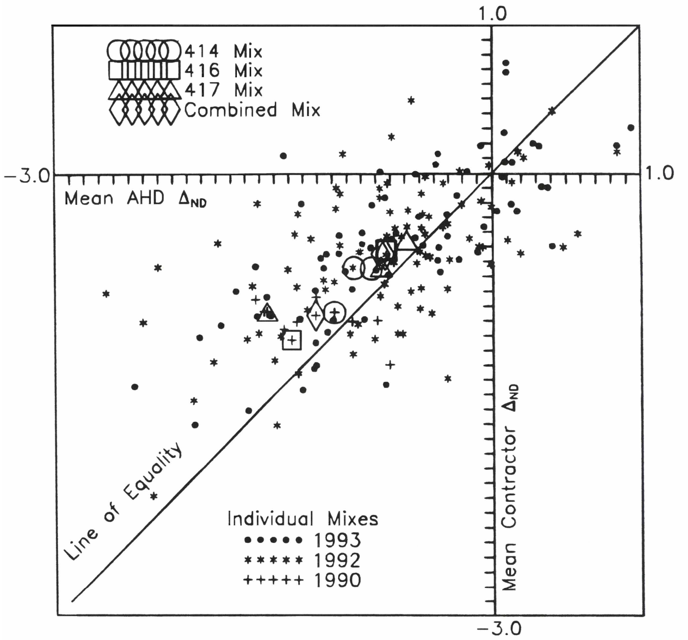


Figure 7. Summary of Nuclear Gage Mat Density Measurement Mean Deviation From Target (Ref.18)

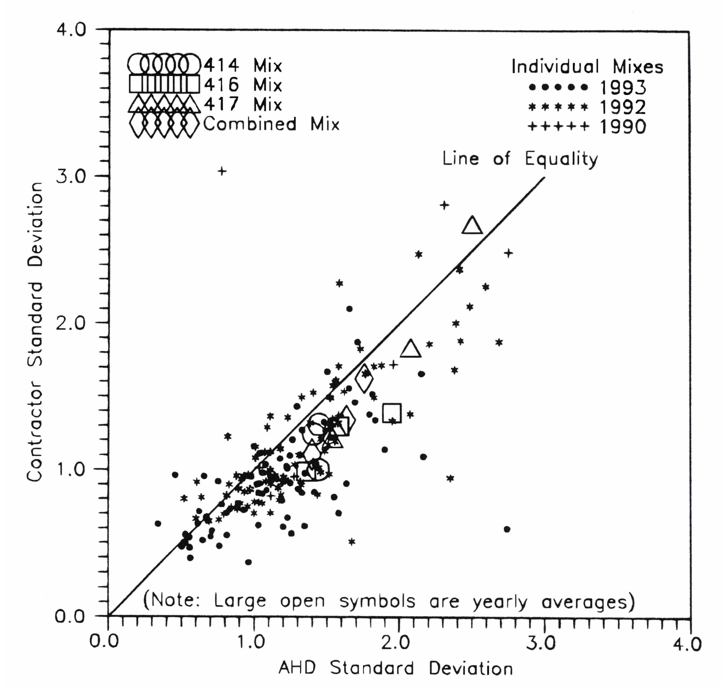


Figure 8. Summary of Nuclear Gage Mat Density Measurement Variability (Ref.18)

process. In the Alabama DOT system, the lowest pay adjustment for asphalt content, air void content, or mat density was applied to each LOT. This means that mat density was, in most cases, the most critical for pay factor computation. Beginning in 2003, acceptance and pay factor computation for mat density were based on Alabama DOT tests on cores. Contractors are still required to test mat density with nuclear gages, but results are for their process (quality) control only.

The Alabama DOT began implementing the Superpave mix design system for HMAC in the mid 1990’s. Data was collected from 1997 to 2000 to determine quality assurance modifications for Superpave designed mixes. Parker and Hossain (14) compared contractor and Alabama DOT measurements for asphalt content, air void content, and mat density collected to support these modifications.

Table 8 contains results from statistical comparisons (5% significance level) of means of deviations from target values for asphalt content, air void content, and mat density. Differences for asphalt content are not significant but differences for mat density are significant. Results are mixed for air void content. In terms of numerical differences, there are no strong indications that either contractor or Alabama DOT asphalt content measurements are closer to targets. However, for air voids and mat density, contractor measurements are consistently closer to targets.

Table 8. Comparison of Deviation from Target Values Between Contractor and Alabama DOT Measurements (Ref. 14)

		Average Deviation from Target		
Measured Properties (Analysis Variable)	Year	DOT	Contractor	Statistical Difference @ 5% Level
Asphalt	1997	-0.130	-0.087	S.D
	1998	-0.006	-0.028	N.S.D.
(AC-Target, JMF)	1999	-0.069	-0.048	N.S.D
	2000	+0.001	+0.006	N.S.D
	Combined	-0.045	-0.036	N.S.D
Air Voids	1997	-0.074	-0.075	N.S.D
	1998	-0.256	-0.229	N.S.D
(Voids – 4%)	1999	-0.477	-0.351	S.D.
	2000	-0.437	-0.371	N.S.D
	Combined	-0.357	-0.281	S.D.
Mat Density	1997	-1.772	-1.763	N.S.D
	1998	-1.700	-1.427	S.D
Density as (% of TMD – 94%)	1999	-1.097	-0.875	S.D.
	2000	-0.981	-0.689	S.D.
	Combined	-1.245	-0.997	S.D.

Of interest in Table 8 is the observation that both air void content and mat density are consistently less than target values. The low air void contents are inconsistent with asphalt contents that are close to design values. The difficulty in achieving mat compaction is consistent with the initially high Superpave mix design compaction levels and coarse gradations that resulted in very harsh mixes. Recent reductions in mix design compaction levels to increase asphalt content and changes in recommended gradations were made by the Alabama DOT to produce more workable mixes.

Table 9 contains results from statistical comparison of variability. There are strong indications that the variability of contractor asphalt content, air void content, and mat density measurements are significantly smaller than Alabama DOT measurements.

HMAC was the first, and to date the only, construction material managed by the Alabama DOT with a statistically based quality assurance procedure. An analysis of data collected during the implementation of this procedure will illustrate how product quality, as quantified by reduced variability and closer proximity to targets for measured properties, improved and stabilized with implementation. There is nothing particularly unusual about Alabama DOT procedures, and it might be argued that if certain details of the procedure were different, then the product quality might have been even better. However, this is an argument that can never be settled, but the noted improvements in quality during implementation are irrefutable.

Table 9. Comparison of Variability of Contractor and Alabama DOT Measurements (Ref. 14)

Measured Properties (Analysis Variable)	Year	Variability (Standard Deviation) DOT	Contractor	Statistical Difference @ 5% Level
Asphalt (AC-Target, JMF)	1997	0.265	0.239	S.D
	1998	0.237	0.197	S.D.
	1999	0.274	0.247	S.D
	2000	0.288	0.219	S.D
	Combined	0.272	0.230	S.D
Air Voids (Voids – 4%)	1997	1.054	0.989	N.S.D
	1998	1.019	0.791	S.D
	1999	1.014	0.847	S.D.
	2000	0.992	0.840	S.D
	Combined	1.025	0.863	S.D.
Mat Density Density as (% of TMD-94%)	1997	1.493	1.475	N.S.D
	1998	1.742	1.406	S.D
	1999	1.276	0.991	S.D.
	2000	1.382	0.975	S.D.
	Combined	1.470	1.175	S.D.

Note: S.D. = significantly different; N.S.D.= not significantly different; JMF= job mix formula.

ALDOT began implementing a statistically based quality assurance program for Marshall designed HMAC in 1990 and completed the process in 1994. Analyses of the data collected during implementation were described above (12 and 13) with additional data and analyses in Reference 15. A chronology for the implementation is as follows:

1990 - Model specification for four trial projects. Pay adjustments computed but not applied.

1991 - Modified specifications for 11 trial projects. Pay adjustments computed and applied at 50% of the computed values.

1992 - Modified specifications for all projects. Pay adjustments computed and applied at full values.

1993 - Final specifications for all projects. Pay adjustments computed and applied at full values.

Figures 9-11 illustrate how variability and proximity to target values for measured properties changed during implementation. The standard deviations of asphalt content and voids decreased from 1990 to 1991 and stabilized at about 0.2% for asphalt content and 0.6 to 0.7% for voids content. The trend for mat density variability was somewhat different with a rather uniform decrease in standard deviation for the entire implementation period.

Amongst the possible reasons for the observed decreases in variabilities are better process control and improvements in technician sampling and testing skills. It is also likely that the application of pay adjustments, beginning in 1991, was an important factor in the considerable improvements in asphalt and voids content variabilities between 1990 and 1991.

A trend for all three properties is that the standard deviations for contractor test results were consistently smaller than standard deviations for ALDOT test results.

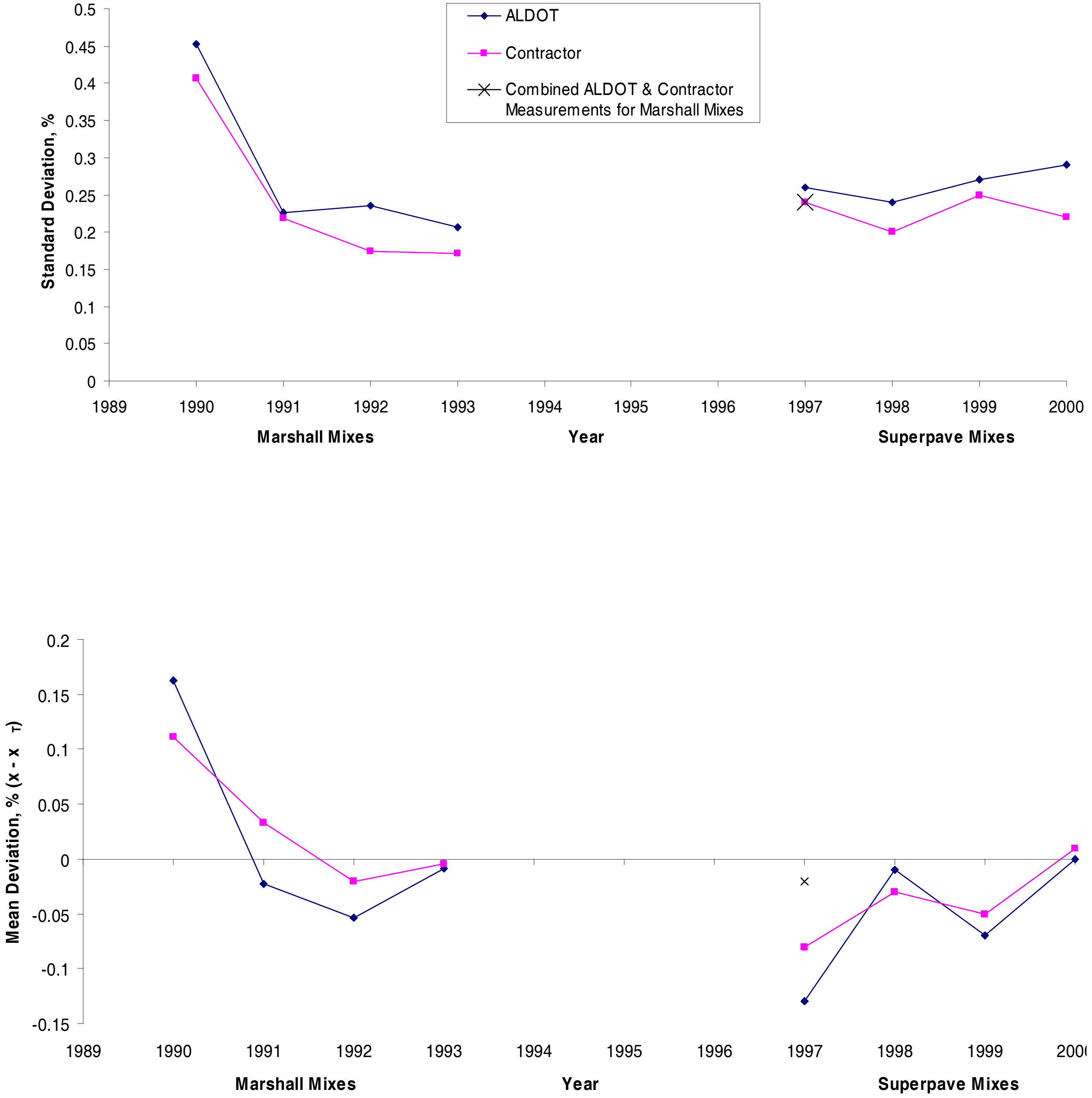


Figure 9. Asphalt Content Statistics During Quality Assurance Implementation

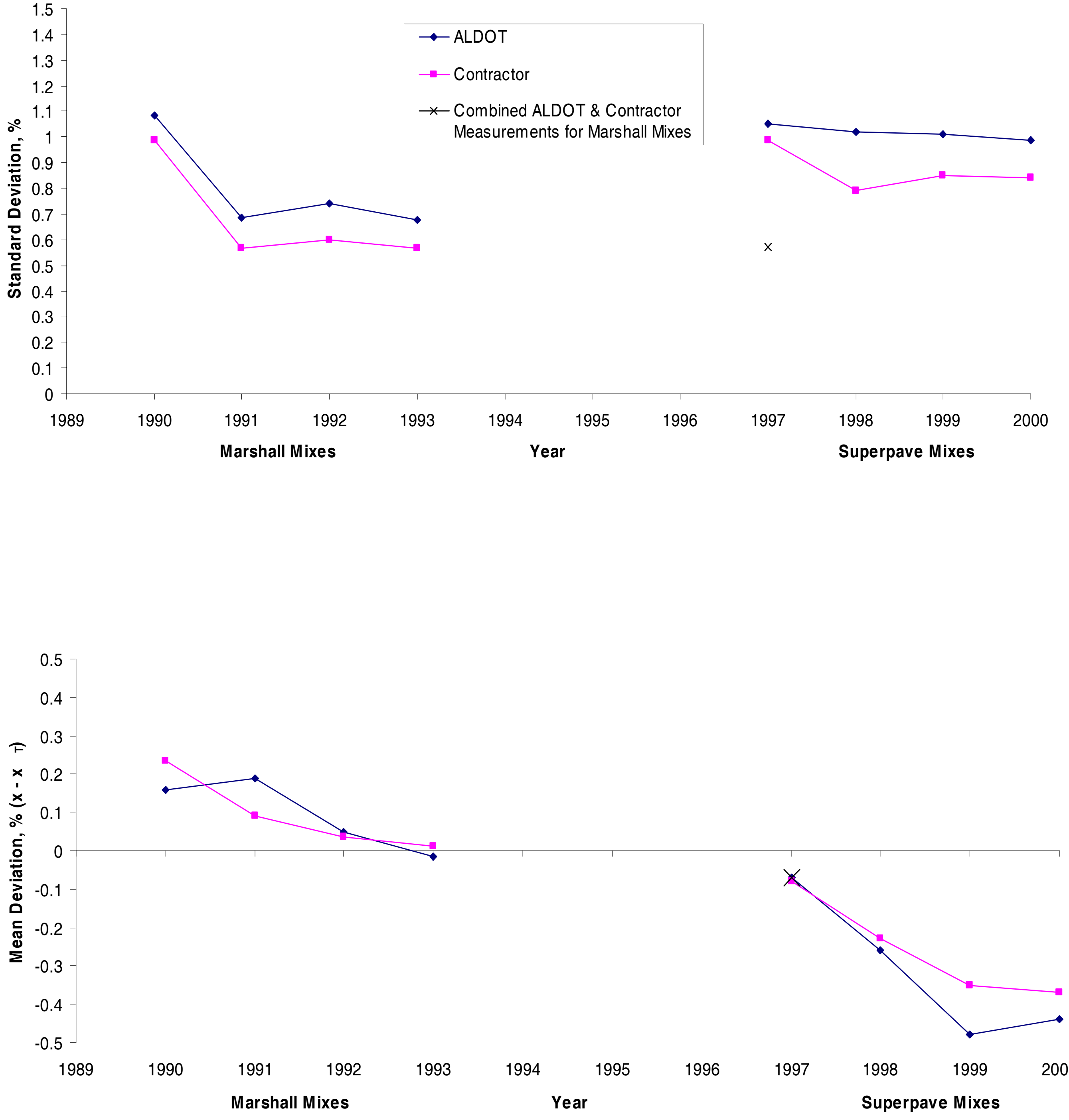


Figure 10. Voids Content Statistics During Quality Assurance Implementation

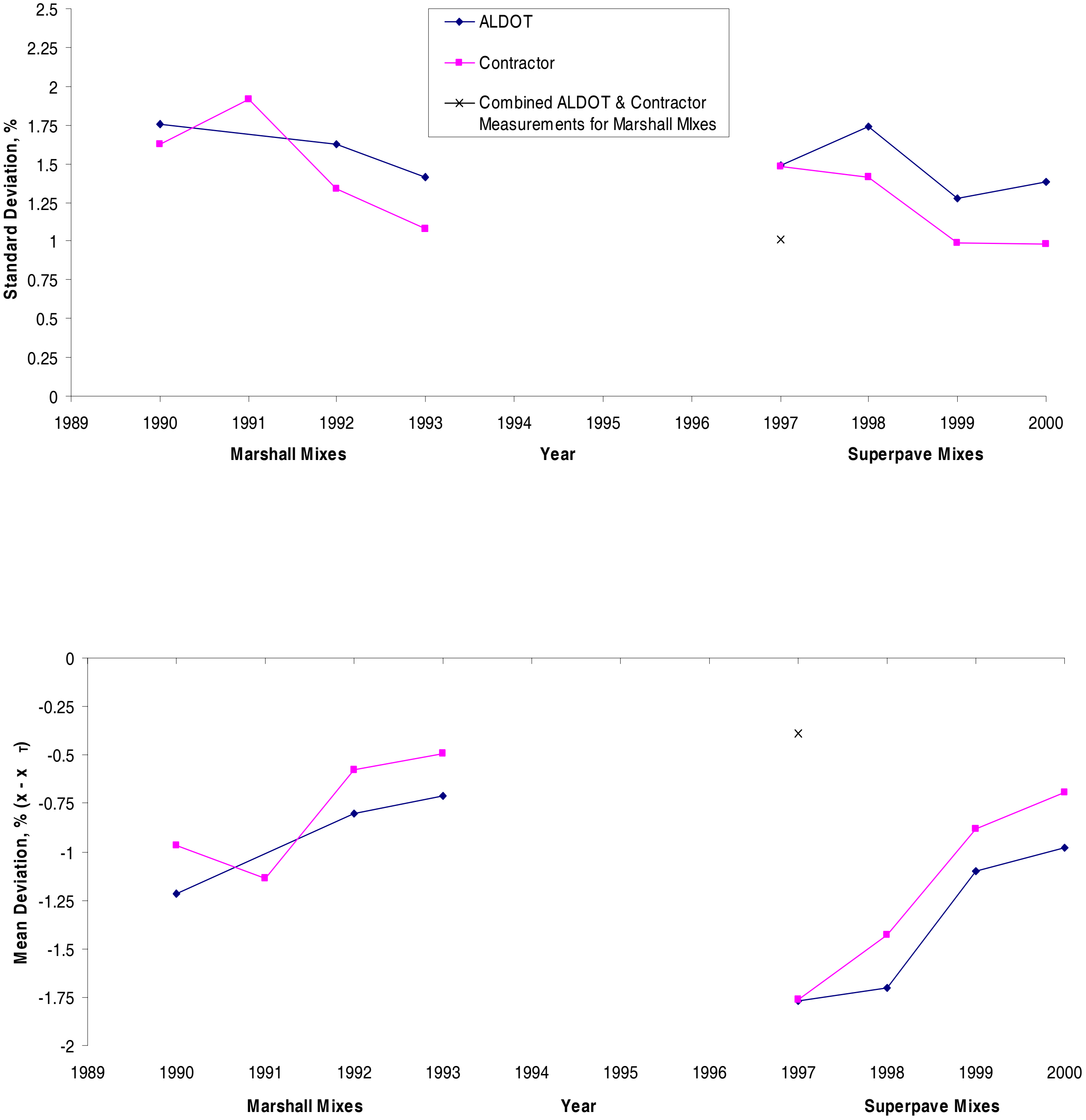


Figure 11. Mat Density (%G_{mm}) Statistics During Quality Assurance Implementation

Figure 9 indicates considerable improvement in achieving target asphalt contents between 1990 and 1991, and stabilization close to target values for the remainder of the implementation period. Deviations from targets are defined as measured values minus target values.

The proximity of measured voids content to the 4% target (Figure 10) does not stabilize after 1991 but continues to improve rather uniformly. By 1993, when implementation was complete, measured air void contents are very close to the 4% target.

The proximity of measured mat density to the 94% target (Figure 11) improves rather uniformly for the entire implementation period. However, unlike air void contents, which were very close to the 4% target in 1993, mat density measurements were still 0.5-0.7% below the 94% target.

The consistent decrease in air void content and increase in mat density are inconsistent with the general decrease in asphalt content. Air void content should increase and mat density should decrease as asphalt content decreases. For mat density, a logical reason or explanation for the observed increase may be greater compactive effort. However, there is no logical physical explanation for the uniform, though small, rate of decrease in voids content for the entire implementation period.

For asphalt and air void contents, there are no consistent differences between the proximity of contractor or Alabama DOT measurements to target values. For mat density, however, contractor test results were consistently closer to target values. As noted above, the variabilities of contractor test results for all three properties were consistently smaller.

Beginning in 1997, the Alabama DOT conducted a study to see if changes to quality assurance procedures would be needed for HMAC designed with the Superpave method (16). Analyses of data collected during this study were described above (14). The chronology of the modification of the quality assurance procedures is as follows:

1997 - Data collected and analyzed for nine trial Superpave projects and nine comparable Marshall-designed projects.
1998 - Data collected and analyzed for 20 Superpave projects.
1999 - Modified specifications for 27 Superpave projects. Pay adjustments computed and applied at 50% of the computed values.
2000 - Final specifications for all Superpave projects. Pay adjustments computed and applied at full values.

The standard deviations for both asphalt content (Figure 9) and voids content (Figure 10) remained relatively constant during the 4-year implementation period. Both deviations were somewhat larger than standard deviations for Marshall-designed mixes. The larger standard deviations for Superpave air void contents are consistent with the larger standard deviations for the asphalt content.

Standard deviations and means of combined Alabama DOT and contractor tests for the 1997 Marshall mixes are shown in Figures 9 through 11. The standard deviation of these asphalt content measurements was larger than the 1991-1993 Marshall measurements and about the same as the standard deviations for the comparable 1997 Superpave projects. The standard deviation of these air void content measurements was essentially the same as 1991-1993 Marshall measurements and smaller than the standard deviations for the comparable 1997 Superpave projects.

The variability of mat density measurements (Figure 11) for the nine Superpave projects in 1997 was higher than the variability for the nine comparable Marshall projects. However, the standard deviation for Superpave mat density measurements decreased during the 4-year implementation period to levels comparable to those achieved for Marshall mixes in 1993.

Similar to Marshall mixes, standard deviations of contractor measured properties for Superpave mixes were consistently smaller than the standard deviations of Alabama DOT measured properties.

The proximity of asphalt content (Figure 9) and mat density (Figure 11) measurements to target values improved during the 4-year implementation period. Conversely, the proximity of air void content measurements (Figure 10) to the 4% target worsened, with the average air void content decreasing from about 3.9% in 1997 to about 3.6% in 2000. For both Marshall and Superpave mixes, asphalt contents were very close to target values after the 4-year implementation period. Mat densities for both mix types improved, but both remained below the 94% target value – by about 0.7% for Marshall mixes and 0.9% for Superpave mixes. Air Void contents of Marshall mixes were very close to the 4% target after the 4-year implementation period. Air voids content of Superpave mixes was the only quality measure that degraded during implementation. An possible reason for this behavior may be the contractors' efforts to minimize potential for pay reductions. The general decrease in air void content and the general increase in mat density are consistent with the general increase in asphalt content. Mat density was the critical property for pay adjustments and the lower than desirable air void content was apparently accepted by contractors in order to achieve higher mat density.

Similar to the Marshall mixes, contractor measured properties for Superpave mixes generally tended to be closer to target values than Alabama DOT measured properties, particularly for air void content and mat density.

The implementation of statistically based quality assurance procedures for HMAC resulted in progressive improvements in quality that stabilized with time. However, there remained differences in the level of quality indicated by contractor and Alabama DOT-performed tests.

Alabama DOT Portland Cement Concrete Tests

Table 10 presents comparisons of tests from an unpublished study of structural PCC for Alabama DOT. The data for the comparisons were collected during a bridge construction project that was part of a study to evaluate the feasibility of a statistically based quality assurance procedure for structural PCC. For this pilot project, Alabama DOT testing frequencies were increased and the contractor was required to conduct quality control sampling and testing. Since the contractor had no testing capabilities, a consultant was hired for this purpose. A model specification combining contractor tests with Alabama DOT tests for computing pay factors was developed. Pay factors were computed, but concrete was actually accepted for pours on a pass/fail basis determined with Alabama DOT compressive strength tests.

Table 10. Comparison of QC/ QA Data for Substructure PCC

Property	n	σ	Difference @ 5% Significance Level	$\bar{x}$	Difference @ 5% Significance Level
QC Slump, in	26	0.87	NSD	3.88	NSD
QA Slump, in	32	0.82		4.01	
QC Air, %	26	0.64	NSD	3.71	NSD
QA Air, %	32	0.58		3.58	
QC Comp. Str., psi	78	629	NSD	5902	NSD
QA Comp. Str., psi	99	539		5737	

Target Slump = 4in Target Air = 4% Minimum 28 day comp. str. = 3500psi

Comparisons in Table 10 indicate no significant differences in variability or estimates of target values for contractor and Alabama DOT tests. These comparisons, however, should be viewed in light of the following facts:

- Contractor tests were not used for acceptance and each pour was accepted based on Alabama DOT tests.
- Slump and entrained air are relatively quick tests and were run, side-by-side and simultaneously, at ready mix truck discharges.
- Cylinder fabrication is a process offering few, if any, opportunities to improve strength but numerous opportunities to impair strength.
- Separate, but side-by-side, initial (24 hour) curing facilities were provided on site for contractor and Alabama DOT cylinders.

- Concrete was purchased by the contractor from a ready mix supplier.
- Substructure construction required about 5 months for completion and was comprised of numerous pours.

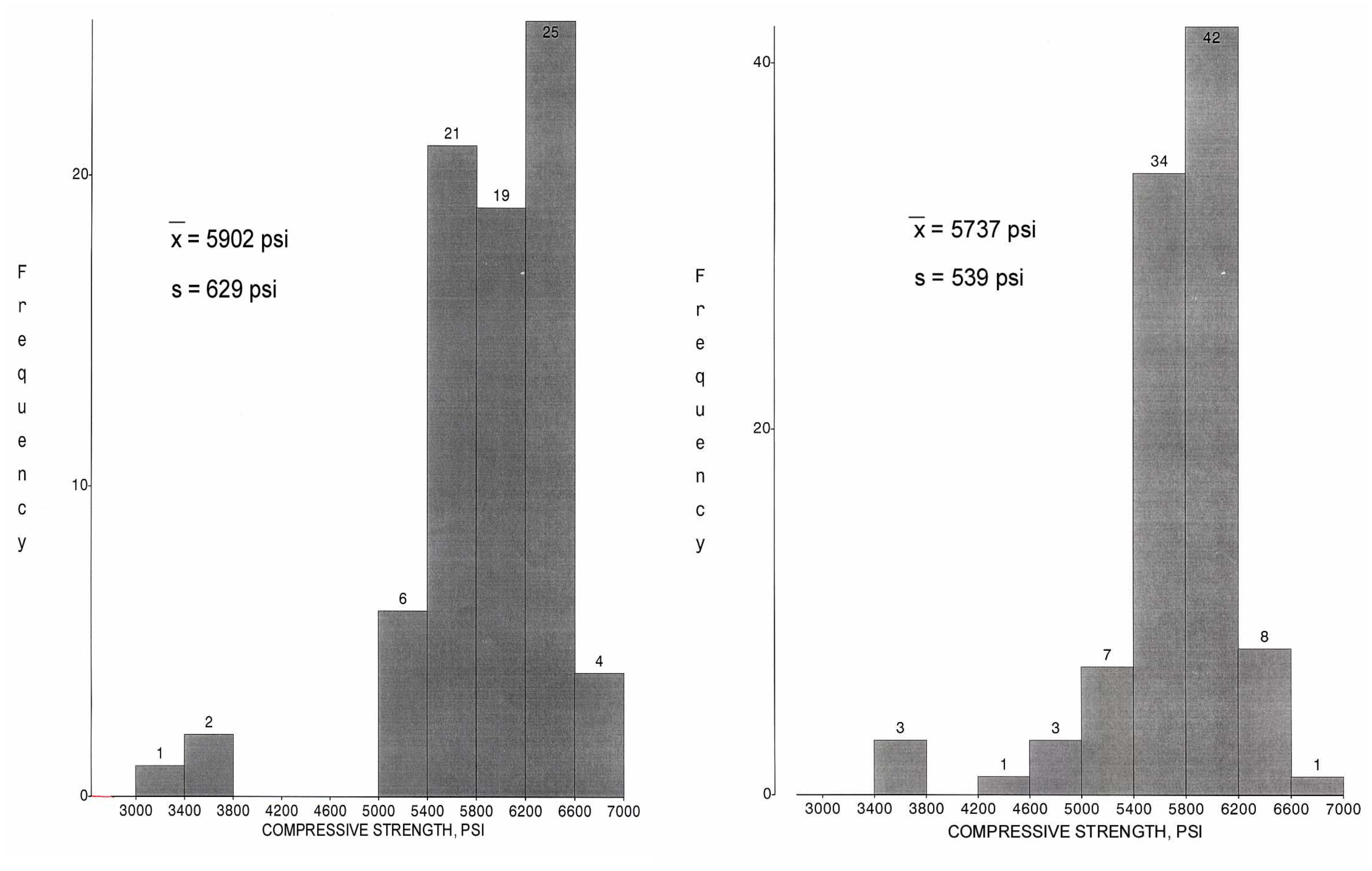
The first four facts should promote comparable test results. Contractor and Alabama DOT slump and air content test results were immediately compared. After initial 24 hour curing, cylinders were transported to separate facilities for final (28 day) curing and testing, but all other sampling, preparation, and testing conditions were similar.

The last two factors are quite different from HMAC. Unlike HMAC where the contractor is also the producer, bridge contractors normally purchase concrete from local ready mix suppliers. This introduces another organization into the system where risk assignment must be considered. The motivation for the contractor in this system is the same as the DOT in a two organization system, i.e., to make sure the quality of the concrete purchased from the ready mix supplier is adequate.

Unlike HMAC where production and placement are relatively continuous, bridge substructure PCC placement can be quite sporadic over an extended period of time. This certainly affects the ability of a ready mix supplier to produce a consistent product. Finally, the “usual” method of acceptance leads to a very conservative approach for meeting strength requirements. The “usual” method of accepting a “pour” requires that average 28-day strength of cylinders be greater than a minimum compressive strength.

Table 10 indicates that mean strengths are much larger than the required minimum 3500 psi, 28-day compressive strength. This may seem overly conservative but, as illustrated in Figure 12, is reasonable in view of the risk inherent in the supply and acceptance systems. Figure 12 shows histograms for the compressive strength data in Table 10. Both histograms show three strengths near minimum strength. These six low strengths were for one pour and show that, considering the consequences of finding out that concrete strength is unacceptable after 28 days, the high mean strengths may indeed be reasonable. Removal and replacement of hardened concrete is a costly exercise that is avoided at all costs.

PCC construction is much less likely than HMAC construction to be controlled with a statistically-based quality assurance process. As noted above, there are reasons for this circumstance. Slump and entrained air content essentially serve as surrogate acceptance tests. They are relatively quick and easy to run and sampling and testing are easily observable on site. But the single most important factor appears to be the 28 days required before definitive acceptance data is available. This time lag increases risk and has the potential to severely strain contractor-state DOT relationships. The introduction of the ready mix producer into the system can also potentially complicate the contractor-state DOT relationship.



a. Contractor Data

b. Alabama DOT Data

Figure 12. Compressive Strength Data for Substructure Portland Cement Concrete

Kentucky Transportation Cabinet Hot Mix Asphalt Concrete and Portland Cement Concrete Tests

Hancher, et al (3) compare contractor and Kentucky Transportation Cabinet measurements of properties of hot-mix asphalt concrete, paving PCC, and structural PCC. The properties compared are asphalt content, air void content, and VMA for HMAC and air content, slump, and strength for both paving and structural PCC. Table 11 contains results from statistical comparisons (5% significance level). It is noted that Table 11 was prepared from information extracted from Reference 3, but that a table in Reference 17 developed, presumably, from the same data has some different p-values and, thus, some different comparisons.

The variability of Kentucky Transportation Cabinet hot-mix asphalt concrete air void content and asphalt content tests are significantly larger than the variability of contractor tests. The variability of VMA tests are not significantly different but the variability of the Kentucky Transportation Cabinet tests are larger. The means for the three HMAC properties were not significantly different.

The paving concrete air content and slump variabilities are significantly different and contractor variabilities are larger. Means of slump and strength are significantly different and Kentucky Transportation Cabinet means are larger. It should be noted that the slump means exceed the specification target range of 1½ to 2 inches and may have been switched with values for structural concrete (Class A target range of 2-4 inches).

Table 11. Comparisons Between Kentucky Transportation Cabinet and Contractor Tests

Property	n_{KTC}	n_{CONT}	s_{KTC}	s_{CONT}	Diff.	p-Value	$\bar{X}_{KTC}$	$\bar{X}_{CONT}$	Diff.	p-Value
HMA-Air Voids (%)	1827	1818	0.978	0.853	SD	<0.001	4.063	4.086	NSD	0.462
HMA - % Asphalt (%)	3082	3082	0.210	0.152	SD	<0.001	-0.007	-0.007	NSD	0.851
HMA-VMA (%)	422	422	1.037	0.940	NSD	0.083	1.255	1.267	NSD	0.854
PCCP – Air (%)	92	428	0.710	0.920	SD	0.004	5.530	5.500	NSD	0.792
PCCP – Slump (in)	92	428	0.836	1.399	SD	<0.001	3.407	2.669	SD	<0.001
PCCP – Strength (psi)	92	421	876	889	NSD	0.854	5676	5366	SD	0.002
PCCS – Air (%)	67	245	0.788	0.815	NSD	0.480	5.727	5.591	NSD	0.223
PCCS – Slump (in)	67	245	0.542	0.589	NSD	0.680	1.795	1.829	NSD	0.669
PCCS – Strength (psi)	67	242	624	622	NSD	0.766	5926	6032	NSD	0.219

None of the variabilities or means of the structural concrete properties are significantly different. There is also no particular tendency for the Kentucky Transportation Cabinet or contractor statistics to be larger. The slump means seem more consistent with requirements for paving concrete (1½ - 2 inches).

The general trends exhibited by the comparisons of the HMAC and structural PCC tests are similar to trends for comparisons of Alabama DOT tests.

SUMMARY

The findings of the review of the state-of-practice for using contractor-performed tests in quality assurance can be summarized as follows:

- There is great diversity in how state DOTs use contractor-performed tests for quality assurance.
- Contractor-performed tests are most used in the quality assurance process for hot-mix asphalt concrete. Other materials, in order of level of use, are PCC (pavements and structures), granular base and earthwork. The use for earthwork is quite limited.

- When construction of one of the materials listed above is controlled with a quality assurance process as currently defined, the use of contractor-performed tests for process (quality) control is widespread and well accepted.

- There is no consensus as to how contractor-performed tests can be best used in the acceptance process.

- Verification that contractor-performed tests provide the same measure of material quality as state DOT-performed tests is a major impediment to the use of contractor-performed tests in the acceptance process.

- Contractor and state DOT-performed tests may provide different measures of material properties. This is most likely for HMAC properties and least likely for properties of PCC. No comparisons of granular base or earthwork properties were found.

CHAPTER 3: COMPARISONS OF CONTRACTOR-PERFORMED AND STATE DOT-PERFORMED TESTS

INTRODUCTION

HMAC test results were collected and analyzed from six state DOT's. Details of verification and acceptance procedures for these six state DOT's are contained in Table 12. Also included in Table 12 are details of procedures for the Alabama DOT and the Kentucky Transportation Cabinet. This information is provided to connect these analyses with the analysis of test results from Alabama and Kentucky discussed in Chapter 2.

The verification and acceptance procedures described in Table 12 provide a range of details that might affect comparisons of contractor and state DOT-performed tests. Ratios of number of contractor to number of state DOT tests range from 2 to 1 to 20 to 1. Simple 1 to 1 comparisons of test results are used by three state DOT's to verify contractor-performed tests. More statistically robust comparisons of variances and means with F and t tests are used by three state DOT's. Pay adjustments are applied by all six state DOT's, but are applied as a last resort for mix properties by the North Carolina DOT. The North Carolina DOT acceptance procedure for HMAC mix properties is basically an accept/reject procedure based on monitoring with control charts of both North Carolina DOT and contractor-performed tests. LOT size varies from 2000 tons or a day's production to the entire project production. Acceptance is based on verified contractor tests or combined DOT and verified contractor tests. When contractor-performed tests are not verified, acceptance is based on state DOT tests. Acceptance criteria may be deviations from targets, absolute deviations from targets or deviations from targets and variability with the percent within limits (PWL) method. The weighted average LOT pay factor for all properties considered is applied by three state DOT's. The lowest pay factor from all properties considered or the pay factors for all properties considered are applied by three state DOT's.

PCC pavement strength data was collected and analyzed from the Colorado DOT and granular base course data was collected and analyzed from the FHWA-WFLHD. Details of verification and acceptance procedures are contained in Table 13. Details for Kentucky Transportation Cabinet PCC procedures are also included in Table 13 to provide a connection with analyses discussed in Chapter 2.

Tests results generated during an entire construction season for a particular material were requested from state DOT's. Some provided the requested data, some provided partial data from a construction season, and some provided limited data from several construction seasons. This resulted in a wide range in the size of data sets. Examples are presented below.

The North Carolina DOT provided HMAC tests for 735 mix designs from the 2004 construction year. This gave data sets with over 14,000 contractor mix tests, over 2000 North Carolina DOT mix tests, over 20,000 contractor mat density tests and over 6,000 North Carolina DOT mat density tests.

The Florida DOT provided HMAC tests from 98 selected projects constructed during the 2003 and 2004 construction years. This gave data sets with over 2000 contractor mix tests, over 500

Table 12. Details of Hot-Mix Asphalt Concrete Verification and Acceptance Procedures

State DOT	Properties	Cont. to DOT Testing Freqency	Verification Comparisons	Acceptance Method	Lot Size	Acceptance Data	Acceptance Criteria	Pay Factor Application
Georgia	AC, Gradation	4 to 1[2]	1 to 1	Adjust Pay	Days Production	Contractor	Absolute Deviation from Targets	Lowest[3] Pay
Florida	AC, VTM, Gradation, Mat Density	4 to 1 and 8 or 12 to 1	1 to 1	Adjust Pay	2000 or 4000 tons[1]	Contractor	PWL	Weighted Average
North Carolina	AC, VTM, VFA, Gradation, Mat Density	10 to 1 and 20 to 1	1 to 1	Adjust Pay[4]	Mix-Indefinite Mat Density-Days Production	Contractor[4] and DOT	Deviations from Target	Lowest[4] Mix Pay and Mat
Kansas	VTM, Mat Density	Mix 4 to 1 Mat 2 to 1	F and t Tests	Adjust Pay	Mix-3000[T] Mat Density–Days Production	Contractor	PWL	Both[5] Mix and Mat
California	AC, Gradation, Mat Density	10 to 1	t Test and 1 to 1	Adjust Pay	Project Production	Contractor	PWL	Weighted Average
New Mexico	AC, VTM, Gradation, Mat Density	3 to 1	F and t Tests	Adjust Pay	Project Production	Contractor and DOT	PWL	Weighted Average
Alabama	AC, VTM, Mat Density	Mix 3 to 1[6] Mat 2 to 1	1 to 1	Adjust Pay	2800 tons[6]	Contractor	Absolute Deviation From Targets	Lowest
Kentucky	AC, VTM, VMA	4 to 1	1 to 1	Adjust Pay	4000 tons	Contractor	Deviations from Targets	Weighted Average[3,7]

Notes:

1. Contractor chooses 2000 or 4000 ton LOTs for acceptance.
2. Will vary based on production rate but data provided indicates about 4 to 1.
3. Mat density pay adjustments are included but are based on state DOT tests.
4. Pay adjustments (reduction only) applied independently for mix properties and mat density. Control charts with both contractor and DOT test results used to control mix production process and to decide when pay reductions applied. Mix pay reductions appear to be a last resort. Mat density pay computed for each LOT.
5. Mix pay factor based on VTM and mat density pay factor applied independently.
6. Definition of a LOT(tonnage or time basis) has varied and, therefore, the mix contractor to ALDOT testing ratio has varied. The 3 to 1 ratio and 2800 ton LOT are approximate. The 2 to 1 mat density testing ratio has been constant.
7. Pay factors are computed for each property for each 1000 ton subLOT. LOT averages are computed for each property and weighting factors applied to compute an overall LOT pay factor.

Table 13. Details of PCC and Granular Base Course Verification and Acceptance Procedures

Agency	Material	Properties	Cont. to Agency Testing Frequency	Verification Comparisons	Acceptance Method	LOT Size	Acceptance Data	Acceptance Criteria	Pay Factor Application
Colorado DOT	PCC Pavement	Flexural Strength	4 to 1	F and t Tests	Adjust Pay	Project Production	Contractor	PWL	-
Kentucky Transportation Cabinet	PCC	Slump, Air and Compressive Strength	4 to 1	1 to 1	Adjust Pay	Structural 200cy Pavement 4000sy	Contractor	PWL	Weighted Average (Air and Comp. Str.)
FHWA-WFLHD	Granular Base	Gradation, LL, PI, % Fractured Particles and SE/P200	10 to 1 after first 3 for a project[1]	F and t Tests	Adjust Pay	Project Production	Contractor	PWL	Lowest[2]

1. Data provided indicates this results in an average testing frequency ratio of about 3 to 1.

2. Pay adjustment for density also included but based only on contractor-performed tests. FHWA-WFLHD witnesses density testing.

Florida DOT mix tests, over 6000 contractor mat density tests and over 1400 Florida DOT mat density tests.

The Colorado DOT provided PCC pavement flexural strength tests from 3 projects constructed in 2000, 2001 and 2003, respectively. The total data sets were comprised of 221 contractor tests and 61 Colorado DOT tests.

STATISTICAL ANALYSIS TECHNIQUES

Variability and proximity to target or limiting values (means) of contractor-performed and state DOT-performed tests were statistically compared. Variability, as measured with variance, was compared with F tests. The proximity to target or limiting values, as measured with means of differences between test results and target or limiting values, were compared with t tests. Means for contractor and state DOT tests from split samples were compared with paired t tests.

Mean square deviations (MSD) provide a way to evaluate process control that considers both accuracy and variability of the process. Mean square deviations for contractor and state DOT tests were compared to determine which indicates the best material quality (process control).

Statistical comparisons were made at a 1% level of significance ($\alpha=0.01$). This is certainly arbitrary but provides a stronger determination of differences than the more widely used 5% level of significance ($\alpha=0.05$).

All data provided by a state DOT for a particular material were combined for analyses. Some properties have target values that vary by project or job mix formula, for example asphalt content for HMAC. Therefore, it was necessary to subtract target values from measurements ($\Delta=X-X_T$) to produce a variable that could be combined for all mixes or projects. For consistency, this practice was followed for all properties, i.e., those with constant target values also.

Data from small projects ($n_{DOT} < 6$) were eliminated to produce reduced data sets. Data from these larger projects were combined and analyzed to see if project size might affect comparisons. In addition, comparisons and analyses were conducted for these larger projects ($n_{DOT} \geq 6$) on a project by project basis, i.e., variability and means for contractor and state DOT were compared for each project or, for the North Carolina DOT, for each job mix formula.

SAMPLING AND TESTING CAPABILITIES

When comparing contractor and state DOT tests there is always the issue of possible differences in technician capabilities. Technician motivation can also be an issue but will be addressed later. The federal regulation “23 CFR 637B” includes requirements for laboratory and sampling and testing qualifications for tests that will be used for acceptance decisions. The regulation states that state DOT central laboratories and non-state DOT laboratories involved with independent assurance or dispute resolution sampling must be accredited by the AASHTO Accreditation Program or comparable laboratory accreditation program approved by the FHWA. The regulation also states that sampling and testing personnel will be qualified. However, the issue related to comparisons of tests is equal contractor and state DOT technician qualifications.

Hughes (9) discusses technician and laboratory requirements with consideration of the terms “qualified” and “certified”. The discussion of technician qualifications is summarized as follows:

> “It is generally understood that technicians must be qualified and that one way to ensure this is to require them to have undergone some form of certification.”

Specifications for the state DOT’s in Tables 12 and 13 contain language that requires some form of certification for contractor technicians. Specifications may contain language indicating the same requirements for DOT technicians, but this is not the case in all states. In these states it is policy that state DOT technician requirements are the same as contractor technicians requirements, even though, this may not be explicitly stated in specifications. The one exception to the equal technician qualification requirement is the FHWA-WFLHD. The FHWA-WFLHD laboratory is AASHTO accredited but contractor technicians must simply “be qualified”.

Because contractor and state DOT technicians have the same qualification requirements and because of the requirement for independent assurance sampling and testing, possible differences in sampling and testing will not be included as a factor when analyzing comparisons. Certainly there are individual differences in technician and laboratory capabilities, but there in no practical way that these differences might be considered when comparing contractor and state DOT tests.

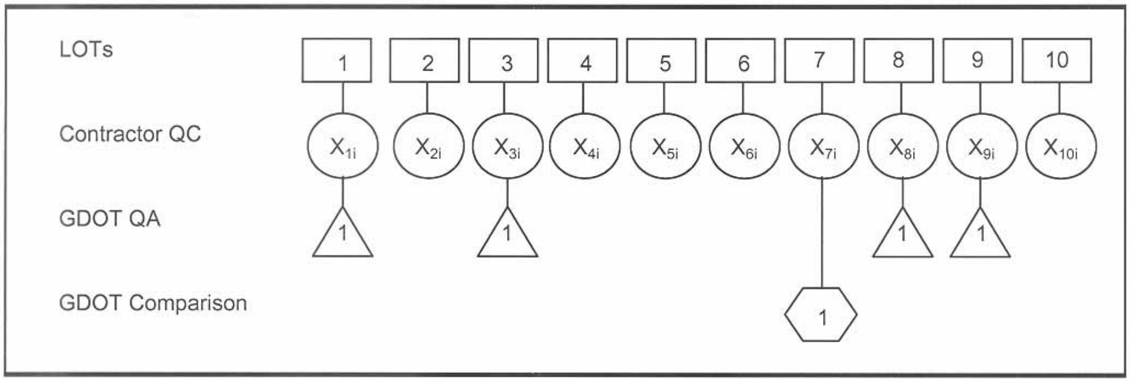
ANALYSIS OF GEORGIA DOT HOT MIX ASPHALT CONCRETE DATA

Test results obtained for HMAC during the 2003 construction year were analyzed. Properties include gradation (% passing 1”, ¾”, ½”, 3/8”, #4, #8, #50 and #200 sieves) and asphalt content measured with either the vacuum solvent extraction or ignition methods. Mat density is also used in the acceptance process, but only Georgia DOT testing is required. Figure 13 illustrates the Georgia DOT sampling and testing requirements for managing the production of HMAC. A LOT is a day's production and contractor QC samples are taken and tested for each 500 ton subLOT. Results from these tests are used for LOT acceptance if verified by Georgia DOT Comparison test results.

Georgia DOT Comparison tests are the type of testing often called "verification" in the vernacular of many state DOTs and Reference 1. Comparison samples are split from the contractor's QC samples for one of every 10 LOTS and results are compared one to one.

Georgia DOT also tests what is referred to as a QA sample from two of every five LOTs. The samples are obtained independently of contractor samples and results are compared with specification mix tolerances. It appears the purpose of this testing may be to satisfy "23 CFR 637B" requirements for validating the quality of material.

When Georgia DOT comparison test results do not validate contractor QC tests results and/or when Georgia DOT QA test results do not compare favorably with specification mix tolerances, additional testing is conducted. If additional testing does not resolve unfavorable comparisons, contractor QC test results may be replaced with Georgia DOT test results for acceptance of the LOTs where comparisons were unfavorable.



Notes:

1. A LOT is 1 days production.
2. Contractor QC: 1 test per 500 ton subLOT. There may be multiple tests per LOT.
3. GDOT QA: 1 test each for 2 of 5 LOTs. Results compared with specification tolerances.
4. GDOT Comparison: 1 test for 1 of 10 LOTs. Results compared one to one with contractor QC results - numerical criteria.
5. Contractor QC and GDOT Comparison tests on split samples. GDOT QA tests on independent samples.

Figure 13. Georgia DOT HMAC Mix Sampling and Testing Requirements

The first comparison will be between means of contractor QC and Georgia DOT Comparison test results with the paired t test. Results are summarized in Table 14. The strength or significance of comparisons are indicated by the p-values from the hypothesis testing. The comparisons indicate significant differences in deviation from targets for only 4 of 8 sieves. However, for the 4 sieves used for pay adjustment computation, differences are significant for 3 sieves. Numerically, mean deviations from targets are larger for Georgia DOT tests for only 5 of 8 sieves. But, for the 4 sieves used for pay adjustment computation, deviations for Georgia DOT tests are always larger (as noted above, significantly so for 3 of 4 sieves). The deviations from target asphalt contents are not significantly different, but the deviations for Georgia DOT tests are larger.

Although not a part of the paired t tests for means, the variances for contractor and Georgia DOT gradation tests were compared with the F test. These comparisons are summarized in Table 15. The variances were significantly different for only 4 of the 8 sieves. However, for the 4 sieves used in pay adjustment computation, 3 variances were significantly different. Numerically, the variances for Georgia DOT gradation tests were larger for 7 of 8 sieves. The variance for the Georgia DOT asphalt content tests was significantly larger than the variance for contractor tests.

Table 14. Comparison of Georgia DOT Comparison and Contractor QC Test Result Means

Property	n	$\overline{\Delta}_{GDOT}$, %	$\overline{\Delta}_{CONT}$, %	Difference	p-value	Pay
% Pass 1”	395	0.258	0.295	NSD	0.462	NO
% Pass $\frac{3}{4}$”	791	0.398	0.469	NSD	0.166	NO
% Pass $\frac{1}{2}$”	1067	0.314	0.118	SD	0.002	YES
% Pass $\frac{3}{8}$”	953	0.516	0.329	SD	0.005	YES
% Pass #4	402	0.506	0.392	NSD	0.128	YES
% Pass #8	1142	0.449	0.244	SD	<0.001	YES
% Pass #50	282	0.897	0.763	NSD	0.094	NO
% Pass #200	1141	0.334	0.447	SD	<0.001	NO
% Asphalt	1135	0.005	0.002	NSD	0.634	YES

Table 15. Comparison of Georgia DOT Comparison and Contractor QC Test Result Variances

Property	n	S^2_{GDOT}	S^2_{CONT}	Difference	p-value	Pay
% Pass 1”	395	1.527	1.363	NSD	0.131	NO
% Pass $\frac{3}{4}$”	791	4.410	3.831	NSD	0.024	NO
% Pass $\frac{1}{2}$”	1067	9.343	6.576	SD	<0.001	YES
% Pass $\frac{3}{8}$”	953	8.479	5.545	SD	<0.001	YES
% Pass #4	402	9.450	8.606	NSD	0.175	YES
% Pass #8	1142	8.673	6.561	SD	<0.001	YES
% Pass #50	282	3.971	4.004	NSD	0.472	NO
% Pass #200	1141	1.137	0.791	SD	<0.001	NO
% Asphalt	1135	0.088	0.045	SD	<0.001	YES

Scatter diagrams, with lines of equality, were plotted for the eight sieves and asphalt content to provide additional insight into the relationship between contractor and Georgia DOT test results from split samples. Examples for % passing the 3/8-inch sieve and asphalt content, Figures 14 and 15. Although somewhat difficult to visualize, the scatter diagram confirm the larger means and variances of contractor-performed tests in Tables 14 and 15. More revealing is the distribution of points that are some distance from the origin but near the horizontal axis, i.e., large Δ_{GDOT} and small Δ_{CONT}. These points are potentially troublesome because contractor test results indicate small deviations from JMF targets which are not corroborated by Georgia DOT test results. It is large deviations from JMF targets that create issues with acceptance.

Table 16 summarizes comparisons between contractor QC and Georgia DOT QA test results. These test results are from independent samples and one to one comparisons, with the paired t test, are not appropriate. Variances were compared with F tests and means were compared with t or modified t tests, as required by equality of variances. It should be noted that the contractor QC test results compared with Georgia DOT Comparison test results in Tables 14 and 15 are a subset of the total contractor QC test results data set.

Table 16 indicates that, except for the % passing the 1 and ¾-inch sieves, the variances of Georgia DOT test results are significantly larger than variances of contractor test results. However, Table 16 indicates no significant differences in the means of any of the test results. The Georgia DOT means for the percents passing the 4 sieves used for pay are larger, but the contractor mean for asphalt content is larger.

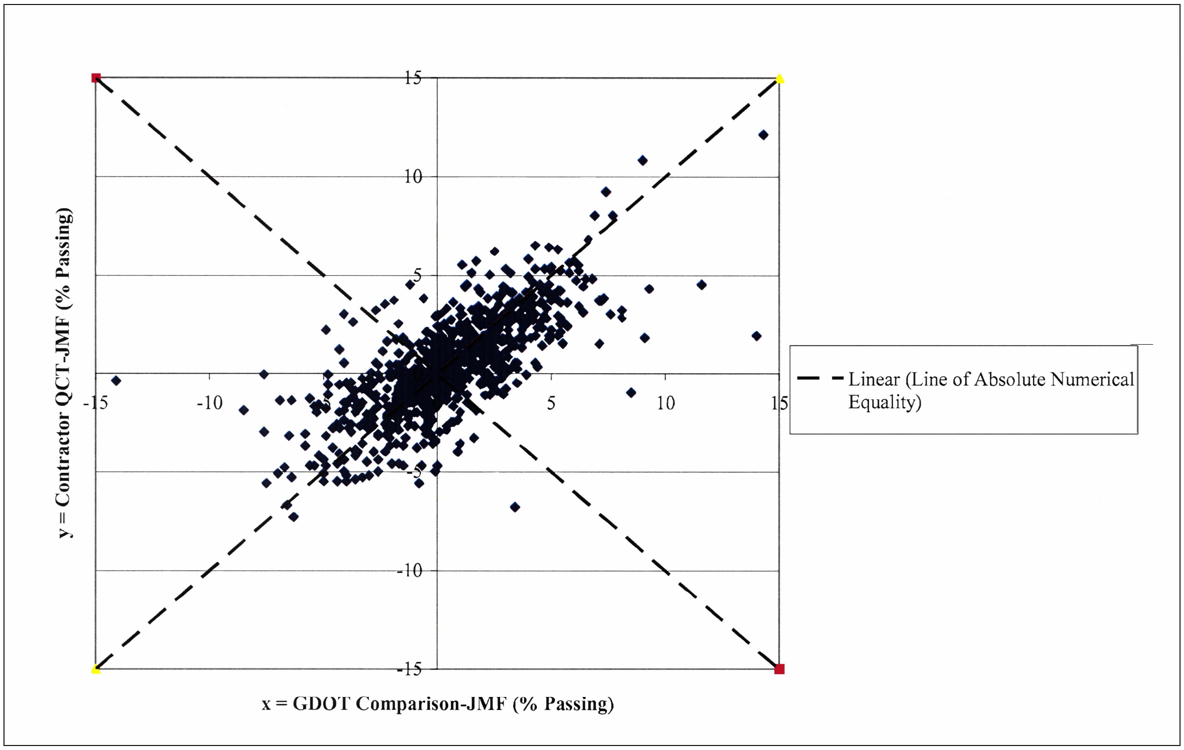


Figure 14. Scatter Diagram for Percent Passing the 3/8" Sieve - GDOT

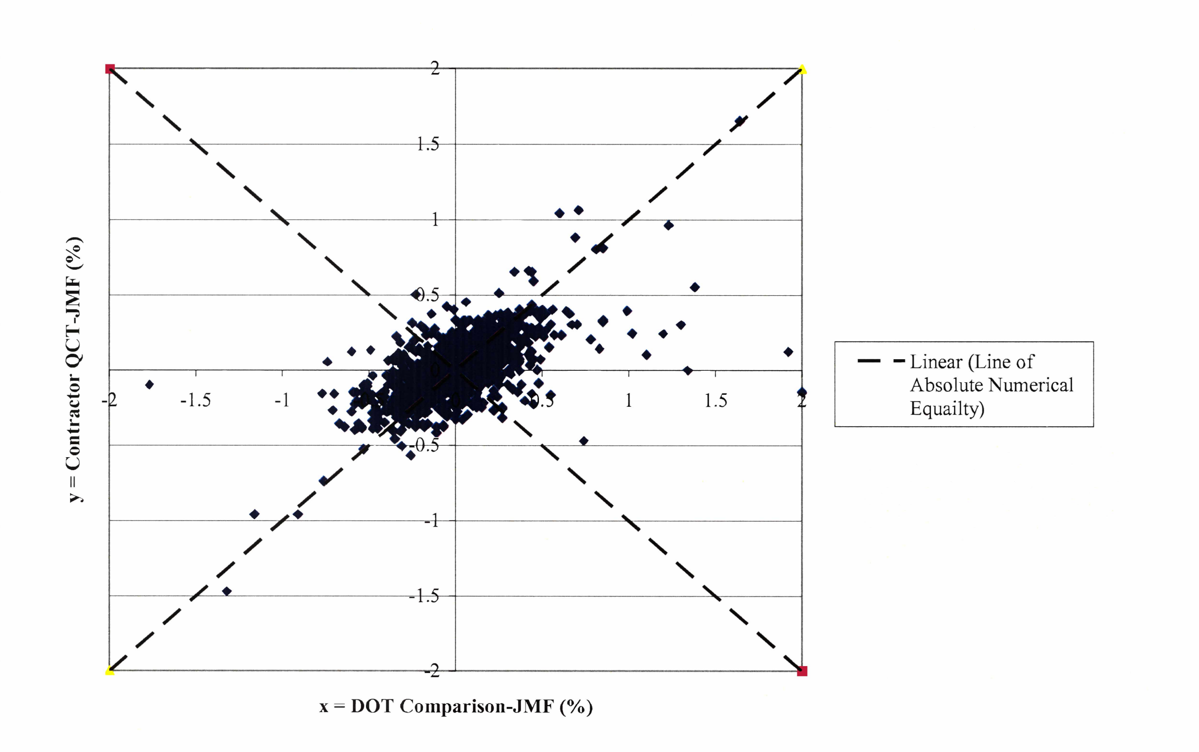


Figure 15. Scatter Diagram for Asphalt Content - GDOT

Table 16. Comparison of Georgia DOT QA and Contractor QC Test Results – All Projects

Property	n_{GDOT}	n_{CONT}	s^2_{GDOT}	s^2_{CONT}	**Difference**	**p-value**	$\overline{\Delta}_{GDOT}$ **, %**	$\overline{\Delta}_{CONT}$ **, %**	**Difference**	**p-value**	**Pay**
% Pass 1”	832	4775	1.425	1.296	NSD	0.034	0.187	0.184	NSD	0.941	NO
% Pass $\frac{3}{4}$”	1637	9444	4.167	4.378	NSD	0.099	0.418	0.535	NSD	0.036	NO
% Pass $\frac{1}{2}$”	2323	13157	6.793	5.565	SD	<0.001	0.196	0.160	NSD	0.530	YES
% Pass $\frac{3}{8}$”	2099	11587	6.605	6.044	SD	0.004	0.246	0.231	NSD	0.805	YES
% Pass #4	1050	5532	9.959	7.707	SD	<0.001	0.320	0.293	NSD	0.792	YES
% Pass #8	2488	14051	9.488	5.534	SD	<0.001	0.253	0.196	NSD	0.380	YES
% Pass #50	749	4047	4.139	3.334	SD	<0.001	0.727	0.837	NSD	0.170	NO
% Pass #200	2488	14036	1.212	0.769	SD	<0.001	0.359	0.400	NSD	0.082	NO
% Asphalt	2487	14061	0.064	0.040	SD	<0.001	0.004	0.005	NSD	0.827	YES

Mean square deviation (MSD) provides a method for considering both accuracy (proximity to target) and precision or variability in evaluating measurements. For the nominal is best (NIB) situation, where test results may be either larger or smaller than targets, the MSD is computed with

$$MSD_{NIB} = \frac{\sum_{i=1}^{n} \left(X_i - X_T \right)^2}{n} \quad \text{..(1)}$$

where X_i = test results,

X_T = target, and

n = number of measurements.

For large n values this can be written as

$$MSD_{NIB} = s^2 + \left(\overline{X} - X_T \right)^2 \quad \text{..(2)}$$

where s^2 = variance of tests and

$\overline{X}$ = mean of tests.

The variable used to combine tests with different target values is the difference between tests and target values. Therefore, the most desirable value is always zero and the equation for MSD_{NIB} reduces to

$$MSD_{NIB} = s^2 + \left(\overline{\Delta} \right)^2 \quad \text{..(3)}$$

where $\overline{\Delta}$ = mean of difference between tests and target values. Smaller MSD_{NIB} values for manufacturing processes mean better control. When comparing MSD_{NIB} values for two sets of test results for the same process, smaller MSD_{NIB} indicate more precise tests with closer conformity to target values.

Table 17 contains MSD_{NIB} for the set of contractor QC tests, the set of Georgia DOT Comparison tests and the set of Georgia DOT QA tests. Values for contractor QC tests are smallest for all properties except percent passing the ¾" sieve. Implications are that contractor tests are consistently more precise and closer to target values.

The MSD_{NIB} for Georgia DOT QA tests are closer to MSD_{NIB} for contractor QC tests for percents passing 4 sieves and asphalt content. The MSD_{NIB} for Georgia DOT Comparison test results are closer to MSD_{NIB} for contractor QC tests for percents passing 4 sieves. This is surprising because Georgia DOT Comparison and contractor QC samples are split samples and test results are directly compared one to one. It is reasonable to assume that this would promote similarities. Georgia DOT QA test results are from independent samples and results are compared to acceptance criteria. It may be that this more direct relationship with the acceptance process is the reason contractor QC and Georgia DOT QA tests are more comparable than contractor QC and Georgia DOT Comparison tests.

It should be noted that variance and, therefore, measurement precision dominates the computation of MSD_{NIB}. Target values are zero and means for the differences from targets, when squared, are small. Except for percent passing the #50 sieve for Georgia DOT Comparison and QA tests, comparisons of variances would provide the same relative rankings as MSD_{NIB}.

Table 17. Comparison of Mean Square Deviations

Property	MSD_{NIB}		
	Contractor QC	GDOT Comp.	GDOT QA
% Pass 1”	1.330	1.594	1.460
% Pass $\frac{3}{4}$”	4.664	4.559	4.342
% Pass $\frac{1}{2}$”	5.591	9.442	6.831
% Pass $\frac{3}{8}$”	6.097	8.745	6.666
% Pass #4	7.793	9.706	10.061
% Pass #8	5.572	8.875	9.552
% Pass #50	4.035	4.768	4.668
% Pass #200	0.929	1.249	1.341
% Asphalt	0.040	0.088	0.064

The preceding analyses were performed on databases containing all test results collected during the 2003 construction season. From these databases, projects with at least 6 Georgia DOT QA tests or 6 Georgia DOT Comparison tests for asphalt content, % passing the ½ inch sieve, and % passing the #200 sieve were identified. Databases from these projects with $n_{GDOT} \geq 6$ were compiled and their variabilities and means compared. In addition, variabilities and means for individual projects were compared.

It should be noted that the format in which data were provided by the Georgia DOT made sorting by project somewhat tedious and was the reason only three properties were selected. Sorting by project or job mix formula of the data provided by other states was somewhat easier. As a result, data for all properties are included in similar analyses for these states that are presented in following sections.

Comparisons of reduced database variances and means for Georgia DOT QA and Contractor QC tests are summarized in Table 18. Comparisons of reduced database variances and means for Georgia DOT Comparison and Contractor QC tests are summarized in Table 19. The variances and means are similar to those for all projects in Tables 14-16. Comparisons in Tables 18 and 19 are also similar to comparisons in Tables 14-16. The only difference is for the means of the % passing the ½” sieve for the Georgia DOT Comparison and contractor QC tests. In Table 14 the means for all projects are significantly different, but in Table 19 the means for the larger project are not significantly different.

Table 18. Comparison of Georgia DOT QA and Contractor QC Test Results – Projects with $n_{GDOT} \geq 6$

Property	Projects	n_{GDOT}	n_{CONT}	s^2_{GDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{GDOT}$, %	$\overline{\Delta}_{CONT}$, %	Difference	p-Value
% Asphalt	114	1410	8453	0.058	0.040	SD	<0.001	0.011	0.010	NSD	0.638
% Pass ½”	114	1385	8072	7.701	6.439	SD	<0.001	0.146	0.208	NSD	0.433
% Pass #200	126	1565	8908	1.210	0.741	SD	<0.001	0.310	0.367	NSD	0.051

Table 19. Comparison of Georgia DOT Comparison and Contractor QC Test Results – Projects With $n_{GDOT} \geq 6$

Property	Projects	n	s^2_{GDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{GDOT}$, %	$\overline{\Delta}_{CONT}$, %	Difference	p-Value
% Asphalt	41	452	0.097	0.053	SD	<0.001	0.018	0.010	NSD	0.148
% Pass ½”	35	400	12.286	9.251	SD	0.005	0.462	0.200	NSD	0.023
% Pass #200	45	470	0.997	0.631	SD	0.719	0.159	0.278	SD	0.003

Project by project comparisons of Georgia DOT and contractor tests for asphalt content and % passing the ½” and #200 sieves are summarized in Tables 20 and 21. This analysis will quantify the numbers of projects where there are significant differences between Georgia DOT and contractor means and variances, and the numbers of projects where Georgia DOT means and variances are largest. The comparisons generally confirm trends indicated by comparisons of combined tests, i.e., that variability of Georgia DOT tests are likely larger than the variability of contractor tests, but that means of Georgia DOT tests are less likely larger than means of contractor tests.

Except for asphalt content, the percentages in column 3 of Tables 20 and 21 indicate no particular tendency for Georgia DOT or contractor tests to be closer to target values. The percentages in column 4 indicate no strong tendency for means of differences from targets to be significant but, when differences are significant, the percentages in column 5 indicate Georgia DOT means are likely larger.

The percentages in column 6 indicate Georgia DOT variances are likely larger. The percentages in column 7 indicate that variances are more likely significantly different than means (column 4). When variances are significantly different, the percentages in column 8 indicate Georgia DOT variances are likely larger.

Table 20. Project by Project Comparisons of Georgia DOT QA and Contractor QC Test Results

Property	Projects	Projects with Larger GDOT $\lvert\bar{\Delta}\rvert$	Projects with SD $\bar{\Delta}$	Projects with Significantly Larger GDOT $\lvert\bar{\Delta}\rvert$	Projects with Larger GDOT s^2	Projects with SD s^2	Projects with Significantly Larger GDOT s^2
% Asphalt	114	68 (60%)	8 (7%)	6 (5%)	77 (68%)	12 (10%)	10 (9%)
% Pass $\frac{1}{2}$”	114	61 (54%)	3 (3%)	3 (3%)	62 (54%)	13 (11%)	10 (9%)
% Pass #200	126	52 (41%)	11 (9%)	5 (4%)	81 (64%)	15 (12%)	13 (10%)

Table 21. Project by Project Comparisons of Georgia DOT Comparison and Contractor QC Test Results

Property	Projects	Projects with Larger GDOT $\lvert\bar{\Delta}\rvert$	Projects with SD $\bar{\Delta}$	Projects with Significantly Larger GDOT $\lvert\bar{\Delta}\rvert$	Projects with Larger GDOT s^2	Projects with SD s^2	Projects with Significantly Larger GDOT s^2
% Asphalt	41	27 (66%)	1 (2%)	0	35 (85%)	1 (2%)	1 (2%)
% Pass $\frac{1}{2}$”	35	16 (46%)	0	0	21 (60%)	2 (6%)	2 (6%)
% Pass #200	35	21 (47%)	2 (4%)	2 (4%)	34 (76%)	3 (7%)	3 (7%)

Numbers in parentheses are percentages of total numbers of projects.

Plots of project means and variances were made to graphically illustrate the trends summarized in Tables 20-21. A complete set of these plots are contained in Appendix A. Figures 16 and 17 are for asphalt content and with row 1 of Table 20 will be used to illustrate interpretation of the plots. The 114 points on Figures 16 and 17 represent the projects where $n_{GDOT} \geq 6$.

The Georgia DOT means are larger for 68 (60%) of the projects and these plot in the half of Figure 16 defined by the lines of absolute equality that is centered about the horizontal axis. The means for 8 (7%) of the projects are significantly different and are represented by points close to the vertical or horizontal axes. The Georgia DOT means are significantly larger for 6 (5%) projects and are represented by points close to the horizontal axis.

The Georgia DOT variances are larger for 77 (68%) of the projects and these points plot below the line of equality in Figure 17. The variances are significantly different for 12 (10%) of these projects, and for 10 (9%) of these projects, the Georgia DOT variances are larger. The distribution of the points below the line of equality and along the horizontal axis in Figure 17 clearly illustrate the larger Georgia DOT test variability.

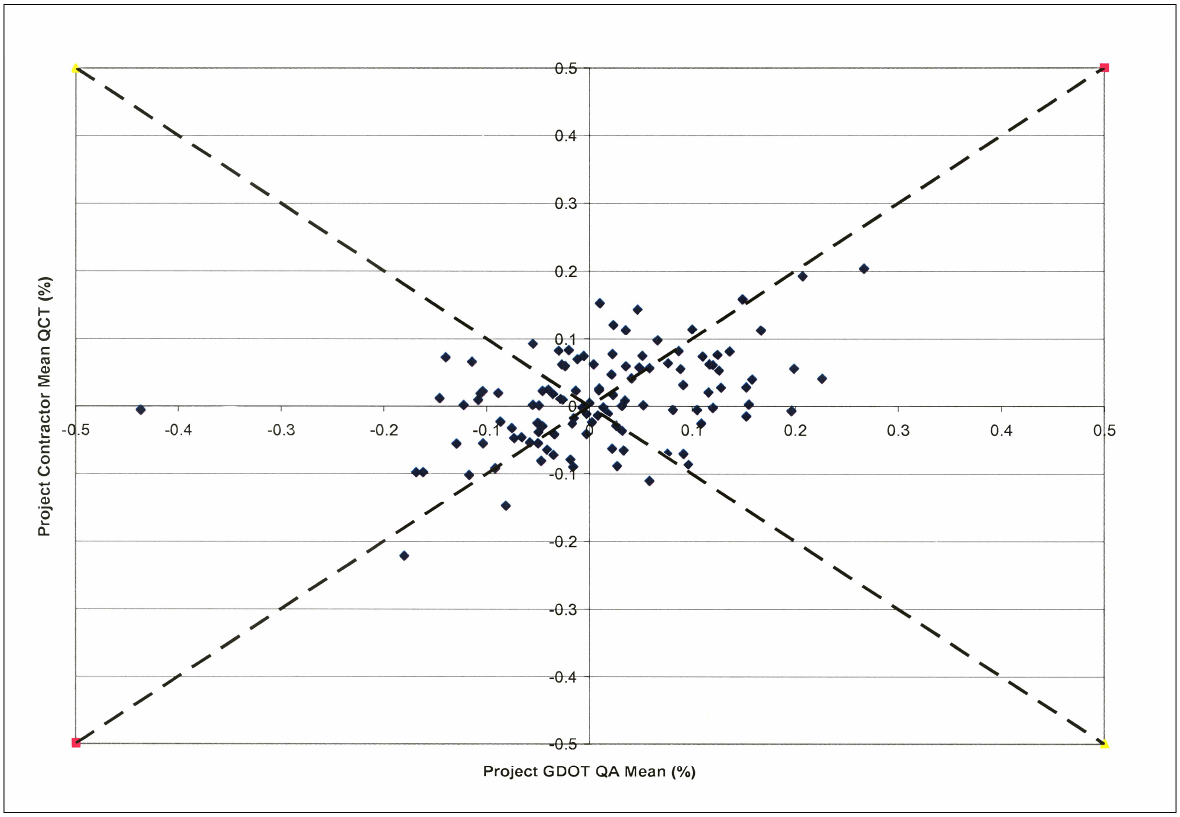


Figure 16. Asphalt Content Project Means – QA and QC

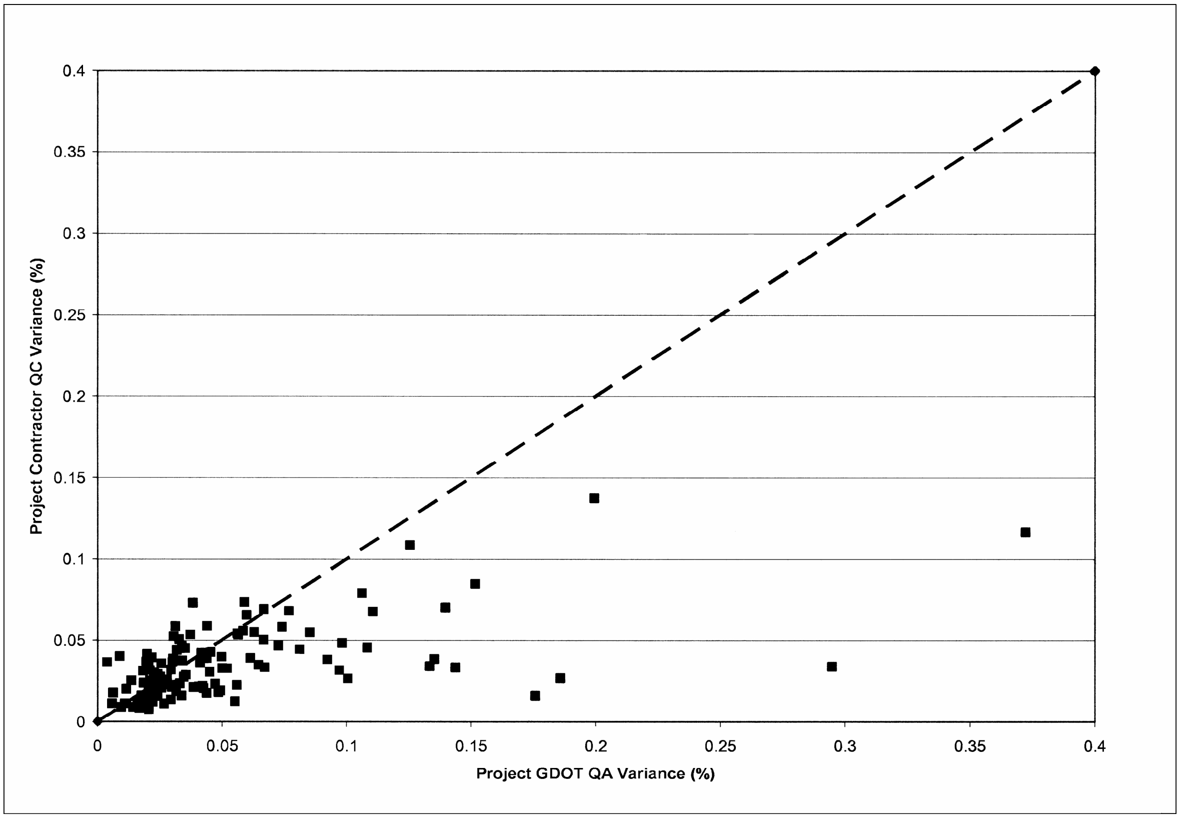


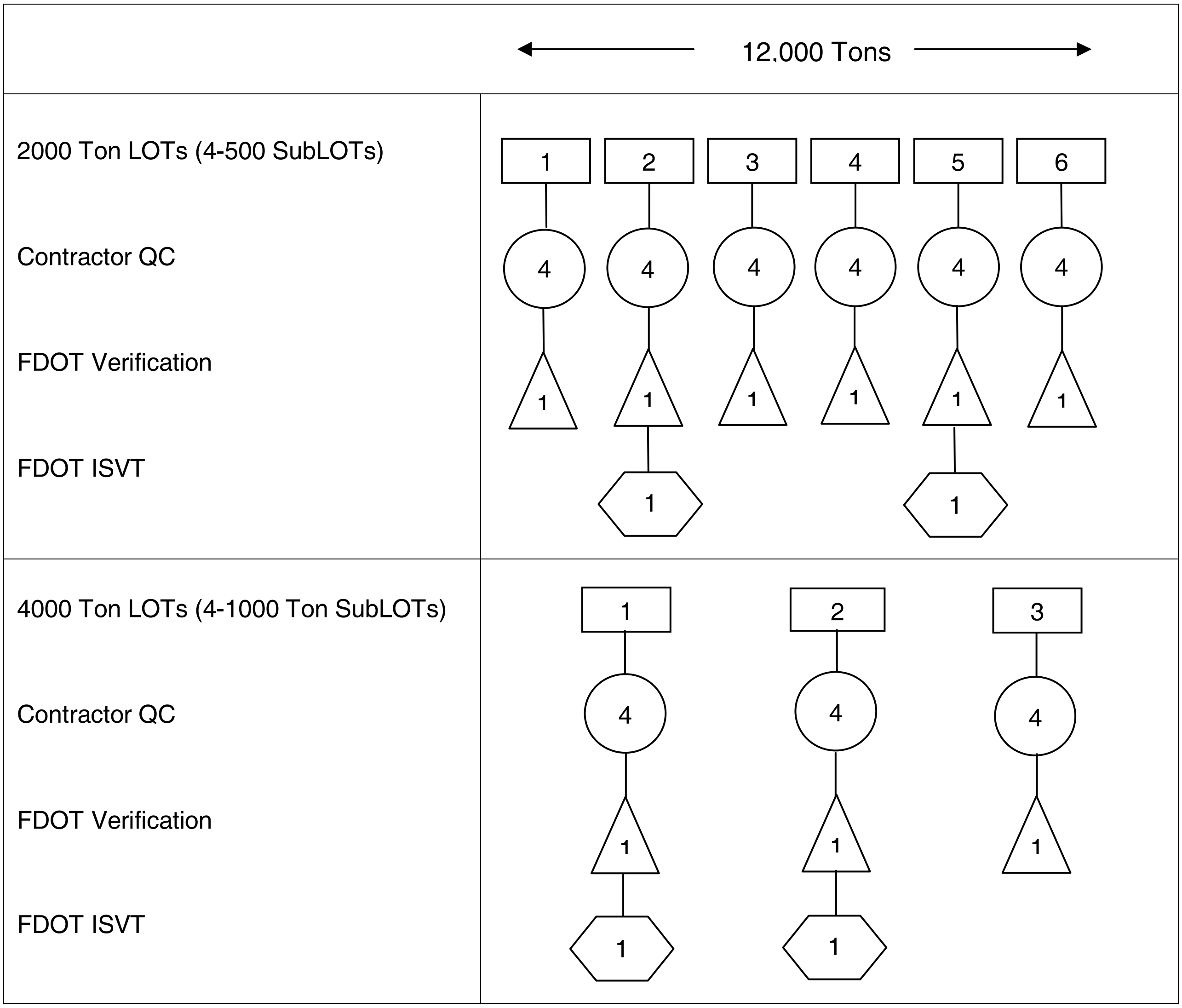
Figure 17. Asphalt Content Project Variances – QA and QC

ANALYSIS OF FLORIDA DOT HOT MIX ASPHALT CONCRETE DATA

HMAC test results from 98 projects constructed during 2003 and 2004 were provided by the Florida DOT. All test results for one year were requested but those provided were described as "an excellent sampling of the types of mixture properties that are used and a good sampling of the contractors that conduct FDOT work."

Test results included gradation (percent passing 3/4", 1/2", 3/8", #4, #8, #16, #30, #50, #100 and #200 sieves), asphalt content, maximum mix specific gravity (G_{mm}), bulk density of laboratory compacted samples (G_{mb}), air voids and VMA (computed with G_{mm} and G_{mb}) and mat density (%G_{mm}, core bulk density as a percentage of G_{mm}). Percent passing the #8 sieve, percent passing the #200 sieve, asphalt content, air voids, and mat density (%G_{mm}) are used in the PWL system to compute LOT composite pay factors. Asphalt content and gradation are determined with the ignition oven method. Mat density is measured with 6"-cores.

Figure 18 illustrates Florida DOT sampling and testing requirements for managing construction of HMAC pavement layers. A LOT may be 2000 or 4000 tons (contractor choice) divided into either 4-500 ton or 4-1000 tons subLOTS. Contractors test one mix sample and five cores per subLOT. Florida DOT conducts two types of sampling and testing: Verification and independent sample verification testing (ISVT). Florida DOT Verification tests and Contractor QC tests are on split samples. Test results are compared one to one with numerical criteria to determine if Contractor QC test results are used for LOT pay factor computation.



Notes:

1. Contractor QC and FDOT mix verification tests on split samples. Results compared one to one with numerical criteria.
2. Independent Sample Verification Testing (ISVT): 2 per 12,000 tons on independent samples. Results compared with specification tolerances.
3. For mat density, contractor QC test 5 cores per subLOT. FDOT Verification tests 5 of these cores from 1 of 4 subLOTs. Results compared one to one with numerical criteria.
4. Mat density ISVT tests 5 independent cores from same LOTs and subLOTs as mix ISVT tests. Results compared with specification tolerances.

Figure 18. Florida DOT HMAC Sampling and Testing Requirements

Florida DOT ISVT results are compared with specification tolerances. Noncompliance with mix specification tolerances can result in stopping production.

The first comparisons performed were between Contractor QC and Florida DOT Verification test results from split samples. Tables 22 and 23 contain comparisons of variances and means of differences from target values for data from all projects and for data from large projects (those with at least 6 Florida DOT test results ($n_{FDOT} \geq 6$)), respectively. Data from the large projects will also be compared on a project by project basis.

The comparisons for all projects and for large projects are very consistent. Variances of contractor and Florida DOT test results are mostly significantly different. Exceptions are for % passing the #16, #30, #50 and #100 sieves. Proximity to target values ($\Delta = X - X_T$) are consistently not significantly different. However, the p-values for mat density (%G_{mm}) indicate the means are approaching statistically significant differences.

Numerically, for all cases, variances of Florida DOT test results are larger than variances of contractor test results.

Except for % passing the #50 sieve and asphalt content among large projects, the mean differences indicate contractor test results closer to target values. For both all and large project comparisons, mean differences from target asphalt contents are quite small. It should also be noted that the target values used for VMA are minimum acceptable values. The negative mean differences ($\Delta = X - X_T$) of about 0.5% indicate that lower than desirable VMA are obtained. Contractor VMA measurements are larger and, therefore, closer to minimum acceptable values.

Table 22. Comparison of Florida DOT Verification and Contractor QC Test Results – All Projects

Property	n_{FDOT}	$n_{CONT.}$	s^2_{FDOT}	$s^2_{CONT.}$	Diff.	p-Value	$\overline{\Delta}_{FDOT}$	$\overline{\Delta}_{CONT}$	Diff.	p-Value	Pay
% Passing 1/2”	518	2288	3.802	2.869	SD	<0.001	0.533	0.409	NSD	0.183	No
% Passing 3/8”	519	2286	10.514	8.553	SD	0.001	1.316	1.176	NSD	0.366	No
% Passing #4	519	2288	17.179	13.247	SD	<0.001	1.237	0.762	NSD	0.016	No
% Passing #8	520	2288	7.533	5.619	SD	<0.001	0.679	0.400	NSD	0.032	Yes
% Passing #16	519	2287	6.576	6.006	NSD	0.089	0.224	0.005	NSD	0.069	No
% Passing #30	519	2286	5.412	4.914	NSD	0.076	0.521	0.376	NSD	0.185	No
% Passing #50	519	2284	5.570	4.614	SD	0.003	0.805	0.698	NSD	0.342	No
% Passing #100	517	2284	2.123	1.850	NSD	0.021	0.755	0.630	NSD	0.063	No
% Passing #200	521	2286	0.491	0.376	SD	<0.001	0.136	0.072	NSD	0.055	Yes
% Asphalt	526	2307	0.084	0.062	SD	<0.001	0.016	-0.012	NSD	0.037	Yes
Air Voids	469	2063	1.308	0.707	SD	<0.001	-0.285	-0.248	NSD	0.513	Yes
VMA	469	2095	1.023	0.737	SD	<0.001	-0.508	-0.490	NSD	0.719	No
%G_{mm}	1490	6874	2.958	2.570	SD	<0.001	-0.222	-0.103	NSD	0.014	Yes

Table 23. Comparison of Florida DOT Verification and Contractor QC Test Results – Large Projects ($n_{FDOT} \geq 6$)

Property	**n_{FDOT}**	**$n_{CONT.}$**	**s^2_{FDOT}**	**$s^2_{CONT.}$**	**Diff.**	**p-Value**	**$\overline{\Delta}_{FDOT}$**	**$\overline{\Delta}_{CONT}$**	**Diff.**	**p-Value**	**Pay**
% Passing 1/2”	377	1528	3.682	2.700	SD	<0.001	0.625	0.494	NSD	0.225	No
% Passing 3/8”	377	1527	10.240	7.334	SD	<0.001	1.277	1.146	NSD	0.462	No
% Passing #4	377	1528	15.886	13.039	SD	0.006	1.211	0.885	NSD	0.148	No
% Passing #8	383	1551	6.840	5.139	SD	<0.001	0.562	0.330	NSD	0.113	Yes
% Passing #16	377	1527	5.652	5.489	NSD	0.353	0.325	0.204	NSD	0.369	No
% Passing #30	377	1526	5.074	4.755	NSD	0.206	0.662	0.587	NSD	0.552	No
% Passing #50	377	1525	5.083	4.655	NSD	0.134	0.825	0.836	NSD	0.932	No
% Passing #100	376	1525	1.958	1.685	NSD	0.030	0.810	0.786	NSD	0.760	No
% Passing #200	383	1549	0.492	0.386	SD	0.001	0.128	0.075	NSD	0.181	Yes
% Asphalt	388	1571	0.078	0.057	SD	<0.001	0.001	-0.019	NSD	0.205	Yes
Air Voids	345	1409	1.301	0.753	SD	<0.001	-0.337	-0.263	NSD	0.263	Yes
VMA	335	1369	1.032	0.751	SD	<0.001	-0.595	-0.537	NSD	0.336	No
$\%G_{mm}$	1408	5770	2.851	2.511	SD	0.001	-0.172	-0.082	NSD	0.070	Yes

The second comparisons were between Contractor QC and Florida DOT ISVT test results from independent samples. Tables 24 and 25 contain, respectively, comparisons of variances and means for data from all projects and for data from large projects.

The comparisons in Tables 24 and 25 for all and for large projects are reasonably consistent. Variances of Florida DOT ISVT and contractor test results are significantly different, except for % passing the #50 sieve and % passing the #200 sieve for large projects. Mean values are mostly not significantly different. Important exceptions are air voids and mat density (%G_{mm}) where means are significantly different. Mean values for % passing the #4 and #8 sieves are also significantly different for test results from all projects.

Numerically, for all cases, variances of Florida DOT test results are larger than variances of contractor test results.

Numerically, contractor gradation test results are closer to target values than Florida DOT test results, except for % passing the ½" sieve. For asphalt content, Florida DOT test results are closer to targets. These differences for asphalt content are, however, quite small and are consistent with Florida Verification test results. The VMA comparisons indicate more favorable Florida DOT ISVT test results, i.e., larger test results relative to minimum acceptable values. This is opposite of indications from comparisons with Florida DOT Verification test results where contractor test results were more favorable, relative to minimum acceptable values.

Table 24. Comparison of Florida DOT ISVT and Contractor QC Test Results – All Projects

Property	n_{FDOT}	$n_{CONT.}$	s^2_{FDOT}	$s^2_{CONT.}$	Diff.	p-Value	$\overline{\Delta}_{FDOT}$	$\overline{\Delta}_{CONT}$	Diff.	p-Value	Pay
% Passing 1/2”	540	2288	3.693	2.869	SD	<0.001	0.342	0.409	NSD	0.455	No
% Passing 3/8”	539	2286	11.809	8.553	SD	<0.001	1.177	1.176	NSD	0.995	No
% Passing #4	539	2288	16.853	13.247	SD	<0.001	1.273	0.762	SD	0.008	No
% Passing #8	540	2288	9.555	5.619	SD	<0.001	0.836	0.400	SD	0.002	Yes
% Passing #16	540	2287	7.525	6.006	SD	<0.001	0.271	0.005	NSD	0.039	No
% Passing #30	540	2286	6.041	4.914	SD	<0.001	0.452	0.376	NSD	0.515	No
% Passing #50	540	2284	5.103	4.614	NSD	0.065	0.873	0.698	NSD	0.091	No
% Passing #100	540	2284	4.024	1.850	SD	<0.001	0.853	0.630	NSD	0.014	No
% Passing #200	539	2286	0.480	0.376	SD	<0.001	0.132	0.072	NSD	0.062	Yes
% Asphalt	545	2307	0.086	0.062	SD	<0.001	0.000	-0.012	NSD	0.386	Yes
Air Voids	490	2036	1.400	0.707	SD	<0.001	-0.057	-0.248	SD	0.001	Yes
VMA	499	2095	1.251	0.737	SD	<0.001	-0.414	-0.490	NSD	0.159	No
%G_{mm}	437	6874	3.536	2.570	SD	<0.001	-0.640	-0.103	SD	<0.001	Yes

Table 25. Comparison of Florida DOT ISVT and Contractor QC Test Results - Large Projects ($n_{FDOT} \geq 6$)

Property	n_{FDOT}	$n_{CONT.}$	s^2_{FDOT}	$s^2_{CONT.}$	Diff.	p-Value	$\overline{\Delta}_{FDOT}$	$\overline{\Delta}_{CONT}$	Diff.	p-Value	Pay
% Passing 1/2"	328	1351	4.246	2.717	SD	<0.001	0.480	0.496	NSD	0.892	No
% Passing 3/8"	322	1330	10.761	7.652	SD	<0.001	1.325	1.192	NSD	0.502	No
% Passing #4	327	1351	17.133	13.190	SD	0.001	1.415	0.942	NSD	0.058	No
% Passing #8	328	1351	9.548	5.396	SD	<0.001	0.794	0.372	NSD	0.021	Yes
% Passing #16	328	1350	7.174	5.601	SD	0.002	0.290	0.058	NSD	0.151	No
% Passing #30	328	1349	6.598	4.813	SD	<0.001	0.616	0.411	NSD	0.183	No
% Passing #50	328	1349	5.770	4.838	NSD	0.019	0.984	0.712	NSD	0.049	No
% Passing #100	328	1348	5.134	1.697	SD	<0.001	1.036	0.790	NSD	0.060	No
% Passing #200	328	1349	0.474	0.393	NSD	0.014	0.104	0.080	NSD	0.549	Yes
% Asphalt	337	1422	0.084	0.057	SD	<0.001	-0.016	-0.017	NSD	0.936	Yes
Air Voids	302	1172	1.185	0.731	SD	<0.001	-0.029	-0.241	SD	0.002	Yes
VMA	302	1172	1.226	0.763	SD	<0.001	-0.374	-0.519	NSD	0.035	No
%G_{mm}	363	2236	3.044	2.381	SD	0.001	-0.687	-0.272	SD	<0.001	Yes

For air voids, the mean differences indicate Florida DOT ISVT test results are significantly closer to the 4% target than contractor test results. This is opposite of comparisons with Florida DOT Verification test results (Tables 22 and 23) where contractor test results were closer to the 4% target, but not significantly closer. The numbers causing this discrepancy appear to be the Florida DOT ISVT mean differences (-0.057 and -0.029%) which indicate unusually close agreement with the 4% target.

For mat density (%G_{mm}), the mean differences indicate contractor test results are significantly closer to targets than Florida DOT ISVT test results. The Florida Verification test result comparisons (Tables 22 and 23) also indicate contractor tests results closer to targets, but not significantly closer. The numbers causing this discrepancy appear to be the Florida DOT ISVT mean differences (-0.640 and -0.687%) which indicate unusually low levels of compaction.

The third comparison will be between means of paired Contractor QC and FDOT Verification test results. Tables 26 and 27 contain the results of paired t tests for data from all projects and large projects, respectively. Note that comparisons of maximum mix specific gravity (G_{mm}), laboratory bulk specific gravity (G_{mb}) and core bulk specific gravity (G_{mb}) samples are added. Note also that means of these three properties are reported rather than means of differences between test results and targets.

Table 26. Comparison of Paired Florida DOT Verification and Contractor QC Test Results – All Projects

Property	n	$\overline{\Delta}_{FDOT}$	$\overline{\Delta}_{CONT}$	Diff.	p-Value	Pay
% Passing 1/2”	489	0.517	0.450	SD	<0.001	No
% Passing 3/8”	491	1.337	1.125	SD	<0.001	No
% Passing #4	490	1.293	0.825	SD	<0.001	No
% Passing #8	492	0.694	0.391	SD	<0.001	Yes
% Passing #16	490	0.214	-0.038	SD	<0.001	No
% Passing #30	489	0.508	0.319	SD	<0.001	No
% Passing #50	490	0.777	0.627	SD	<0.001	No
% Passing #100	487	0.752	0.644	SD	<0.001	No
% Passing #200	490	0.143	0.084	SD	<0.001	Yes
% Asphalt	499	0.016	0.003	NSD	0.418	Yes
Air Voids	450	-0.302	-0.304	NSD	0.972	Yes
VMA	449	-0.511	-0.490	NSD	0.713	No
%G_{mm}	1374	-0.198	-0.052	SD	<0.001	Yes
G_{mm}	443	2.433*	2.432*	NSD	0.741	No
Lab. G_{mb}	450	2.342*	2.341*	NSD	0.760	No
Core G_{mb}	1399	2.257*	2.259*	SD	<0.001	No

* Mean of G_{mm} and G_{mb} (not of difference from target).

Table 27. Comparison of Paired Florida DOT Verification and Contractor QC Test Results – Large Projects ($n_{FDOT} \geq 6$)

Property	n	$\overline{\Delta}_{FDOT}$	$\overline{\Delta}_{CONT}$	Diff.	p-Value	Pay
% Passing 1/2"	346	0.615	0.587	NSD	0.144	No
% Passing 3/8"	340	1.350	1.247	NSD	0.035	No
% Passing #4	346	1.281	0.884	SD	<0.001	No
% Passing #8	352	0.582	0.283	SD	<0.001	Yes
% Passing #16	346	0.277	0.057	SD	<0.001	No
% Passing #30	345	0.630	0.498	SD	<0.001	No
% Passing #50	346	0.784	0.719	SD	<0.001	No
% Passing #100	345	0.826	0.779	SD	<0.001	No
% Passing #200	352	0.119	0.087	SD	<0.001	Yes
% Asphalt	359	0.003	-0.004	NSD	0.570	Yes
Air Voids	319	-0.377	-0.355	NSD	0.584	Yes
VMA	319	-0.592	-0.546	NSD	0.137	No
%G_{mm}	1302	-0.138	-0.005	SD	<0.001	Yes
G_{mm}	318	2.433*	2.432*	NSD	0.096	No
Lab. G_{mb}	320	2.343*	2.342*	NSD	0.040	No
Core G_{mb}	1248	2.259*	2.261*	SD	<0.001	No

* Mean of G_{mm} and G_{mb} (not of difference from target).

The comparisons for gradation indicate significant differences, in % passing for all except the 1/2” and 3/8” sieves for large projects. This is quite different from comparisons of unpaired test results in Tables 22 and 23 where none of the differences were significant. The magnitude of the mean differences in Tables 22 and 23 are similar to those in Tables 26 and 27, so the inconsistencies in comparisons may be attributed to the paired t test being somewhat more discerning than the t test.

The results of comparisons of paired % asphalt, air voids and VMA test results are the same as unpaired comparisons in Tables 22 and 23, i.e., differences in means are not significant. Likewise, differences in G_{mm} and Lab. G_{mb} are not significant.

However, unlike the unpaired data, the differences for the paired % G_{mm} test results are significant. This is surprising as are the significant differences for core G_{mb}. The same cores are tested by Florida DOT and contractors and used to compute %G_{mm}. It would seem that pairing test results from the same cores would make significant differences unlikely, but this was not the case. An analysis of the magnitude of mean differences of %G_{mm} in Tables 22, 23, 26 and 27 provides a clue as to why the paired results are significantly different. The magnitudes of the mean differences are reasonably consistent for all except the paired contractor data, i.e., $\overline{\boldsymbol{\Delta}}_{\mathbf{CONT}}$ = -0.052 and -0.005%. These indicate compaction are much closer to target densities than any of the other test results.

The next analysis performed was project by project comparisons for large projects, i.e., projects where there were 6 or more Florida DOT test results. This analysis quantified the numbers of projects where there were significant differences between Florida DOT and contractor means and variances, and the numbers of projects where Florida DOT means and variances were the largest. These analyses are summarized in Tables 28-30 for Contractor QC vs. Florida DOT Verification, Contractor QC vs. Florida DOT ISVT and Paired Contractor QC vs. Paired Florida DOT Verification test results, respectively.

The project by project comparisons generally confirm trends indicated by comparisons of combined test results. These trends can be summarized as follows:

- Numerically, differences from target values of Florida DOT test results tend to be larger than contractor test results. Evidence for this conclusion are the percentages in column 3 of Tables 28-30 which are mostly greater than 50%. As noted previously for VMA, the opposite is true for the numerical differences, but contractor test results are closer to minimum values. A graphical illustration is provided in Figure 19 where contractor and Florida DOT Verification air voids mean differences are plotted. Points for 25 of the 28 projects (89%) fall in the portion of the figure bounded by the dashed lines of absolute equality and centered about the horizontal axis. A complete set of figures for mean differences and variances for all the Florida DOT project by project comparisons is contained in Appendix B.

- Numerically, the variances of Florida DOT test results are larger than the variances of contractor test results. Evidence for this conclusion are percentages in column 6 of Tables 28-30 that are mostly greater than 50%. A graphical illustration is provided in Figure 20 where contractor and Florida DOT Verification air voids variances are plotted. Points for 23 of the 28 projects (82%) fall below the dashed line of equality.

Table 28. Project by Project Comparisons of Florida DOT Verification and Contractor QC Test Results

Property	Projects	Projects with Larger FDOT $\lvert\bar{\Delta}\rvert$	Projects with SD $\bar{\Delta}$	Projects with Sig. Larger FDOT $\lvert\bar{\Delta}\rvert$	Projects with Larger FDOT s^2	Projects with SD s^2	Projects with Sig. Larger FDOT s^2	Pay
% Passing 1/2"	29	20 (69%)	1 (3%)	1 (3%)	14 (48%)	3 (10%)	2 (7%)	No
% Passing 3/8"	29	19 (66%)	0	0	13 (45%)	2 (7%)	2 (7%)	No
% Passing #4	29	17 (59%)	0	0	14 (48%)	4 (14%)	4 (14%)	No
% Passing #8	30	24 (80%)	1 (3%)	1 (3%)	18 (60%)	3 (10%)	3 (10%)	Yes
% Passing #16	29	19 (66%)	1 (3%)	1 (3%)	15 (52%)	1 (3%)	1 (3%)	No
% Passing #30	29	16 (55%)	2 (7%)	2 (7%)	12 (41%)	0	0	No
% Passing #50	29	14 (48%)	1 (3%)	1 (3%)	13 (45%)	2 (7%)	1 (3%)	No
% Passing #100	29	18 (62%)	1 (3%)	1 (3%)	17 (59%)	2 (7%)	2 (7%)	No
% Passing #200	30	21 (70%)	2 (7%)	1 (3%)	11 (37%)	6 (20%)	5 (17%)	Yes
% Asphalt	30	22 (73%)	0	0	18 (60%)	3 (10%)	3 (10%)	Yes
Air Voids	28	25 (89%)	0	0	23 (82%)	3 (11%)	3 (11%)	Yes
VMA	28	17 (61%)*	0	0	20 (71%)	2 (7%)	2 (7%)	No
%G_{mm}	49	32 (65%)	2 (4%)	2 (4%)	33 (67%)	2 (4%)	1 (2%)	Yes
G_{mm}	29	-	0	-	12 (41%)	1 (3%)	0	No
Lab. G_{mb}	29	-	0	-	21 (72%)	2 (7%)	2 (7%)	No
Core G_{mb}	49	-	1 (2%)	-	26 (53%)	1 (2%)	0	No

Numbers in parentheses are percentages of projects.
*Minimum VMA requirements are specified. These numbers indicate projects and percent of projects where FDOT VMA test results were smaller than contractor VMA test results.

No targets for G_{mm}, Lab G_{mb} or Core G_{mb} and, therefore, which test results might be larger is of no particular importance. Means of test results rather than means of differences between test results and targets are compared.

Table 29. Project by Project Comparisons of Florida DOT ISVT and Contractor QC Test Results

Property	Projects	Projects with Larger FDOT $\lvert\overline{\Delta}\rvert$	Projects with SD $\overline{\Delta}$	Projects with Sig. Larger FDOT $\lvert\overline{\Delta}\rvert$	Projects with Larger FDOT s^2	Projects with SD s^2	Projects with Sig. Larger FDOT s^2	Pay
% Passing 1/2”	25	12 (48%)	1 (4%)	1 (4%)	18 (72%)	5 (20%)	5 (20%)	No
% Passing 3/8”	24	11 (46%)	2 (8%)	1 (4%)	17 (71%)	3 (12%)	3 (12%)	No
% Passing #4	25	13 (52%)	2 (8%)	0	18 (72%)	5 (20%)	5 (20%)	No
% Passing #8	25	16 (64%)	1 (4%)	0	18 (72%)	5 (20%)	5 (20%)	Yes
% Passing #16	25	14 (56%)	1 (4%)	1 (4%)	14 (56%)	1 (4%)	1 (4%)	No
% Passing #30	25	14 (56%)	1 (4%)	1 (4%)	15 (60%)	1 (4%)	1 (4%)	No
% Passing #50	25	12 (48%)	1 (4%)	0	21 (84%)	2 (8%)	2 (8%)	No
% Passing #100	25	15 (60%)	1 (4%)	1 (4%)	14 (56%)	1 (4%)	1 (4%)	No
% Passing #200	25	17 (68%)	2 (8%)	1 (4%)	16 (64%)	0	0	Yes
% Asphalt	26	19 (73%)	2 (8%)	2 (8%)	16 (62%)	3 (12%)	3 (12%)	Yes
Air Voids	24	18 (75%)	0	0	16 (67%)	3 (12%)	3 (12%)	Yes
VMA	24	10 (42%)*	2 (8%)	2 (8%)*	18 (75%)	4 (17%)	4 (17%)	No
%G_{mm}	14	10 (71%)	3 (21%)	3 (21%)	7 (50%)	1 (7%)	1 (7%)	Yes
G_{mm}	25	-	2 (8%)	-	14 (56%)	0	0	No
Lab. G_{mb}	25	-	1 (4%)	-	15 (60%)	1 (4%)	1 (4%)	No
Core G_{mb}	13	-	3 (23%)	-	6 (46%)	2 (15%)	2 (15%)	No

Numbers in parentheses are percentages of projects.

* Minimum VMA requirements are specified. These numbers indicate projects and percent of projects where FDOT VMA test results were smaller than contractor VMA test results.

No targets for G_{mm}, Lab. G_{mb} or Core G_{mb} and, therefore, which test results might be larger is of no particular importance. Means of test results rather than means of differences between test results and targets are compared.

Table 30. Project by Project Comparisons of Paired Florida DOT Verification and Contractor QC Test Results

Property	Projects	Projects with Larger FDOT $\overline{\Delta}$	Projects with SD $\overline{\Delta}$	Projects with Sig. Larger FDOT $\overline{\Delta}$	Projects with Larger FDOT s^2	Pay
% Passing 1/2"	27	16 (59%)	0	0	13 (48%)	No
% Passing 3/8"	26	14 (54%)	0	0	12 (46%)	No
% Passing #4	27	15 (56%)	0	0	13 (48%)	No
% Passing #8	28	18 (64%)	1 (4%)	0	18 (64%)	Yes
% Passing #16	27	17 (63%)	1 (4%)	1 (4%)	17 (63%)	No
% Passing #30	27	18 (67%)	1 (4%)	1 (4%)	17 (63%)	No
% Passing #50	27	15 (55%)	0	0	16 (59%)	No
% Passing #100	27	13 (48%)	3 (11%)	3 (11%)	19 (70%)	No
% Passing #200	28	19 (68%)	2 (7%)	2 (7%)	14 (50%)	Yes
% Asphalt	28	19 (68%)	0	0	16 (57%)	Yes
Air Voids	27	23 (85%)	0	0	19 (70%)	Yes
VMA	27	15 (56%)*	0	0	16 (59%)	No
%G_{mm}	48	26 (54%)	19 (40%)	11 (23%)	31 (65%)	Yes
G_{mm}	27	-	1 (4%)	-	12 (44%)	No
Lab. G_{mb}	27	-	1 (4%)	-	14 (52%)	No
Core G_{mb}	48	-	12 (25%)	-	36 (75%)	No

Number in parentheses are percentages of projects.

Statistical comparisons of variances were not conducted.

No targets for G_{mm}, Lab G_{mb} or Core G_{mb} and, therefore, test results might be larger is of no particular importance. Means of test results rather than means of differences between test results and targets are compared.

*Minimum VMA requirements are specified. These numbers indicate projects and percents of projects where FDOT VMA test results were smaller than contractor VMA test results.

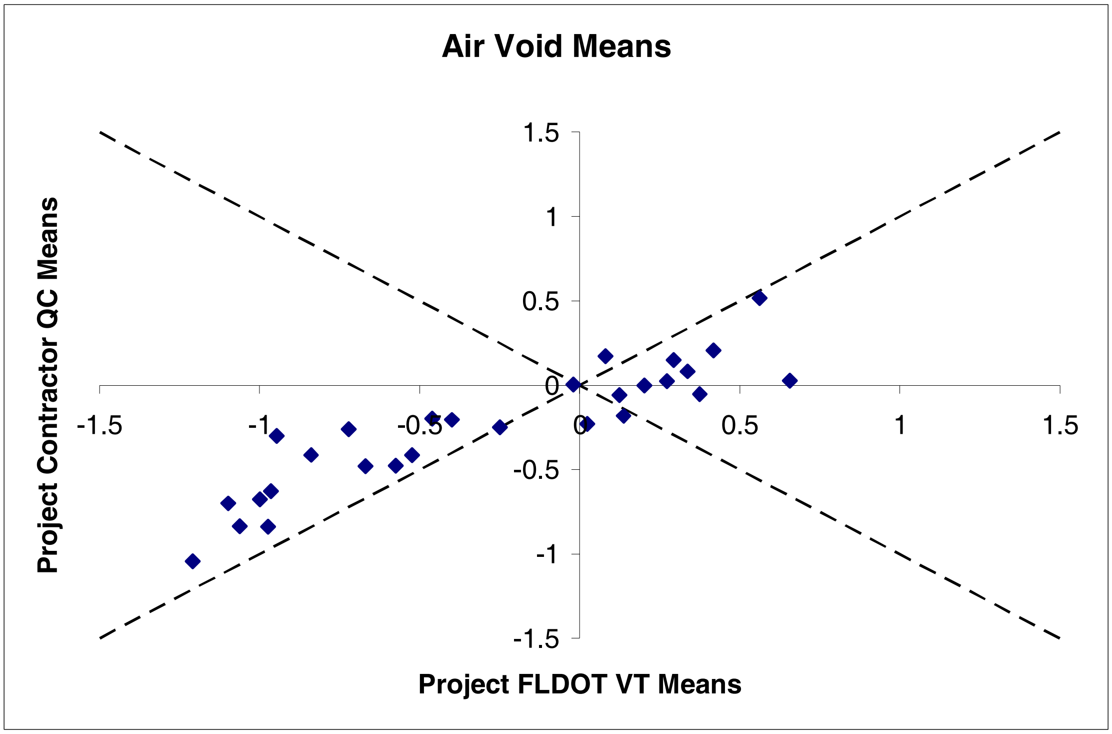


Figure 19. Project Air Voids Mean Differences

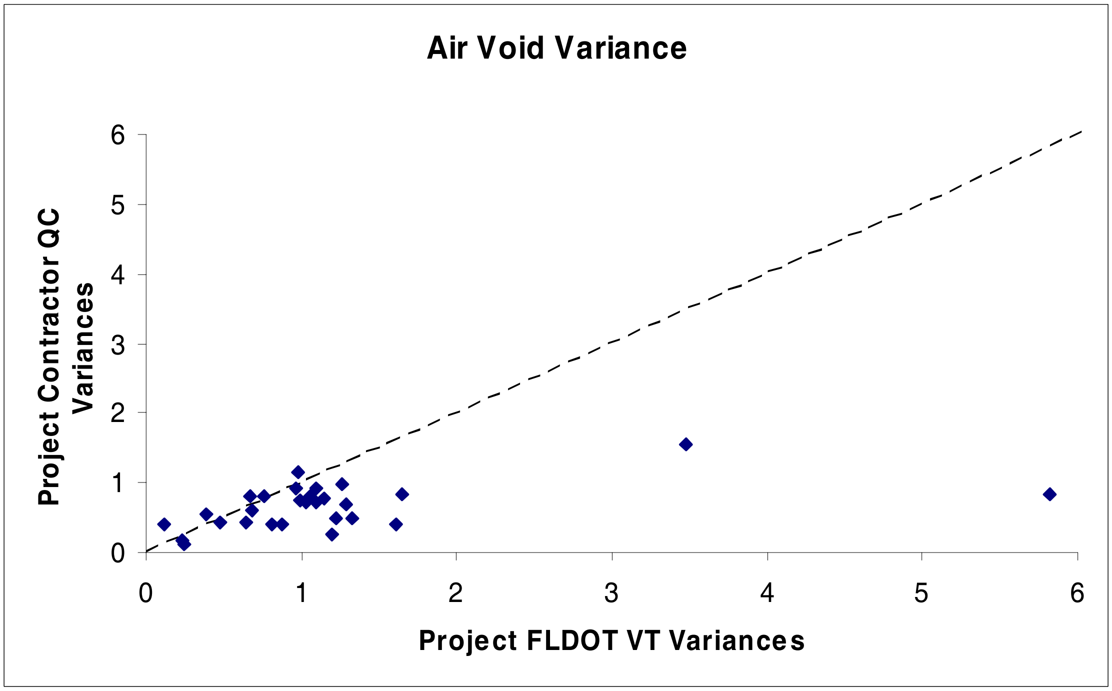


Figure 20. Project Air Voids Variances

- The variances of project test results are more likely to be significantly different than mean differences. This is confirmed by comparing numbers and percentages of projects in column 4 of Tables 28 and 29 with numbers and percentages of projects in column 7.
- When mean differences from target values are significantly different, mean differences for Florida DOT test results are likely larger. This can be confirmed by comparing numbers and percentages of projects in columns 4 and 5 of Tables 28-30. The numbers and percentages of projects in columns 4 and 5 are quite similar.
- When variances are significantly different, variances for Florida DOT test results are likely larger. This can be confirmed by comparing numbers and percentages of projects in columns 7 and 8 of Tables 28 and 29. The numbers and percentages of projects in columns 7 and 8 are quite similar. This is graphically illustrated in Figure 20 by the number of points close to the horizontal axis.

A final analysis will compare mean square deviations (nominal is best) computed with means and variances from Tables 22 and 24. The nominal is best mean square deviation (MSD_{NIB}) is computed with Equation 3. Mean square deviations for VMA are not included because Florida DOT specification contains minimum acceptable requirements. Therefore, for VMA, a larger is best situation is applicable, but appropriate statistics were not available for computing MSD_{LIB}.

Mean square deviations are contained in Table 31. These values confirm trends indicated by comparisons of mean differences and variances that contractor test results are more accurate, relative to target values, and more precise (less variable) than Florida DOT test results. The mean square deviations for contractor test results are all smaller than Florida DOT test results from split (Verification) and independent (ISVT) samples.

Table 31. Comparisons of Mean Square Deviations for Florida DOT Data

Property	MSD_{NIB}		
	Contractor QC	**FDOT Verification**	**FDOT ISVT**
% Asphalt*	0.062	0.084	0.086
Air Voids*	0.768	1.392	1.403
%G_{mm}*	0.977	1.281	1.422
% Passing 1/2”	3.036	4.086	3.810
% Passing 3/8”	9.936	10.516	13.194
% Passing #4	13.828	18.709	18.474
% Passing #8*	5.779	7.994	10.254
% Passing #16	6.006	6.626	7.598
% Passing #30	5.055	5.683	6.245
% Passing #50	5.101	6.218	5.865
% Passing #100	2.247	2.693	4.752
% Passing #200*	0.381	0.509	0.497

* Property used for pay factor computation.

ANALYSIS OF NORTH CAROLINA DOT HOT MIX ASPHALT CONCRETE DATA

Test results for HMAC produced and placed for the North Carolina DOT during the 2004 construction year were provided. The North Carolina DOT manages HMAC production by job mix formula (JMF). Compaction is managed by project and, therefore, there is a disconnect between test results for mix properties and mat properties. However, mat densities were provided in a format so that sorting and, therefore, analysis was convenient only by JMF.

Mix Properties Comparisons

Test results for mix properties were received for a total of 735 mix designs. These were combined into a data set of all JMFs and sorted into a reduced data set comprised of JMFs where there was 6 or more North Carolina DOT test results. Proximity to targets and variances of contractor and North Carolina DOT test results were compared for the combined and reduced data sets. Comparisons were also conducted for each JMF with 6 or more North Carolina DOT test results.

Test results included gradation (percent passing 1”, $3/4$”, $1/2$”, $3/8$”, #4, #8 and #200 sieves), asphalt content, air voids, VMA, VFA and % G_{mm} @ N_i in the gyratory compactor. The ignition oven method is used for asphalt content and gradation, except that the contractor may request an alternative method for asphalt content. Individual and moving averages for 4 test results for percents passing the #8 and #200 sieves, asphalt content, air voids, VMA and % G_{mm} @ N_i are plotted on control charts with control limits. When test results exceed control limits a series of actions may be taken that include notification of the engineer, process adjustment, additional testing, retesting and, as a last resort, pay reduction.

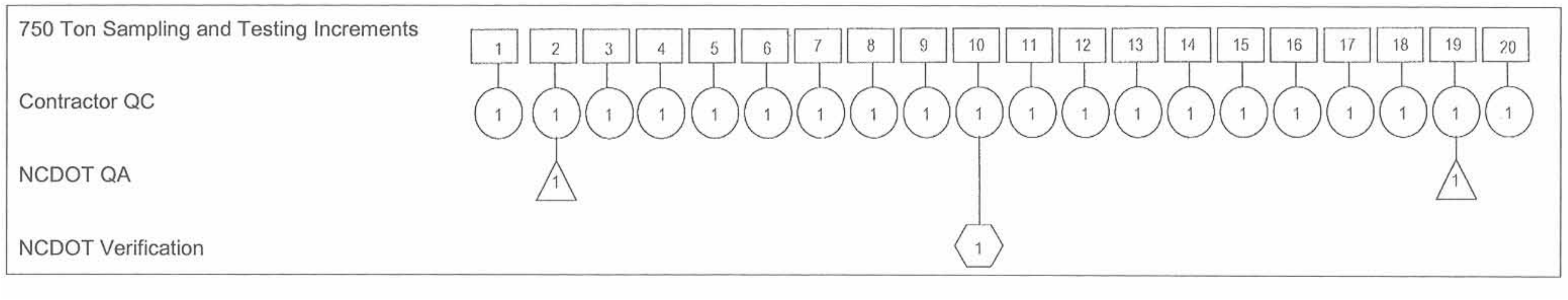
Figure 21 illustrates North Carolina DOT sampling and testing requirements for managing the production of HMAC. The increment for Contractor QC sampling and testing is 750 tons but mix acceptance is not on a LOT basis. For mat compaction a LOT is a days production. North Carolina DOT conducts two types of mix sampling and testing; QA and Verification. North Carolina DOT QA tests are on split samples with Contractor QC and North Carolina DOT Verification tests are on independent samples.

Contractor QC and North Carolina DOT QA test results are compared one to one with numerical criteria, with control limits on control charts and with specification requirements. Unacceptable comparisons result in an investigation as described below

> "In the event comparison test results are outside the above acceptable limits of precision or the quality assurance test results are either outside the individual test control limits or fail to meet specification requirements, the engineer will immediately investigate the reason for the difference."

Pay adjustments for mix properties appear to be applied only as a last resort. It was not clear from the review of specifications exactly how North Carolina DOT Verification test results are used in the QA process.

The first comparisons made were between Contractor QC and North Carolina DOT QA test results for all 735 JMFs. Table 32 contains comparisons of variances and means of differences from target values. The first 6 properties in the table are plotted on control charts and are, therefore, used directly in the acceptance process.



Notes:

1. Contractor QC and NCDOT QA tests on split samples.
2. NCDOT Verification tests on independent samples.
3. NCDOT QA tests at 10% and NCDOT Verification tests at 5% of Contractor QC test rate.
4. Contractor QC and NCDOT QA test results compared one to one with precision limits.

Figure 21. North Carolina DOT HMAC Mix Sampling and Testing Requirement

Table 32. Comparison of NCDOT QA and Contractor QC Test Results – All JMFs

Property	**n_{NCDOT}**	**n_{CONT}**	**s^2_{NCDOT}**	**s^2_{CONT}**	**Difference**	**p-Value**	**$\overline{\Delta}_{NCDOT}$**	**$\overline{\Delta}_{CONT}$**	**Difference**	**p-Value**	**Control**
% Asphalt	2295	14396	0.095	0.059	SD	<0.001	-0.021	-0.003	SD	0.008	Yes
Air Voids	2269	14225	1.080	0.564	SD	<0.001	-0.212	-0.097	SD	<0.001	Yes
VMA	2268	14225	1.856	1.803	NSD	0.177	1.224	1.507	SD	<0.001	Yes
% G_{mm} @ N_i	2223	14017	2.665	2.091	SD	<0.001	-0.969	-1.028	NSD	0.107	Yes
% Pass #200	2294	14396	0.765	0.490	SD	<0.001	0.221	0.095	SD	<0.001	Yes
% Pass #8	2296	14397	14.519	8.210	SD	<0.001	0.335	0.307	NSD	0.729	Yes
% Pass #4	2258	14175	20.717	15.277	SD	<0.001	1.333	1.140	NSD	0.056	No
% Pass 3/8"	2251	14194	19.008	13.753	SD	<0.001	0.928	0.547	SD	<0.001	No
Pass 1/2"	2281	14347	15.349	10.621	SD	<0.001	0.921	0.506	SD	<0.001	No
% Pass 3/4"	2281	14335	6.903	5.316	SD	<0.001	0.179	0.121	NSD	0.316	No
% Pass 1"	2277	14383	1.385	0.992	SD	<0.001	0.018	-0.020	NSD	0.147	No
VFA	2015	12795	45.123	28.629	SD	<0.001	8.863	8.574	NSD	0.066	No

Except for VMA, Table 32 indicates that the variances of North Carolina DOT and contractor test results are statistically significantly different. For all properties, North Carolina DOT variances are larger.

Significant differences for means are not so consistent. Table 32 indicates that means of 4 of the 6 properties used in control charts are statistically significantly different but that only 2 of the remaining 6 properties have significantly different means. Except for VMA and % G_{mm} @ N_i, the means of differences from target values indicate contractor test results are closer to targets than North Carolina DOT test results. The specification requirement for VMA is a minimum acceptable value and for % G_{mm} @ N_i is a maximum acceptable values. The means of differences in Table 32 indicate more favorable contractor test results for both VMA and % G_{mm} @ N_i.

Comparisons of paired Contractor QC and NCDOT QA test results (paired t tests) are contained in Table 33. These comparisons indicate statistically significant differences for means of all properties. Except for % passing the 1” sieve, contractor test results are either closer to target values or, for VMA and % G_{mm} @ N_i, more favorable relative to specification requirements.

The comparisons, summarized in Table 34, are for test results in a reduced data set ($n_{NCDOT} \geq 6$). The numbers of test results are about 40% of those in Table 32 and represent about 110 of the 735 JMFs. There are a few differences for specific comparisons, but the general trends indicated in Table 32 are confirmed by Table 34.

Table 33. Comparison of Paired NCDOT QA and Contractor QC Test Results – All JMFs

Property	n	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value	Control
% Asphalt	2287	-0.021	-0.002	SD	<0.001	Yes
Air Voids	2261	-0.214	-0.112	SD	<0.001	Yes
VMA	2260	1.221	1.464	SD	<0.001	Yes
% G_{mm} @ N_i	2214	-0.966	-1.129	SD	<0.001	Yes
% Pass #200	2286	0.222	0.130	SD	<0.001	Yes
% Pass #8	2286	0.366	0.161	SD	<0.001	Yes
% Pass #4	2249	1.341	1.062	SD	<0.001	No
% Pass 3/8”	2243	0.906	0.609	SD	<0.001	No
Pass 1/2”	2273	0.904	0.517	SD	<0.001	No
% Pass 3/4”	2273	0.176	0.048	SD	0.007	No
% Pass 1”	2268	0.020	-0.048	SD	0.006	No
VFA	2005	8.900	8.629	SD	0.005	No

Table 34. Comparison of NCDOT QA and Contractor QC Test Results – JMFs with $n_{NCDOT} \geq 6$

Property	n_{NCDOT}	n_{CONT}	s^2_{NCDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value	Control
% Asphalt	994	6059	0.083	0.057	SD	<0.001	-0.017	-0.001	NSD	0.098	Yes
Air Voids	973	5920	1.018	0.490	SD	<0.001	-0.285	-0.115	SD	<0.001	Yes
VMA	973	5920	2.338	2.374	NSD	0.380	1.186	1.451	SD	<0.001	Yes
% G_{mm} @ N_i	960	5864	2.400	1.971	SD	<0.001	-0.863	-0.981	NSD	0.027	Yes
% Pass #200	994	6059	0.751	0.462	SD	<0.001	0.179	0.064	SD	<0.001	Yes
% Pass #8	993	6059	11.955	8.412	SD	<0.001	0.524	0.321	NSD	0.080	Yes
% Pass #4	972	5926	17.785	13.627	SD	<0.001	1.504	1.166	NSD	0.019	No
% Pass 3/8”	972	5926	14.027	11.738	SD	<0.001	0.815	0.424	SD	0.002	No
Pass 1/2”	989	6039	11.608	9.597	SD	<0.001	0.731	0.505	NSD	0.050	No
% Pass 3/4”	988	6009	4.849	4.357	NSD	0.012	0.033	0.079	NSD	0.531	No
% Pass 1”	994	6058	1.056	0.799	SD	<0.001	-0.054	-0.002	NSD	0.128	No
VFA	836	5210	35.811	24.960	SD	<0.001	9.657	8.845	SD	<0.001	No

Comparisons of paired Contractor QC and NCDOT QA test results in the reduced data set are contained in Table 35. As was the case for all JMFs, the comparisons of paired test results indicate more consistent statistically significant differences than comparisons of unpaired test results. Only the comparisons for % passing the ¾ and 1" sieves are not significantly different.

The reduced dataset will be analyzed by comparing JMF statistics. The analyses are similar to those project by project comparisons for Florida and Georgia DOT test results and are summarized in Table 36.

The JMF by JMF comparisons generally confirm trends indicated by comparisons of combined test results. These trends can be summarized as follows:

- Numerically, differences from target values of North Carolina DOT test results tend to be larger than contractor test results. Evidence for this conclusion are percentages in column 3 of Table 36 that are equal to 50% for passing ½" sieve or greater than 50% for all other properties.
  As noted previously, interpretation for VMA and % G_{mm} @ N_i are different. A graphical illustration for asphalt content is provided in Figure 22. Points for 80 of the 112 JMFs (71%) fall in the portion of the figure bounded by the dashed lines of absolute equality and centered on the horizontal axis. A complete set of figures for means and variances of the comparisons in Table 36 is contained in Appendix C. A final observation is that use of a property on control charts for acceptances appears to affect the percentages in column 3. The average is 72% for the first 6 properties, which are used for acceptance, and 61% for the last 6 properties, which are not used for acceptance.

Table 35. Comparison of Paired NCDOT QA and Contractor QC Test Results – JMFs with $n_{NCDOT} \geq 6$

Property	n	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value	Control
% Asphalt	992	-0.017	0.005	SD	0.003	Yes
Air Voids	971	-0.286	-0.146	SD	<0.001	Yes
VMA	971	1.185	1.452	SD	<0.001	Yes
% G_{mm} @ N_i	956	-0.863	-1.069	SD	<0.001	Yes
% Pass #200	992	0.181	0.124	SD	0.006	Yes
% Pass #8	991	0.526	0.223	SD	<0.001	Yes
% Pass #4	970	1.510	1.085	SD	<0.001	No
% Pass 3/8”	970	0.819	0.491	SD	<0.001	No
Pass 1/2”	987	0.728	0.459	SD	0.002	No
% Pass 3/4”	986	0.038	-0.024	NSD	0.314	No
% Pass 1”	991	-0.047	-0.031	NSD	0.618	No
VFA	834	9.663	9.112	SD	<0.001	No

Table 36. JMF by JMF Comparisons of North Carolina DOT QA and Contractor QC Mix Properties Test Results

Property	JMFs	JMFs with Larger NCDOT $\lvert\bar{\Delta}\rvert$	JMFs with SD $\bar{\Delta}$	JMFs with Sig. Larger NCDOT $\lvert\bar{\Delta}\rvert$	JMFs with Larger NCDOT s^2	JMFs with SD s^2	JMFs with Sig. Larger NCDOT s^2	Control
% Asphalt	112	80 (71%)*	5 (4%)	5 (4%)	59 (53%)	9 (8%)	7 (6%)	Yes
Air Voids	110	89 (81%)	15 (14%)	15 (14%)	88 (80%)	8 (7%)	8 (7%)	Yes
VMA	110	89 (81%)**	15 (14%)	15 (14%)**	73 (66%)	11 (10%)	9 (8%)	Yes
% G_{mm} @ N_i	108	71 (66%)***	16 (15%)	14 (13%)***	77 (71%)	9 (8%)	7 (6%)	Yes
% Pass #200	112	81 (72%)	28 (25%)	18 (16%)	61 (54%)	16 (14%)	13 (12%)	Yes
% Pass #8	112	71 (63%)	5 (4%)	4 (4%)	70 (62%)	9 (8%)	6 (5%)	Yes
% Pass #4	110	74 (67%)	2 (2%)	2 (2%)	55 (50%)	4 (4%)	4 (4%)	No
% Pass 3/8”	110	66 (60%)	4 (4%)	3 (3%)	48 (44%)	8 (7%)	4 (4%)	No
Pass 1/2”	92	46 (50%)	5 (5%)	4 (4%)	43 (47%)	11 (12%)	11 (12%)	No
% Pass 3/4”	46	28 (61%)	0	0	21 (46%)	1 (2%)	1 (2%)	No
% Pass 1”	21	12 (57%)	0	0	12 (57%)	1 (5%)	1 (5%)	No
VFA	94	60 (64%)	12 (13%)	10 (11%)	72 (77%)	10 (11%)	9 (10%)	No

* Numbers in parentheses are percentages of JMFs.

** Minimum VMA requirements are specified. These numbers indicate projects and percentages of projects where NCDOT VMA test results were smaller than contractor test results.

*** Maximum %G_{mm} @ N_i requirements are specified. These numbers indicate projects and percentages of projects where NCDOT %G_{mm} @ N_i test results were larger than contractor test results.

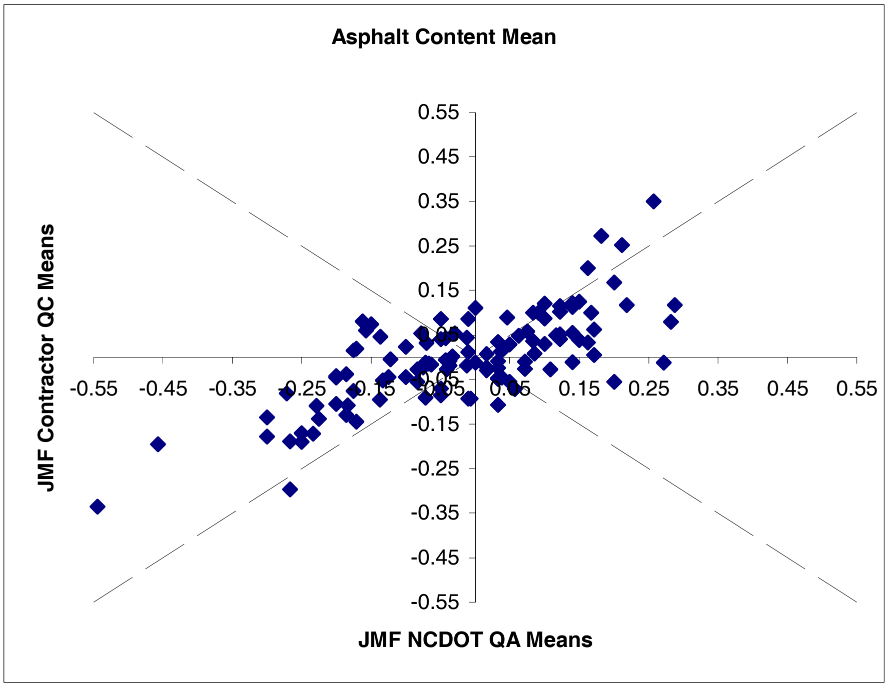


Figure 22. JMF Asphalt Content Mean Differences

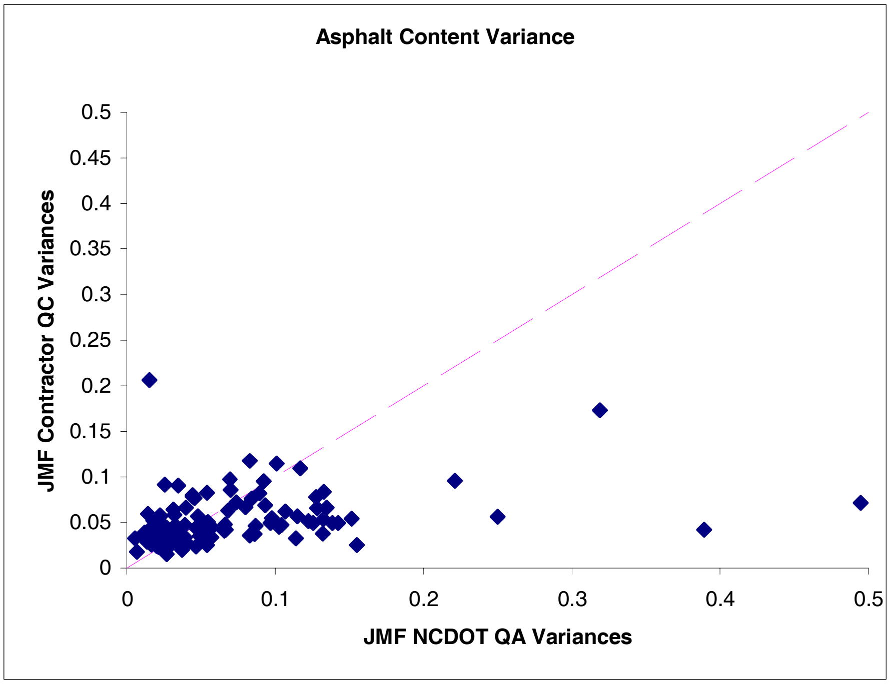


Figure 23. JMF Asphalt Content Variances

- Numerically, the variances of North Carolina DOT test results are generally larger than the variances of contractor test results. Evidence for this conclusion are the percentages in column 6 of Table 36 that are mostly (9 of 12) greater than or equal to 50%. A graphical illustration for asphalt content is shown in Figure 23 where points for 59 of 112 JMFs (53%) plot below the line of equality. The average percentage for the first 6 properties that are used for acceptance is 64%. For the last 6 properties that are not used for acceptance, the average is 54%.The average of 54% for the last 6 properties and the number of percentages near 50% is somewhat unusual. Larger, and significantly larger, DOT variances have been the norm in most analyses of data from Georgia and Florida.

- When mean differences from target values are significantly different, mean differences for North Carolina DOT test results are likely larger (90 of 107 JMFs). This can be confirmed by comparing numbers and percentages of JMFs in columns 4 and 5 of Table 36. The numbers and percentages of JMFs are quite similar. Again the use of a property for acceptance affects the percentages in columns 4 and 5. The average is 13% of JMFs with significantly different means for the first 6 properties (those used for acceptance) and 4% for the last 6 properties (column 4). The average is 11% of JMFs with significantly larger North Carolina DOT means for the first 6 properties and 3% for the last 6 properties (column 5).

- When variances are significantly different, variances for North Carolina DOT are likely larger (80 of 97 JMFs). This can be confirmed by comparing numbers and percentages of JMFs in columns 7 and 8 which are quite similar. The distribution of points along the horizontal axis in Figure 23 graphically illustrates the trend of significantly larger North Carolina DOT variances.

The second set of comparisons made were between Contractor QC and NCDOT Verification test results from all 735 JMFs. These test results are from independent samples. Table 37 contains comparisons of variances and means of differences from target values. The n_{NCDOT} values in Table 37 are about 35% of the n_{NCDOT} values in Table 32.

Except for % G_{mm} @ N_i, Table 37 indicates that the variances of North Carolina DOT and contractor test results are statistically significantly different. For all properties, North Carolina DOT variances are larger. The comparisons of variances in Table 37 for test results from independent samples are quite similar to the comparisons in Table 32 for test results from split samples. The only difference being the one property in each (VMA among split samples and % G_{mm} @ N_i among independent samples) that is not significantly different.

Significant differences for means are not as consistent. Table 37 indicates that means for 3 of 6 properties used in control charts were statistically significantly different, but that none of the remaining 6 properties have significantly different means. In total only 3 of 12 means are significantly different compared to 6 of 12 in Table 32. These numbers seem reasonable since Table 32 comparisons are for split sample test results and Table 37 comparisons are for test results from independent samples. Contractor means of differences are smaller for all properties except VMA and % G_{mm} @ N_i. However, the mean differences for these properties also indicate more favorable contractor test results.

Table 37. Comparison of NCDOT Verification and Contractor QC Test Results – All JMFs

Property	n_{NCDOT}	n_{CONT}	s^2_{NCDOT}	s^2_{CONT}	**Difference**	**p-Value**	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	**Difference**	**p-Value**	**Control**
% Asphalt	814	14396	0.082	0.059	SD	<0.001	-0.021	-0.003	NSD	0.067	Yes
Air Voids	817	14225	1.079	0.564	SD	<0.001	-0.161	-0.097	NSD	0.086	Yes
VMA	808	14225	2.130	1.803	SD	<0.001	1.217	1.507	SD	<0.001	Yes
% G_{mm} @ N_i	798	14017	2.262	2.091	NSD	0.060	-0.826	-1.028	SD	<0.001	Yes
% Pass #200	814	14396	0.841	0.490	SD	<0.001	0.194	0.095	SD	0.002	Yes
% Pass #8	814	14397	13.829	8.210	SD	<0.001	0.489	0.307	NSD	0.168	Yes
% Pass #4	798	14175	22.830	15.277	SD	<0.001	1.428	1.140	NSD	0.094	No
% Pass 3/8”	797	14194	20.914	13.753	SD	<0.001	0.749	0.547	NSD	0.220	No
Pass 1/2”	810	14347	16.661	10.621	SD	<0.001	0.776	0.506	NSD	0.065	No
% Pass 3/4”	808	14335	7.208	5.316	SD	<0.001	0.139	0.121	NSD	0.852	No
% Pass 1”	810	14383	1.586	0.992	SD	<0.001	-0.032	-0.020	NSD	0.792	No
VFA	723	12795	48.719	28.629	SD	<0.001	8.919	8.574	NSD	0.192	No

The comparisons summarized in Table 38 are for a reduced database (JMFs for which $n_{NCDOT} \geq 6$). The numbers of test results are only about 10% of those in Table 37 and represent only 12 of the 735 JMFs. There are a few differences in the various comparisons but the general trends indicated in Table 38 are similar to those indicated in Table 37.

The reduced Verification database was analyzed for JMF by JMF comparisons. The comparisons are similar to those for the reduced QA database (Table 36) and are summarized in Table 39. The number of JMFs compared by property in Table 39 (12 maximum) is small compared to the number in Table 36 (112 maximum), but the general trends demonstrated are similar.

Mean square deviations for mix properties are summarized in Table 40. The nominal is best (NIB) condition is applicable for the properties in Table 40 since each has a target value. VMA and % G_{mm} @ N_i are not included since they have variable minimum and maximum acceptable values, respectively, and statistics for computation were not available. Statistics (s^2 and $\overline{\Delta}$) for all JMFs from Tables 32 and 37 were used in Equation 3 to compute MSD_{NIB}.

The MSD_{NIB} for Contractor QC tests of all properties were smallest indicating the best process control (material properties). The North Carolina DOT QA test MSD_{NIB} were largest for three properties and the North Carolina Verification test MSD_{NIB} were largest for seven properties.

Table 38. Comparison of NCDOT Verification and Contractor QC Test Results – JMFs with $n_{NCDOT} \geq 6$

Property	n_{NCDOT}	n_{CONT}	s^2_{NCDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value	Control
% Asphalt	93	1318	0.041	0.044	NSD	0.350	-0.041	-0.003	NSD	0.093	Yes
Air Voids	92	1318	0.663	0.403	SD	<0.001	-0.218	-0.111	NSD	0.220	Yes
VMA	92	1318	0.798	0.689	NSD	0.154	0.733	1.043	SD	0.001	Yes
% G_{mm} @ N_i	93	1318	0.740	1.030	NSD	0.022	-0.415	-0.717	SD	0.005	Yes
% Pass #200	93	1318	0.721	0.375	SD	<0.001	0.013	0.053	NSD	0.653	Yes
% Pass #8	93	1318	9.535	6.387	SD	0.002	0.495	0.291	NSD	0.535	Yes
% Pass #4	93	1318	13.529	8.879	SD	0.001	1.419	0.848	NSD	0.146	No
% Pass 3/8”	93	1318	10.013	7.911	NSD	0.050	-0.290	-0.957	NSD	0.029	No
% Pass 1/2”	93	1318	10.056	4.511	SD	<0.001	0.290	-0.162	NSD	0.178	No
% Pass 3/4”	93	1318	6.846	2.647	SD	<0.001	-0.258	0.083	NSD	0.218	No
% Pass 1”	93	1318	1.839	0.324	SD	<0.001	-0.290	-0.035	NSD	0.074	No
VFA	84	1227	32.760	20.346	SD	0.001	8.818	8.498	NSD	0.617	No

Table 39. JMF by JMF Comparisons of North Carolina DOT Verification and Contractor QC Mix Properties Test Results

Property	JMFs	JMFs with Larger NCDOT $\lvert\overline{\Delta}\rvert$	JMFs with SD $\overline{\Delta}$	JMFs with Sig. Larger NCDOT $\lvert\overline{\Delta}\rvert$	JMFs with Larger NCDOT s^2	JMFs with SD s^2	JMFs with Sig. Larger NCDOT s^2	Control
% Asphalt	12	8 (67%)	0	0	5 (42%)	1 (8%)	0	Yes
Air Voids	11	10 (91%)	1 (9%)	1 (9%)	8 (73%)	2 (18%)	2 (18%)	Yes
VMA	11	8 (73%)**	2 (18%)	2 (18%)**	6 (55%)	1 (9%)	1 (9%)	Yes
% G_{mm} @ N_i	12	8 (67%)***	1 (8%)	1 (8%)***	7 (58%)	1 (8%)	0	Yes
% Pass #200	12	10 (83%)	5 (42%)	5 (42%)	8 (67%)	0	0	Yes
% Pass #8	12	7 (58%)	0	0	6 (50%)	0	0	Yes
% Pass #4	12	9 (75%)	0	0	5 (42%)	0	0	No
% Pass 3/8"	12	5 (42%)	0	0	5 (42%)	1 (8%)	0	No
Pass 1/2"	8^+	2 (25%)	1 (12%)	0	3 (38%)	1 (12%)	1 (12%)	No
% Pass 3/4"	5^+	3 (60%)	1 (20%)	1 (20%)	2 (40%)	1 (20%)	0	No
% Pass 1"	2^+	2 (100%)	0	0	2 (100%)	1 (50%)	1 (50%)	No
VFA	11	8 (73%)	1 (9%)	1 (9%)	8 (73%)	1 (9%)	1 (9%)	No

Numbers in parentheses are percentages of JMFs.

** Minimum VMA requirements are specified. These numbers indicate JMFs and percents of JMFs where NCDOT VMA test results were smaller than contractor test results.

*** Maximum %G_{mm} @ N_i requirements are specified. These numbers indicate JMFs and percents of JMFs where NCDOT %G_{mm} @ N_i test results were larger than contractor test results.

\+ JMFs with 100% passing required and achieved were not included.

Table 40. Comparisons of Mean Square Deviations for North Carolina DOT Mix Data

Property	**MSD_{NIB}**		
	Contractor QC	**NCDOT QA**	**NCDOT Verification**
% Asphalt*	0.059	0.095	0.082
Air Voids*	0.573	1.125	1.105
VFA	102.142	123.676	126.494
% Passing #200*	0.499	0.814	0.879
% Passing #8*	8.304	14.631	14.068
% Passing #4	16.577	22.494	24.869
% Passing 3/8”	14.052	19.869	21.475
% Passing ½”	10.877	16.197	17.263
% Passing ¾”	5.331	6.935	7.227
% Passing 1”	0.992	1.385	1.587

* Property used for control.

Mat Density Comparisons

As noted previously, mat compaction is managed by project and acceptance is by LOT. A LOT is a days production and contractors may choose testing with nuclear gages or cores. A minimum mat density of 92% of G_{mm} is specified and pay factors computed with the equation

$$PF = 100\text{-}10\ (D)^{1.465} \quad \text{......} (4)$$

where

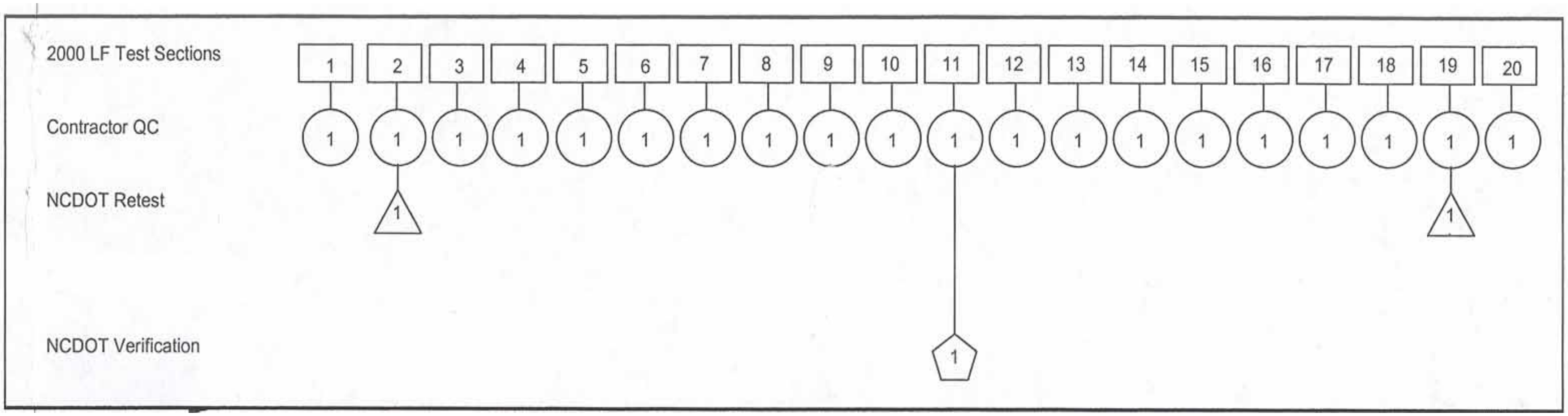
D = the deficiency in average LOT density, i.e., less than 92% of G_{mm}.

Average LOT compaction of 92% of G_{mm} and greater results in 100% pay.

Figure 24 illustrates North Carolina DOT's nuclear gage mat density testing requirements. Contractors conduct 5 tests at equal intervals in each 2000 foot test section. The North Carolina DOT conducts retest (same locations) in 10% of the test sections and conducts verification tests (independent locations) in 5% of the test sections. Results are reported as the average of 5 tests.

Analysis of combined nuclear gage testing for 141 JMFs is summarized in Table 41. The comparisons of variances and means are consistent for both North Carolina DOT Retest and Verification results and for all and for large JMFs ($n_{NCDOT} \geq 6$).

- Variances of North Carolina DOT nuclear gage mat density tests are significantly larger than contractor tests.



Notes:

1. Contractor may select cores or nuclear gages for mat density testing.
2. 5 tests per 2000 LF test section. Results reported as average of 5 tests.
3. NCDOT Retesting at 10% of Contractor QC rate. Conducted at same test locations.
4. NCDOT Verification testing at 5% of Contractor QC rate. Independent test locations.
5. Contractor QC and NCDOT Retest compared (Acceptable difference is ±2% G_{mm}).

Figure 24. North Carolina DOT HMAC Nuclear Gage Mat Density Testing Requirements

Table 41. Comparisons of North Carolina DOT and Contractor Nuclear Gage Mat Density Test Results

Data Sets	n_{NCDOT}	n_{cont}	s^2_{NCDOT}	s^2_{CONT}	**Difference**	**p-Value**	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	**Difference**	**p-Value**
QC vs. Retest All JMFs*	1255	9011	2.200	1.657	SD	<0.001	0.695	1.114	SD	<0.001
QC vs. Retest JMFs,** $n_{NCDOT} \geq 6$	1090	7466	1.992	1.118	SD	<0.001	0.663	1.118	SD	<0.001
QC vs. Verif. All JMFs*	588	9011	2.200	1.657	SD	<0.001	0.489	1.114	SD	<0.001
QC vs. Verif.* JMFs,** $n_{NCDOT} \geq 6$	379	4586	1.800	1.326	SD	<0.001	0.593	1.165	SD	<0.001

* Total of 141 JMFs analyzed.

** 76 JMFs with Retest $n_{NCDOT} \geq 6$

*** 34 JMFs with Verification $n_{NCDOT} \geq 6$

- Mean differences of North Carolina DOT nuclear gage mat density tests from the 92% G_{mm} minimum target are significantly different from contractor tests, and North Carolina DOT tests indicate poorer compaction, i.e., smaller Δ = X-92.

The nuclear gage mat density test results were provided in a format so that North Carolina DOT Retest test results could not be matched with specific Contractor QC test results. Therefore, paired t tests could not be performed on the subsets of matched Contractor QC and North Carolina DOT Retest test results.

JMF by JMF comparisons of nuclear gage tests are summarized in Table 42. Numerically, North Carolina DOT JMF mean differences from the 92% G_{mm} minimum indicate lower achieved densities (column 3). This is graphically illustrated in Figures 25 and 27 where 71% and 85%, respectively, of the points plot above the line of equality. In Figures 25 and 27 it is interesting to note the number of JMF where contractor test results show densities exceeding the 92% G_{mm} minimum ($+\overline{\Delta}$), but North Carolina DOT test results show densities less than the 92% G_{mm} minimum ($-\overline{\Delta}$). When JMF mean differences are significantly different, the North Carolina DOT values are likely smaller (columns 4 and 5 of Table 42).

Based on differences in variances for combined tests, as shown in Table 41, the differences in JMF variances are smaller than expected (61% and 50% in column 6 of Table 42). However, when differences in variances are statistically significant, North Carolina DOT variances are always larger (columns 7 and 8). These trends are graphically illustrated in Figures 26 and 28 by the distribution of points along the horizontal axes.

Table 42. JMF Comparisons of North Carolina DOT and Contractor Nuclear Gage Mat Density Test Results

Data Sets	**JMFs***	**JMFs with Smaller NCDOT $\overline{\Delta}$**	**JMFs with SD $\overline{\Delta}$**	**JMFs with Sig. Smaller NCDOT $\overline{\Delta}$**	**JMFs with Larger NCDOT s^2**	**JMFs with SD s^2**	**JMFs with Sig. Larger NCDOT s^2**
QC vs. Retest	76	54 (71%)	20 (26%)	18 (24%)	46 (61%)	16 (21%)	16 (21%)
QC vs. Verif.	34	29 (85%)	8 (24%)	7 (21%)	17 (50%)	8 (24%)	8 (24%)

* Total of 141 JMFs analyzed.

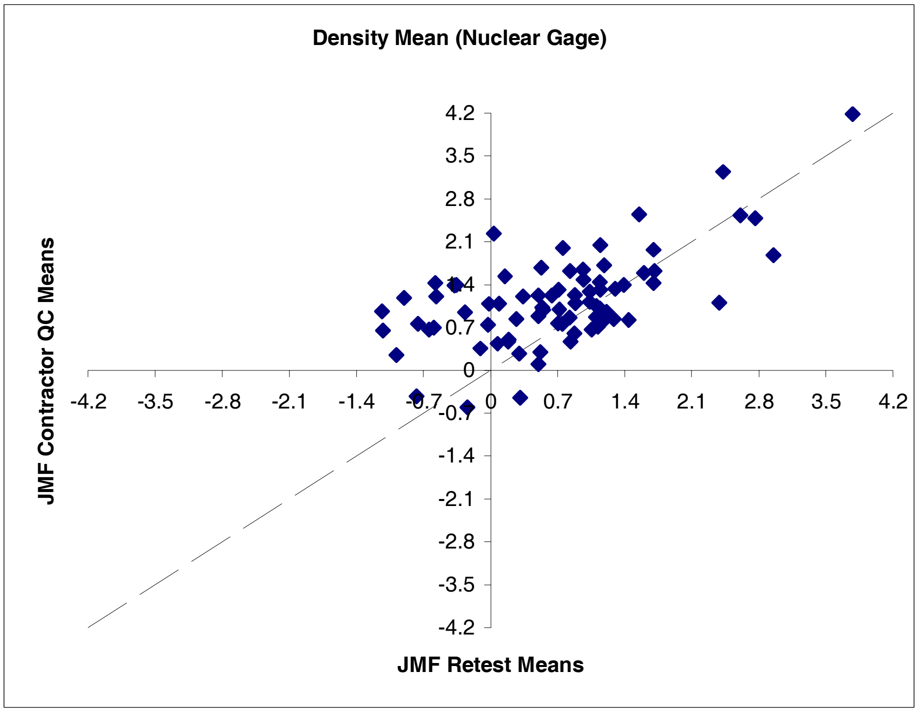


Figure 25. JMF Nuclear Gage Mat Density Mean Differences-NCDOT Retest and Contractor QC

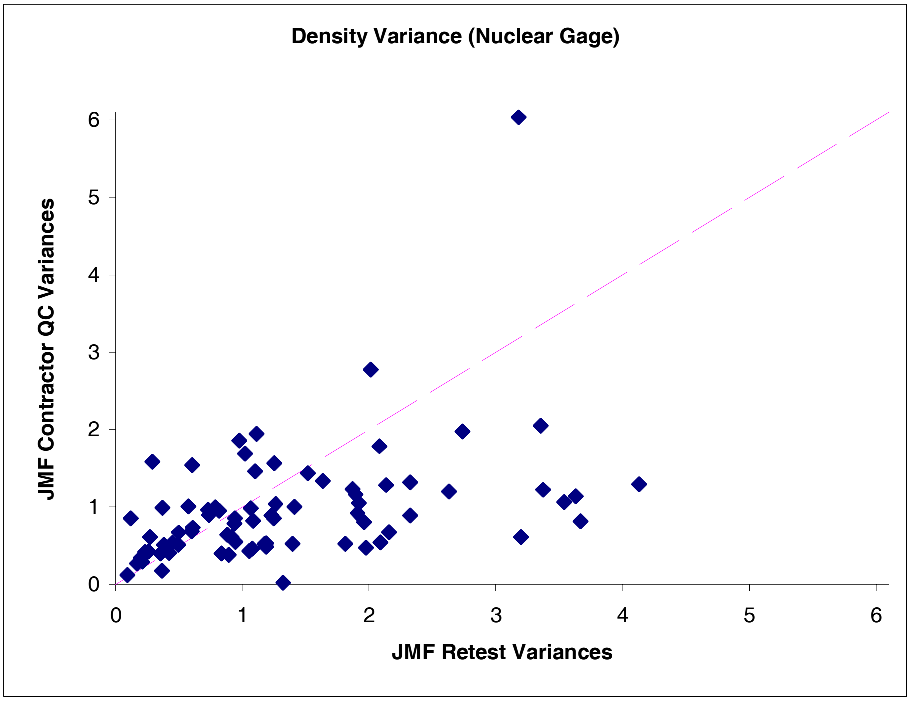


Figure 26. JMF Nuclear Gage Mat Density Variances – NCDOT Retest and Contractor QC

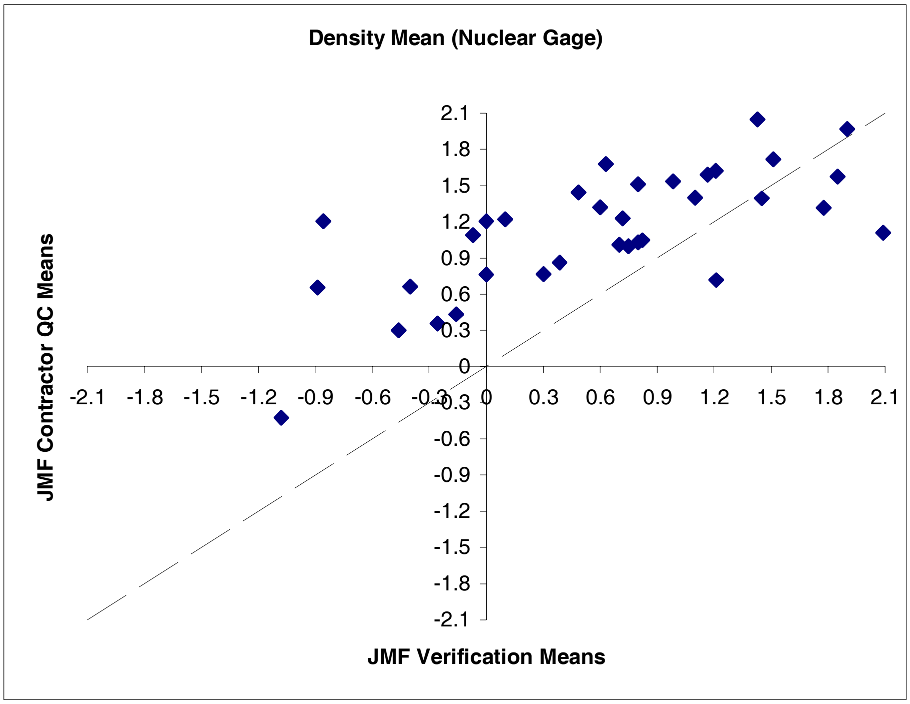


Figure 27. JMF Nuclear Gage Mat Density Mean Differences - NCDOT Verification and Contractor QC

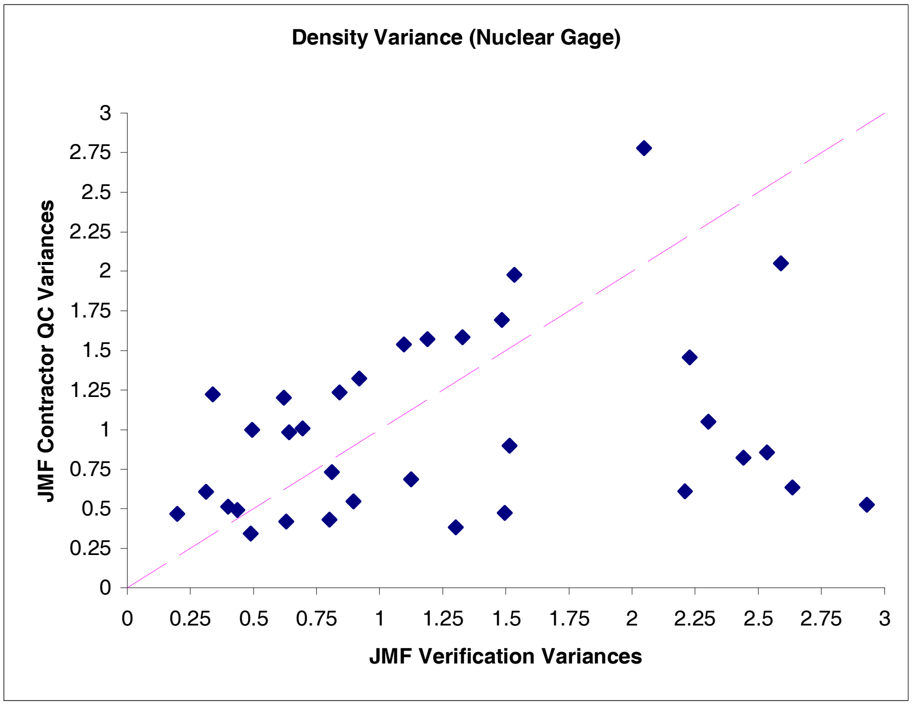


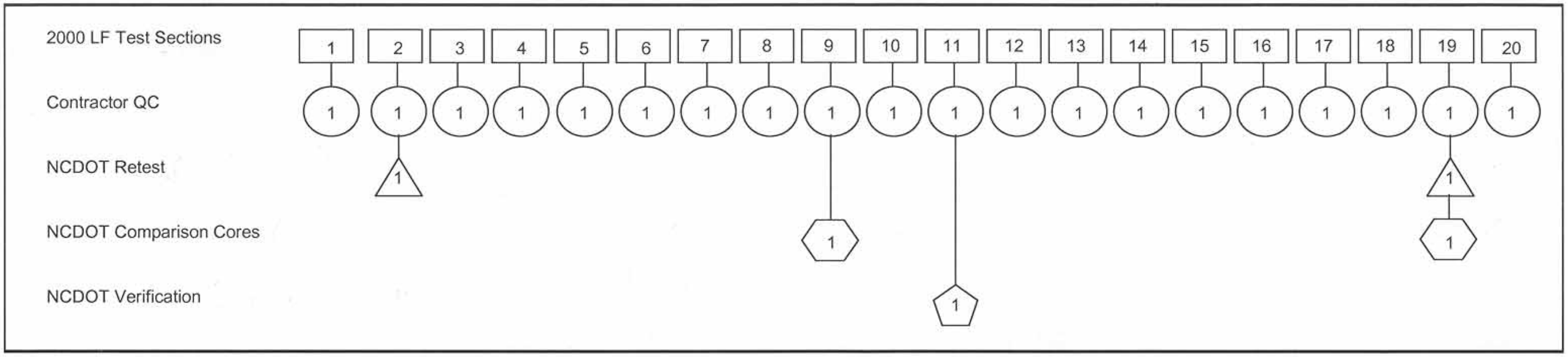
Figure 28. JMF Nuclear Gage Mat Density Variances – NCDOT Verification and Contractor QC

As noted previously, contractors may choose testing with either nuclear gages or cores for control and acceptance of mat compaction. Figure 29 illustrates North Carolina DOT core mat density testing requirements. Contractors take and test one core in each 2000 foot test section. The North Carolina DOT conducts retest (same cores) and tests comparison cores (taken adjacent to Contractor QC core locations) in 10% of the test sections. In addition, the North Carolina DOT tests one verification core from an independent location in 5% of the test sections.

Analyses of combined core testing for 585 JMFs are summarized in Table 43. The comparisons are consistent for North Carolina DOT Retest, Comparison and Verification test results for all and for large JMFs ($n_{NCDOT} \geq 6$).

- Variances of North Carolina DOT core mat density tests are significantly larger than contractor tests

- Mean differences of North Carolina DOT core mat density tests from the 92% G_{mm} minimum target are significantly different from contractor tests, and North Carolina DOT tests indicate poorer compaction, i.e., smaller Δ = X-92.



Notes:

1. Contractor may select cores or nuclear gages for mat density testing.
2. Contractors take and test 1 core per 2000 LF test section
3. NCDOT Retest and NCDOT Comparison Cores testing at 10% of Contractor QC rate.
4. NCDOT Comparison Cores taken adjacent to Contractor QC core location
5. NCDOT Verification testing at 5% of Contractor QC rate. Cores taken from independent locations.
6. NCDOT Retest and NCDOT Comparison Core test results compared, 1 to 1, with Contractor QC Core test results – NCDOT Retest limit of precision is ±0.030 and NCDOT Comparison Core limit of precision is ±0.050.

Figure 29. North Carolina DOT HMAC Core Mat Density Sampling and Testing Requirements

Table 43. Comparisons of North Carolina DOT and Contractor Core Mat Density Test Results

Data Sets	n_{NCDOT}	n_{cont}	s^2_{NCDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{NCDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value
QC vs. Retest All JMFs*	1530	20282	3.790	3.005	SD	<0.001	0.588	1.109	SD	<0.001
QC vs. Retest JMFs, $n_{NCDOT} \geq 6$**	1260	6379	3.674	3.086	SD	<0.001	0.411	1.043	SD	<0.001
QC vs. Comp. All JMFs*	3250	20282	4.897	3.005	SD	<0.001	0.794	1.109	SD	<0.001
QC vs. Comp.* JMFs, $n_{NCDOT} \geq 6$**	2254	13567	5.230	2.780	SD	<0.001	0.702	1.050	SD	<0.001
QC vs. Verif. All JMFs*	1817	20282	6.218	3.005	SD	<0.001	0.674	1.109	SD	<0.001
QC vs. Verif.+ JMFs, $n_{NCDOT} \geq 6$	1017	9331	7.167	2.970	SD	<0.001	0.473	1.063	SD	<0.001

* Total of 585 JMFs analyzed.

** 76 JMFs with Retest $n_{NCDOT} \geq 6$

*** 170 JMFs with Comparison $n_{NCDOT} \geq 6$

\+ 95 JMFs with Verification $n_{NCDOT} \geq 6$

The comparisons for core mat density tests are similar to those for nuclear gage tests in Table 41, i.e., variances and means are significantly different. The mean differences from the 92% G_{mm} minimum target are also similar in magnitude. However, the variances for nuclear gage and core tests are numerically different, with core variances consistently larger. Although there may be differences in the variability of nuclear gage and core testing, at least some portion of the observed differences are thought due to sample size. One core is taken per 2000 linear foot test section, but 5 nuclear gage tests are run per test section and the average recorded as a test result. This is thought to be the primary reason the variances of nuclear gage density tests are smaller than variances of core density tests. Since the acceptance procedure is the same for either type testing, it is surprising that contractors choose the core option (larger variance) about two times as often as the nuclear gage option (contractor n_{CORE}=20,282 and n_{NG}=9011).

As was the case for nuclear gage tests, the core test results were provided in a format so that North Carolina DOT Retest and Comparison test results could not be matched with specific contractor QC test results for paired t test analyses.

JMF by JMF comparisons are summarized in Table 44. Numerically, North Carolina DOT JMF mean differences from the 92% G_{mm} minimum indicate lower achieved densities (column 3). The percentages in column 3 of Table 44 are similar to percentages in column 3 of Table 42 for nuclear gage tests. The differences in contractor and North Carolina DOT core mean differences are illustrated in Figures 30, 32 and 34 where 80, 75 and 78%, respectively, of the points plot above the line of equality. As with nuclear gage tests, there are a surprising number of JMFs where

Table 44. JMF Comparisons of North Carolina DOT and Contractor Core Mat Density Test Results

Data Sets	JMFs*	JMFs with Smaller NCDOT $\overline{\Delta}$	JMFs with SD $\overline{\Delta}$	JMFs with Sig. Smaller NCDOT $\overline{\Delta}$	JMFs with Larger NCDOT s^2	JMFs with SD s^2	JMFs with Sig. Larger NCDOT s^2
QC vs. Retest	76	61 (80%)	8 (11%)	8 (11%)	37 (49%)	9 (12%)	4 (5%)
QC vs. Comparison	170	128 (75%)	8 (5%)	8 (5%)	113 (66%)	34 (20%)	32 (19%)
QC vs. Verification	95	74 (78%)	9 (9%)	9 (9%)	59 (62%)	15 (16%)	15 (16%)

* Total of 585 JMFs analyzed

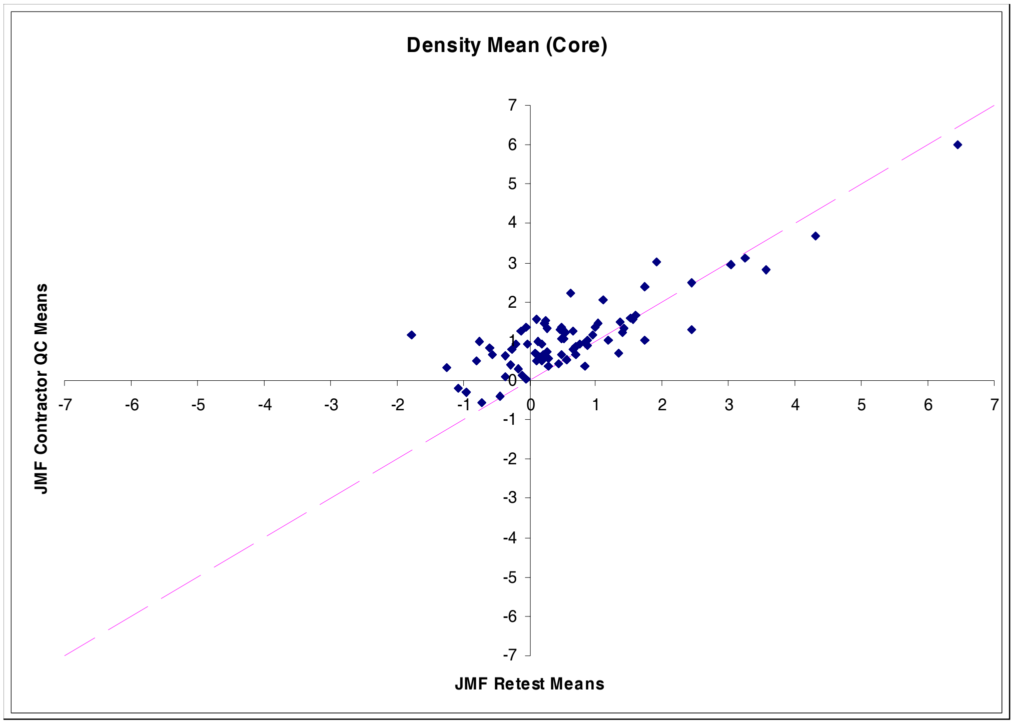


Figure 30. JMF Core Mat Density Mean Differences – NCDOT Retest and Contractor QC

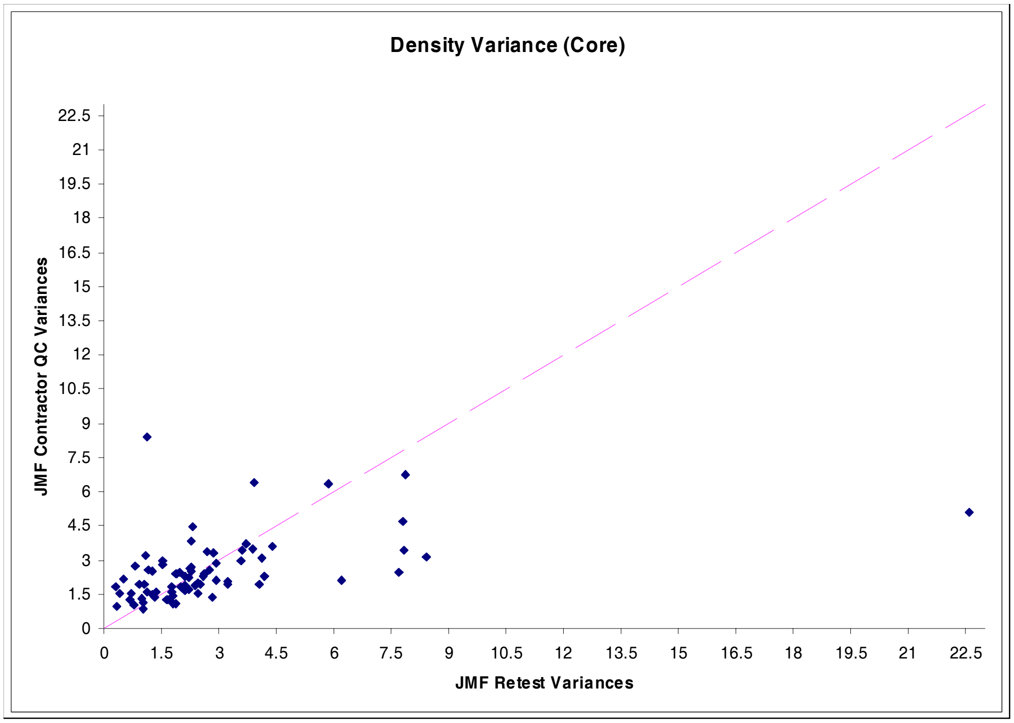


Figure 31. JMF Core Mat Density Variances – NCDOT Retest and Contractor QC

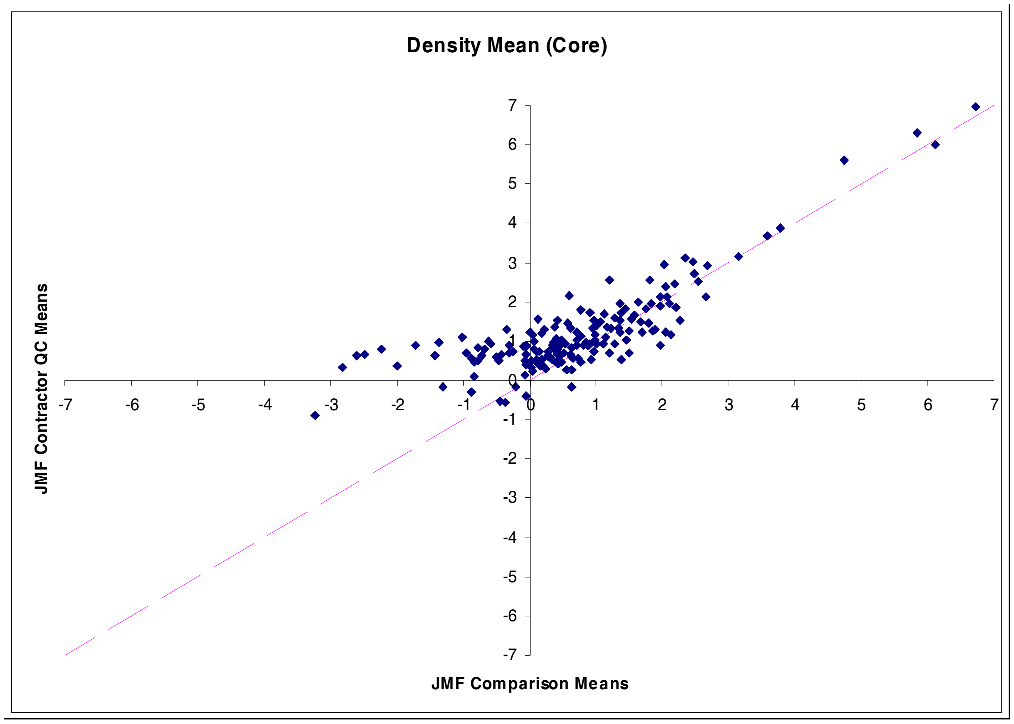


Figure 32. Core Mat Density Mean Differences – NCDOT Comparison and Contractor QC

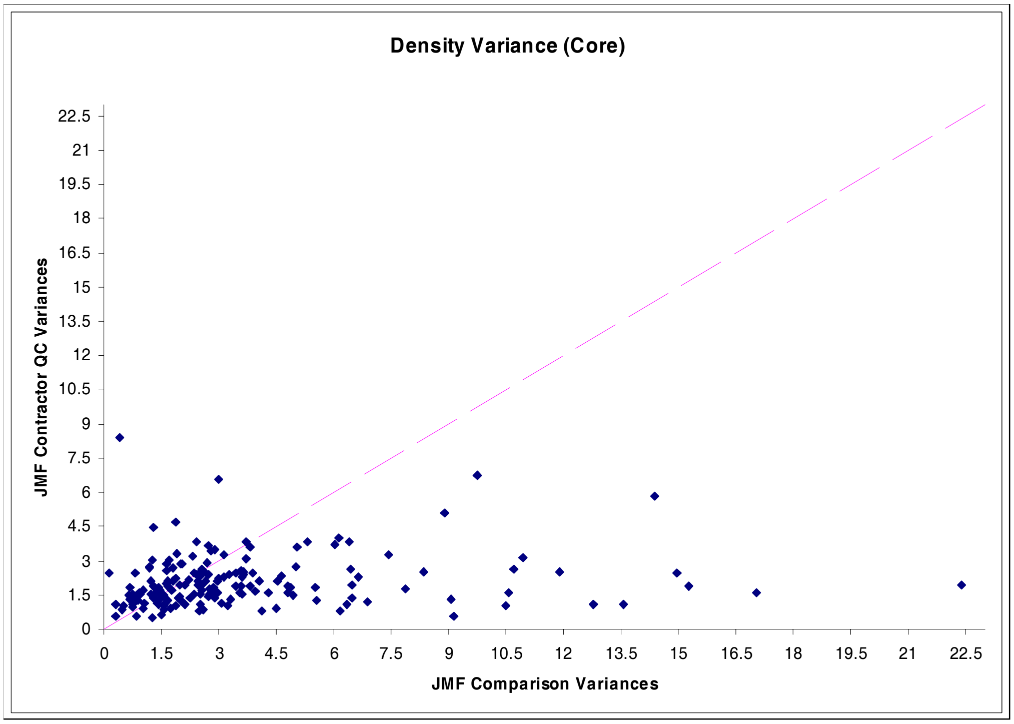


Figure 33. Core Mat Density Variances – NCDOT Comparison and Contractor QC

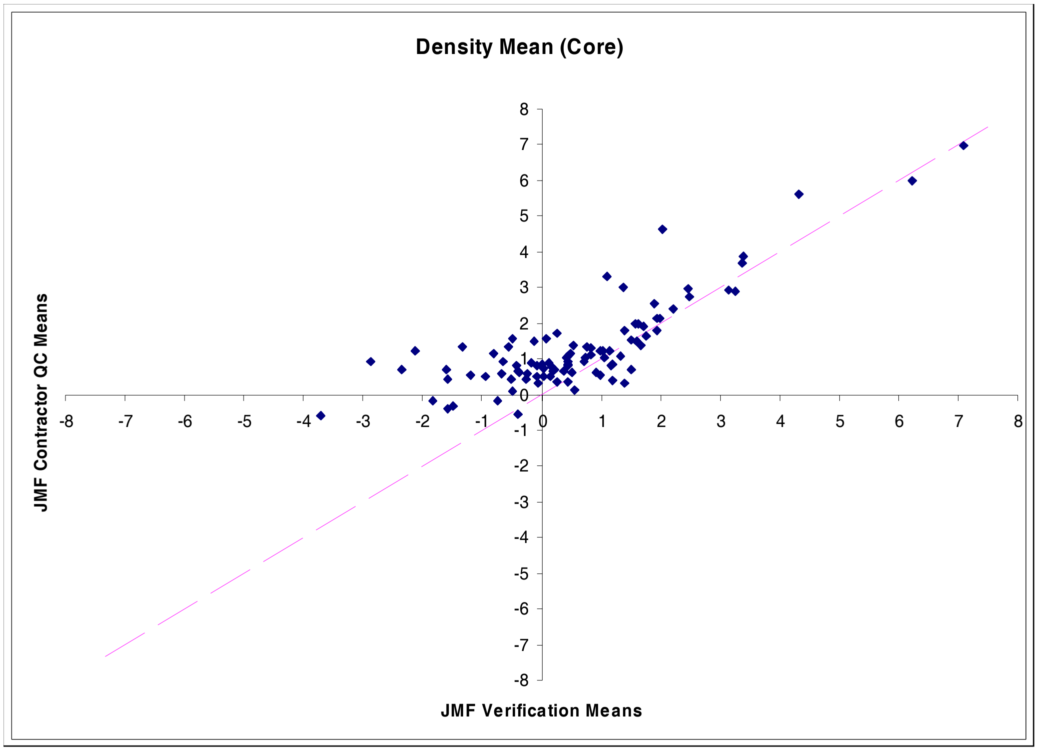


Figure 34. JMF Core Mat Density Mean Differences – NCDOT Verification and Contractor QC

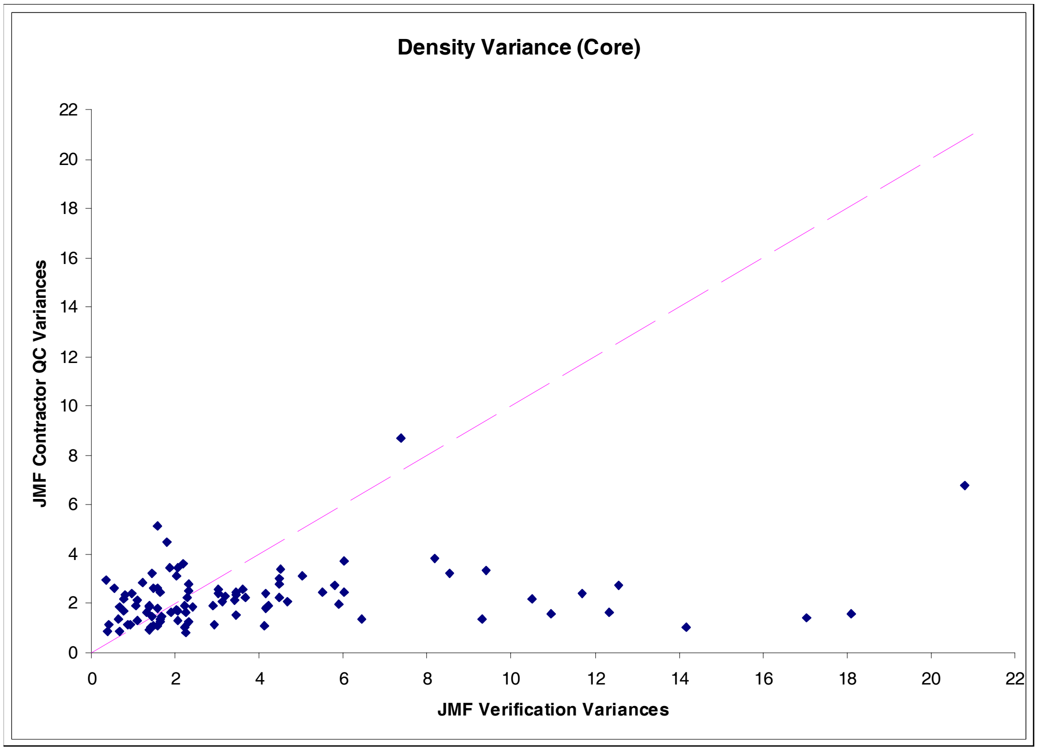


Figure 35. JMF Core Mat Density Variances – NCDOT Verification and Contractor QC

contractor tests indicate densities exceeding the 92% G_{mm} minimum but North Carolina DOT tests indicate densities less than the 92% G_{mm} minimum. When JMF mean differences are significantly different, the North Carolina DOT values are always smaller (columns 4 and 5 of Table 44).

Based on differences in variances for combined tests illustrated in Table 43, the differences in JMF variances in Table 44 are smaller than expected, (49, 66 and 62% in column 6). However, when differences in variances are significant, North Carolina DOT tests variances are almost always larger (columns 7 and 8). An exception is the Contractor QC and North Carolina DOT Retest core comparisons where the North Carolina DOT variances are larger for only 4 of 9 JMFs. Since the same cores are tested by both agencies what is surprising is any significant differences in mean differences from targets or variance. Job mix variances are plotted in Figures 31, 33 and 35. The distributions of points along the horizontal axes graphically illustrate the larger North Carolina DOT test variances.

North Carolina DOT specifications have a minimum acceptable mat density requirement of 92% of G_{mm}. Therefore, when computing mean square deviations, the largest is best situation is applicable. The largest is best mean square deviation (MSD_{LIB}) can be approximated with the equation

$$MSD_{LIB} \approx \frac{1}{\left(\overline{X}\right)^2}\left[1+\frac{3s^2}{\left(\overline{X}\right)^2}\right] \qquad \text{...(5)}$$

where

$\overline{X}$ = mean of measurements and

s^2 = variance of measurements.

To compute the MSD_{LIB} for mat density tests in Table 45, the statistics (s^2 and $\overline{\Delta}$) for all JMFs from Tables 41 and 43 were used. Means were computed by adding the minimum mat density requirement (92% of G_{mm}) to the mean deviations ($\overline{X} = \overline{\Delta} + 92$).

The contractor MSD_{LIB} are smallest for both nuclear gage and core tests of mat density indicating the best process control (mat compaction). The MSD_{LIB} for the several North Carolina DOT tests are all relatively similar. Comparable values for nuclear gage and core tests are close and are an indication that the means dominate the computations since the variances of core tests are considerable larger than variances of nuclear gage tests.

Table 45. Comparisons of Mean Square Deviations for North Carolina DOT Mat Density Data

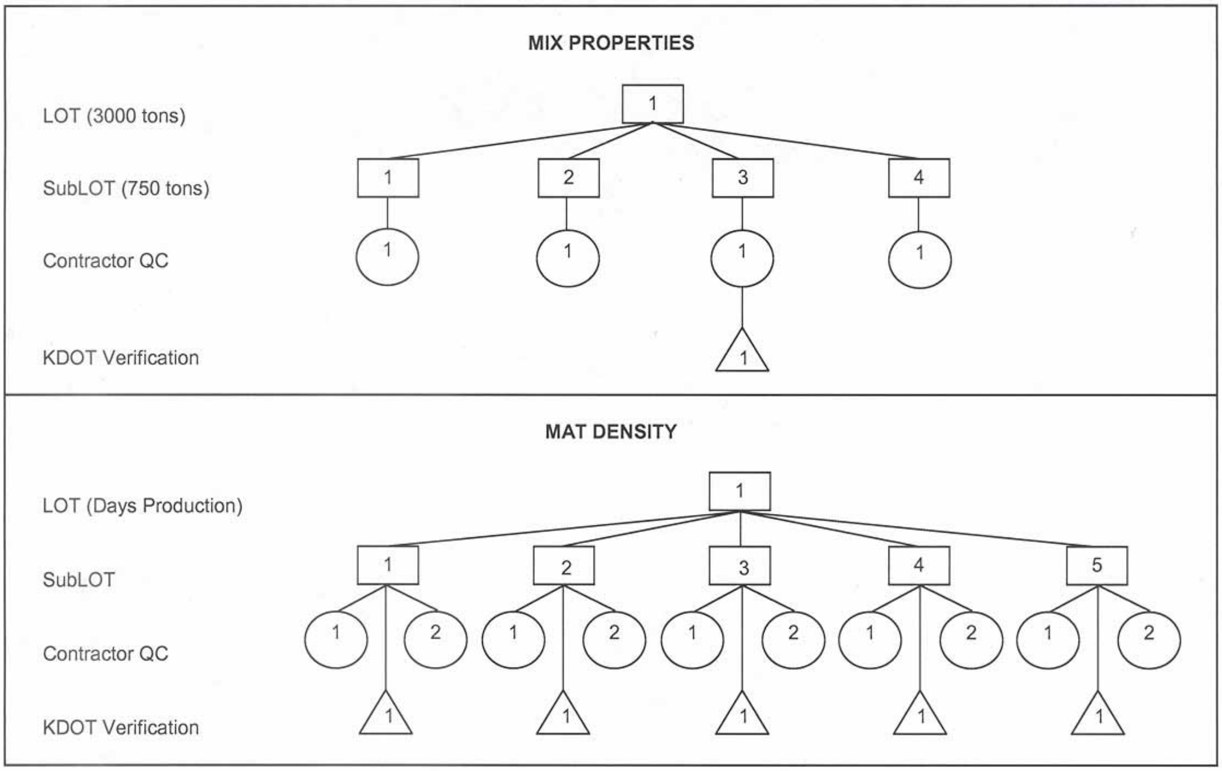
Data Set	**MSD_{LIB}**	
	Nuclear Gage	**Core**
Contractor QC	1.154×10^{-4}	1.155×10^{-4}
NCDOT Retest	1.165×10^{-4}	1.168×10^{-4}
NCDOT Verification	1.170×10^{-4}	1.167×10^{-4}
NCDOT Comparison	-	1.163×10^{-4}

ANALYSIS OF KANSAS DOT HOT MIX ASPHALT CONCRETE DATA

Test results from 49 projects constructed during the 2003 season were analyzed. Properties compared were theoretical maximum mix specific gravity, air void content of laboratory compacted specimens and mat density. Mat density is typically measured with nuclear gages but may also be measured with cores. Gradation and asphalt content are measured by both contractors and Kansas DOT, but only for process control. Gradation and asphalt content test results are not archived by the Kansas DOT and, therefore, were not available for analysis.

Figure 36 illustrates Kansas DOT sampling and testing requirements for managing the production and placement of HMAC. A LOT for mix properties is 3000 tons that is divided into four-750 ton subLOTs. Contractors take one QC sample per subLOT and the Kansas DOT takes one independent verification sample for each LOT (4 to 1 sampling ratio). Means of contractor QC test results are compared with means of Kansas DOT verification test results with t or modified t tests ($\alpha = 0.01$). If verified, contractor QC test results are used for LOT acceptance.

A LOT for mat density is a day’s production that is divided in 5 subLOTs. Contractors make two and the Kansas DOT one independent mat density measurement for each subLOT (2 to 1 sampling ratio). Means of the 10 contractor LOT QC test results are compared with means of the 5 Kansas DOT LOT Verification test results with t or modified t tests ($\alpha = 0.01$). If verified, contractor QC test results are used for LOT acceptance.



Notes:

1. KDOT Verification sampling and testing independent of Contractor QC.
2. Mix properties for LOTs 1 and 2: KDOT Verification test result compared with means of Contractor LOT QC test results. For LOTs 3 and greater, *t* or modified *t* tests used to compare Contractor QC and KDOT Verification test result means. Test results for a maximum of 5 consecutive LOTs are combined.
3. Mat density may be measured with nuclear gages or cores.
4. Means of contractor LOT QC mat density test results (n = 10) compared to means of KDOT LOT Verification mat density test results (n = 5) with *t* or modified *t* tests. Same average LOT G_{mm} used with contractor and KDOT measure mat densities to compute $\%G_{mm}$ values.

Figure 36. Kansas DOT HMAC Sampling and Testing Requirements

Kansas DOT has no target mat density but uses the PWL system for computing pay adjustments with a lower specification limit (LSL). To combine data from multiple projects with different LSL, the following variable was defined:

$$\Delta = X\text{-}LSL \qquad (6)$$

where X = = 90% for shoulder paving
= 91 % for mainline paving 2 inches thick and less
= 92 % for mainline paving thicker than 2 inches.

Comparisons of variances and means of Kansas DOT and contractor tests for combined data from all projects are summarized in Table 46. Variances for Kansas DOT tests are significantly larger for all comparisons. Means are significantly different for mat density (%G_{mm}) for the combined data and for both thin (≤ 2”) or thick (>2”) mainline (ML) paving.

The Kansas DOT mean of differences from the air voids target is the largest. Contractor means of differences from mat density lower specification limits (LSL) are largest and indicate better mat compaction.

The data was sorted into a reduced data set for projects with $n_{KDOT} \geq 6$. Comparisons of variances and means for this reduced data set are summarized in Table 47. The comparisons for air voids and %G_{mm} are the same as those in Table 46. Kansas DOT variances are significantly larger than contractor variances. The air voids means are not significantly different but the contractor mean difference from lower compaction specification limits is significantly larger than the Kansas DOT mean difference.

Table 46. Comparisons of Kansas DOT Verification and Contractor QC Test Results – All Projects

Property	n_{KDOT}	n_{CONT}	s^2_{KDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{KDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value
Air Voids	393	1494	0.643	0.318	SD	<0.001	0.322	0.262	NSD	0.164
% G_{mm} Combined	2281	4554	3.016	1.674	SD	<0.001	1.429	1.642	SD	<0.001
% G_{mm} shoulders	341	681	2.443	0.927	SD	<0.001	2.322	2.375	NSD	0.569
% G_{mm} ML ≤ 2”	1301	2606	3.190	2.086	SD	<0.001	1.448	1.655	SD	<0.001
% G_{mm} ML > 2”	639	1267	2.283	0.764	SD	<0.001	0.914	1.219	SD	<0.001

Table 47. Comparisons of Kansas DOT Verification and Contractor QC Test Results – Projects with $n_{KDOT} \geq 6$

Property	n_{KDOT}	n_{CONT}	s^2_{KDOT}	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{KDOT}$	$\overline{\Delta}_{CONT}$	Difference	p-Value
Air Voids	298	1140	0.568	0.310	SD	<0.001	0.366	0.281	NSD	0.068
% G_{mm} Combined	2214	4438	3.021	1.704	SD	<0.001	1.454	1.645	SD	<0.001

Project by project comparisons are summarized in Table 48. Data for theoretical maximum mix specific gravity (G_{mm}) are included in project comparisons. The numbers of projects and percentages in column 3 indicate Kansas DOT differences from target air voids and G_{mm} test results are likely largest but that contractor differences from mat density lower specification limits are likely largest. These trends are graphically illustrated in Figures 37, 39 and 41. Column 4 indicates only project deviations from mat density lower specification limits are likely significantly different and column 5 indicates that it is contractor project deviations that are likely larger.

Column 6 indicates project variances for Kansas DOT test are likely largest. These trends are graphically illustrated in Figures 38, 40 and 42 where more points plot below the lines of equality. The numbers of projects and percentages in column 7 show the likelihood that variances of Kansas DOT and contractor tests are significantly different. The numbers of projects and percentages in column 8 are the same as those in column 7 and indicates that, when variances are significantly different, Kansas DOT variances are always largest. The points that lie along the horizontal axes in Figures 38, 40 and 42 illustrate this trend.

A final comparison will be between the mean square deviations of Kansas DOT and contractor tests in Table 49. The nominal is best situation is applicable for air voids and Equation 3 was used for computations. The largest is best situation is applicable for mat density and Equation 5 was used for computations. The MSD for contractor tests are always smaller indicating better process control (material quality).

Table 48. Project Comparisons of Kansas DOT and Contractor QC Test Results

Property	**Projects**	**Projects with Smaller KDOT $\overline{\Delta}$**	**Projects with SD $\overline{\Delta}$**	**Projects with Significantly Smaller KDOT $\overline{\Delta}$**	**Projects with Larger KDOT s^2**	**Projects with SD s^2**	**Projects with Significantly Larger KDOT s^2**
Air Voids	24	18 (75%)	0	0	19 (75%)	5 (21%)	5 (21%)
G_{mm}*	23	14 (61%)	3 (13%)	3 (13%)	16 (70%)	2 (9%)	2 (9%)
%G_{mm} Combined	24	18 (75%)	11 (46%)	10 (42%)	22 (92%)	13 (54%)	13 (54%)

* No target values for G_{mm} so comparisons are for actual measurements.

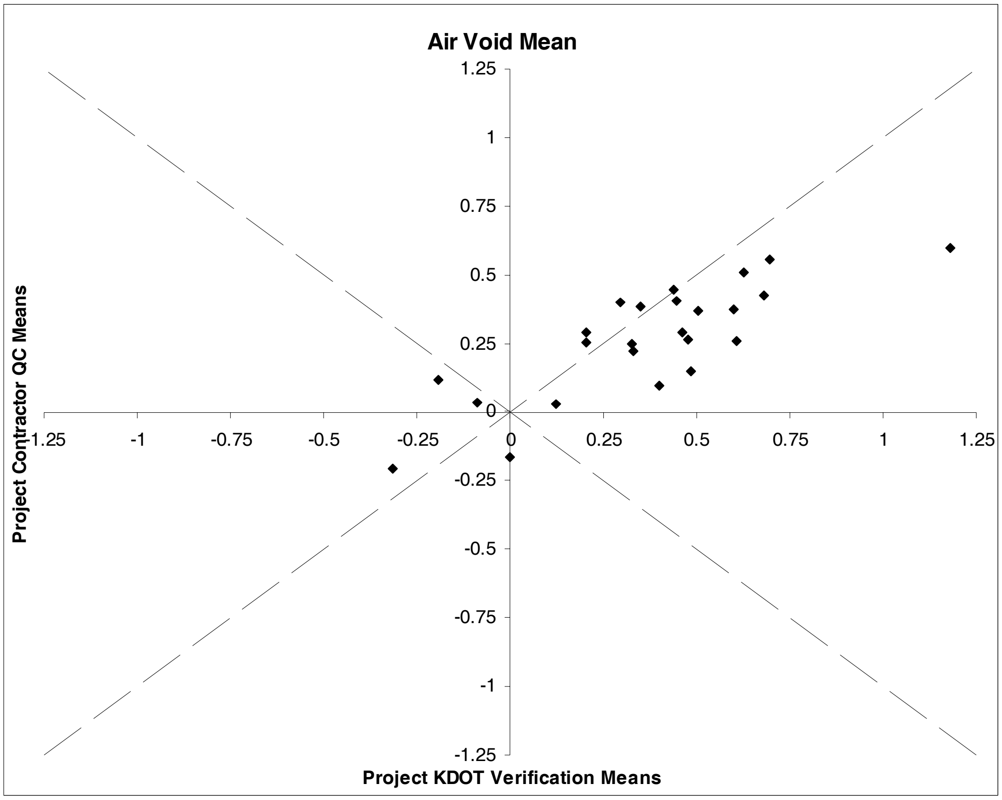


Figure 37. Air Void Project Means - KDOT Verification and Compliance

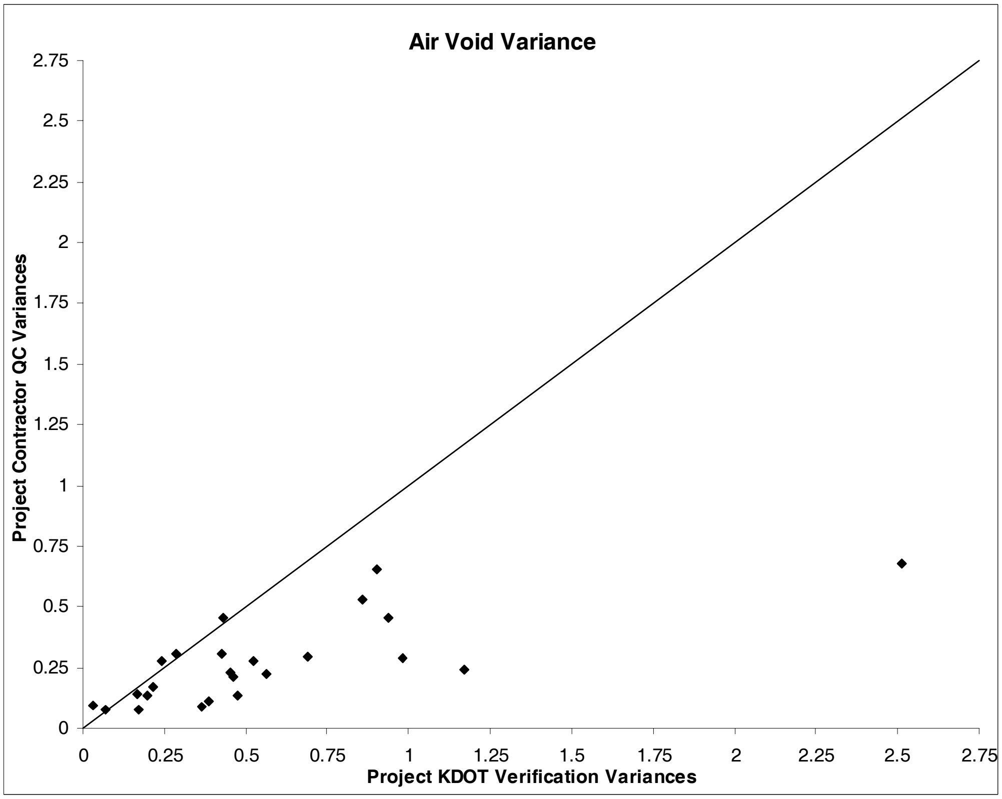


Figure 38. Air Void Project Variances - KDOT Verification and Contractor QC

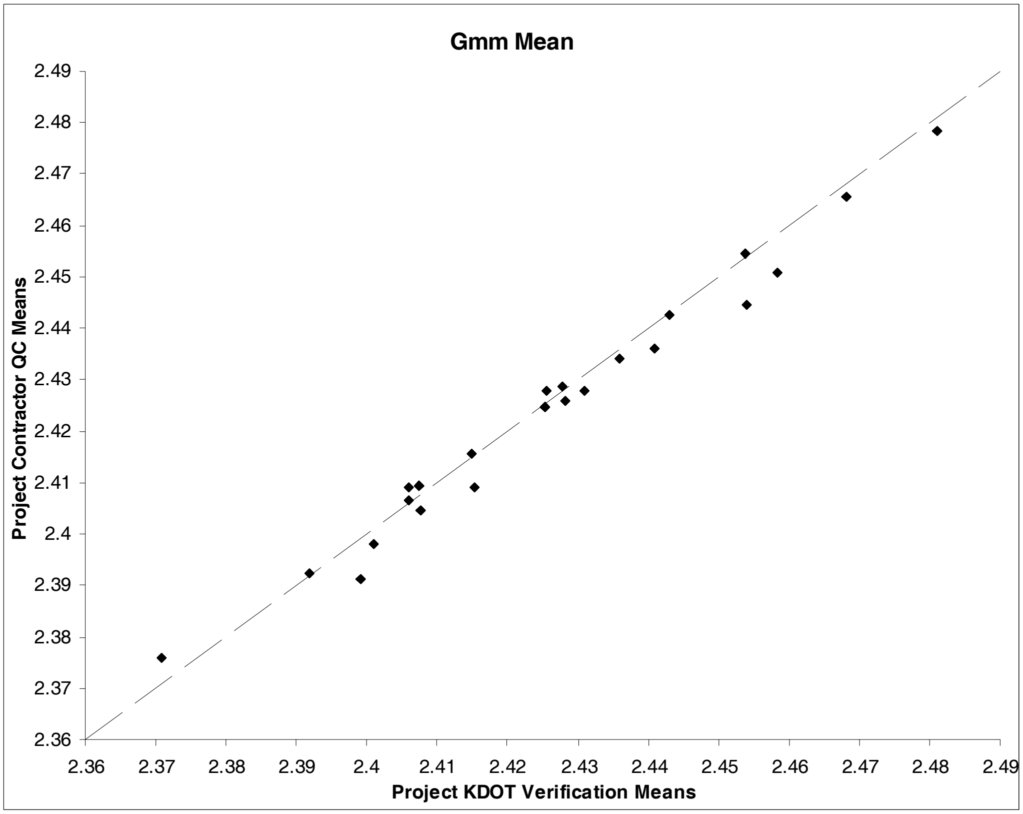


Figure 39. Theoretical Maximum Mix Specific Gravity Project Means - KDOT Verification and Contractor QC

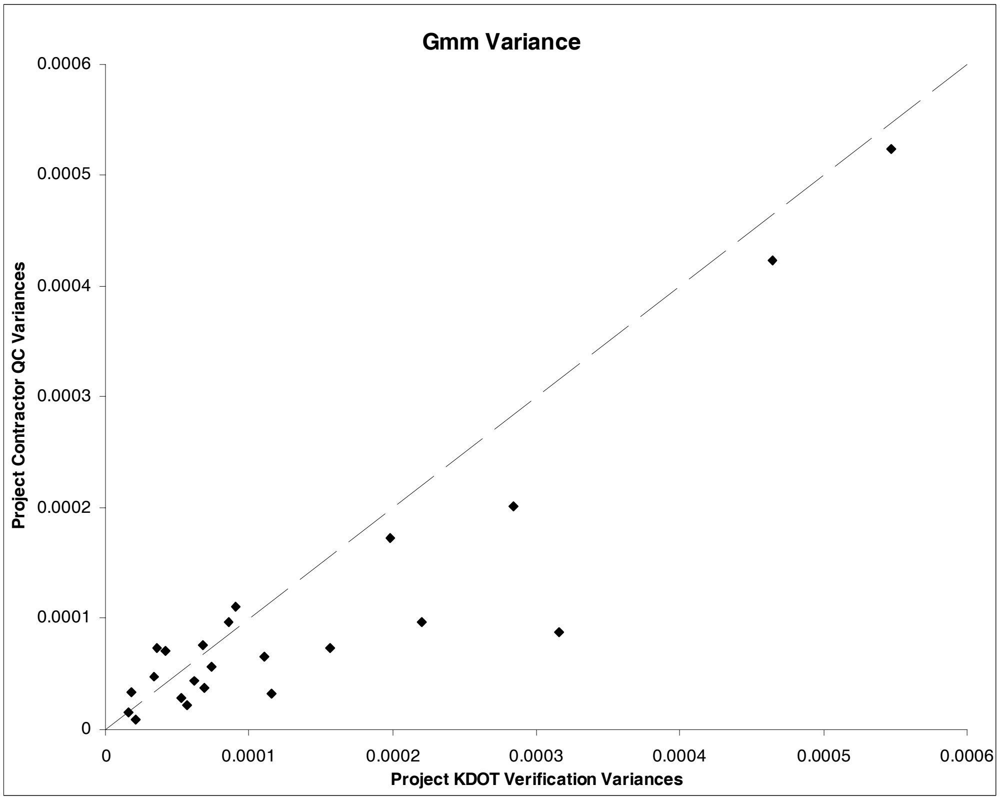


Figure 40. Theoretical Maximum Mix Specific Gravity Project Variances - KDOT Verification and Contractor QC

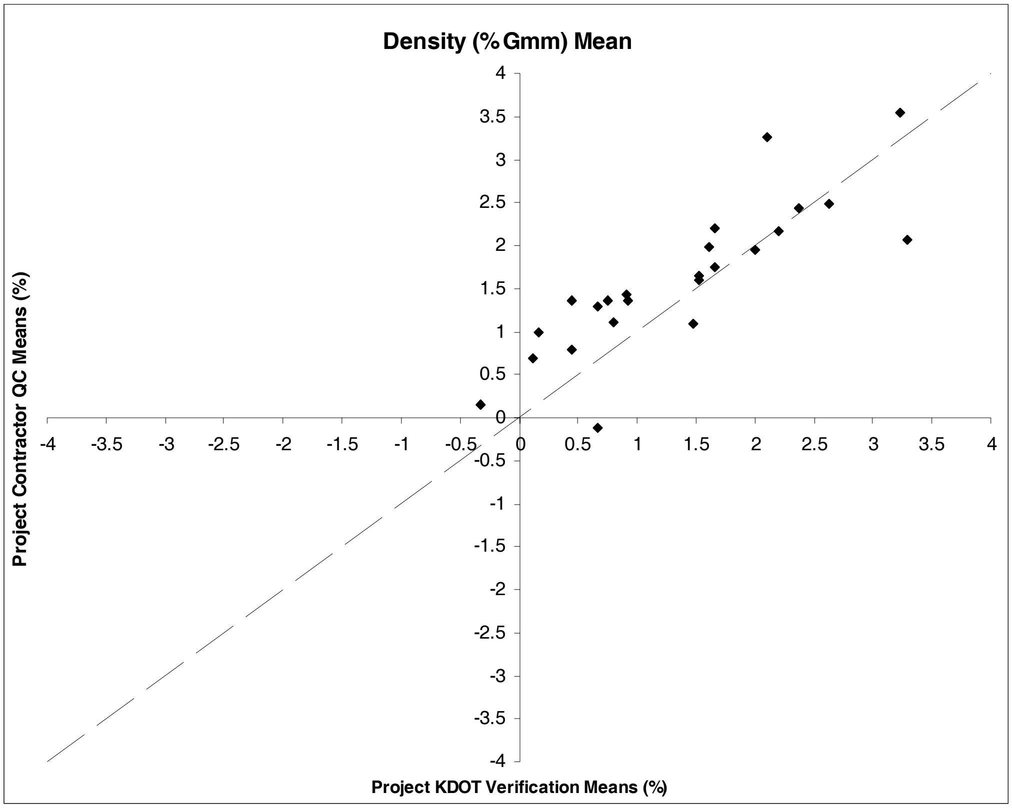


Figure 41. Mat Density Project Means - KDOT Verification and Contractor QC

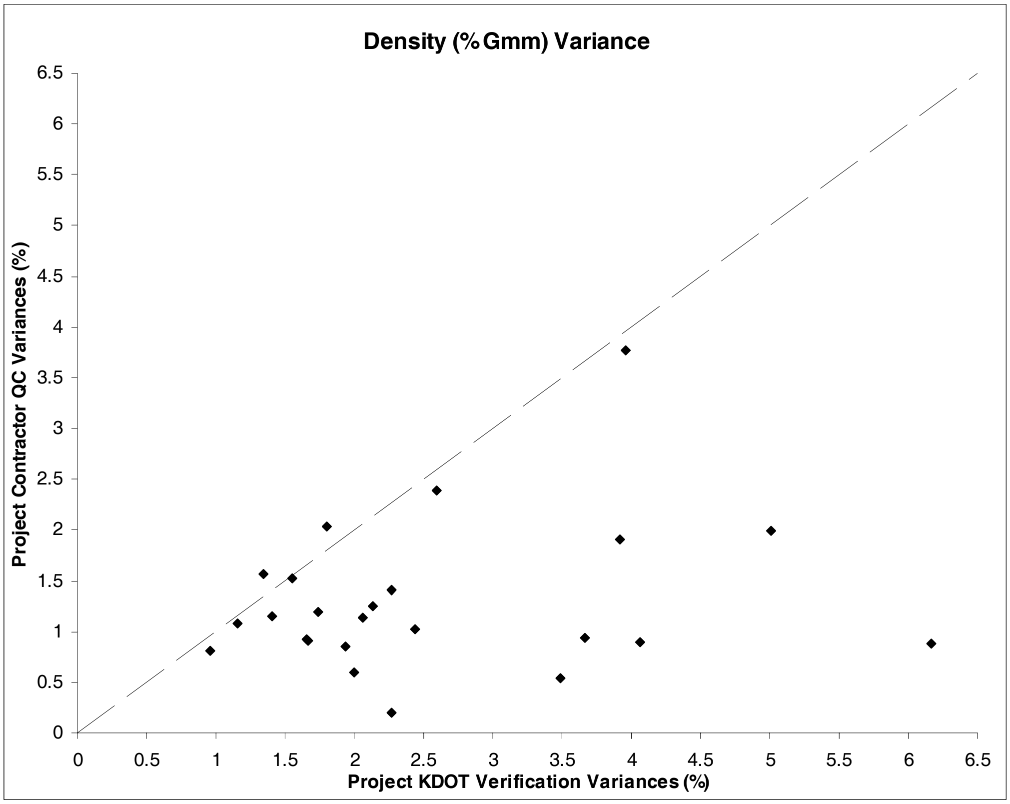


Figure 42. Mat Density Project Variances - KDOT Verification and Contractor QC

Table 49. Mean Square Deviations for Kansas DOT Verification and Contractor QC Tests

Property	MSD	
	KDOT Verification	Contractor QC
Air Void Content	0.747	0.387
Mat Density – LSL = 90%	1.174×10^{-4}	1.172×10^{-4}
Mat Density – LSL = 91%	1.171×10^{-4}	1.165×10^{-4}
Mat Density – LSL = 92%	1.159×10^{-4}	1.151×10^{-4}

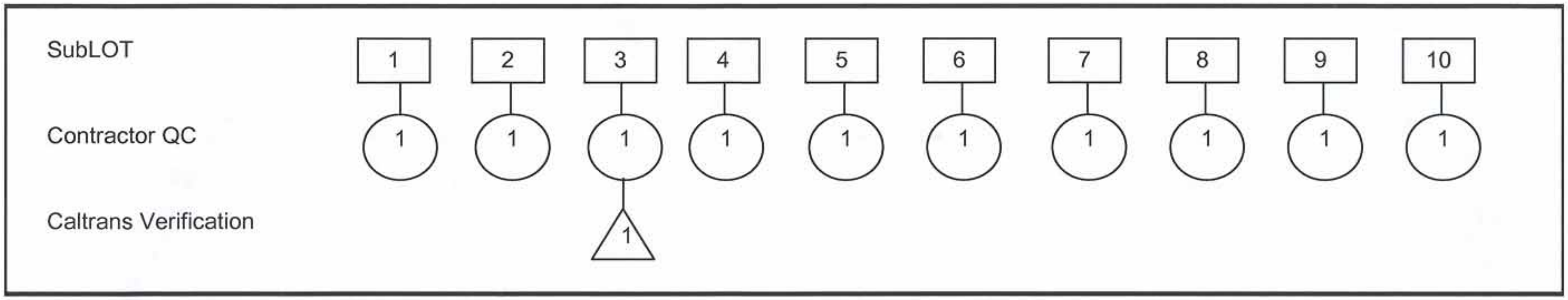
ANALYSIS OF CALTRANS HOT MIX ASPHALT CONCRETE DATA

HMAC test results from 149 projects constructed from 1996 to 2005 were provided by Caltrans. Caltrans' quality assurance procedures use both mix properties and mat density for acceptance, but only test results for mix properties were provided. Test results included asphalt content and gradation (percents passing ¾" or ½", 3/8", #4, #8, #30 and #200 sieves).

Figure 43 illustrates Caltrans sampling and testing requirements for managing construction of HMAC pavement layers. A LOT for acceptance is the entire project production. For contractor QC sampling and testing a subLOT is 500 tons; Caltrans samples and tests for verification at a frequency not less than 10% of the contractor QC frequency. Caltrans samples independently for mix properties.

The PWL system is used to compute pay factors for mix properties and mat density. These pay factors are combined with weighting factors to compute composite LOT pay adjustments which may include up to a 5% bonus. Contractor QC test results are used for pay factor computation if verified by comparisons with Caltrans test results.

Verification requires acceptable comparison of means with the t test (α=0.01) and with numerical allowable testing differences. During production comparisons are apparently made that, if unfavorable, can result in a review process. Detection of errors can lead to retesting (portions of split samples), recalculations and, as a last resort, independent third party involvement.



Notes:

1. A LOT for acceptance is the entire project production for a specific mix design.
2. A subLOT for contractor QC sampling and testing is 500 tons. Samples are split and one split portion is retained for possible dispute resolution.
3. Caltrans samples and tests at a frequency not less than 10% of the contractor QC sampling and testing frequency.
4. Caltrans verification samples for mix properties are independent of contractor QC samples. Samples are split into 4 portions. One portion is provided to the contractor and 2 portions are retained for possible dispute resolution.
5. Caltrans verification samples for theoretical maximum mix density are split samples with the contractor. Caltrans and contractor nuclear gage mat density tests are conducted at the same location. Therefore, theoretical maximum mix density and relative compaction test results are paired.

Figure 43. Caltrans HMAC Sampling and Testing Requirements

The first comparisons made were between contractor QC and Caltrans tests for all 149 projects. Table 50 contains comparisons of variances and means of differences from target values for mix properties.

The variances for all 7 properties are significantly different and the variances of Caltrans tests are always largest.

The mean differences from targets for 4 of the 7 properties are significantly different. Except for the % passing the #30 sieve, the Caltrans mean differences from targets are largest for these 4 properties. The mean differences from targets are not significantly different for 3 properties, but the Caltrans mean differences from targets for all 3 of these properties are largest.

A reduced data set for large ($n_{CAL.} \geq 6$) projects was created from the total data set. Comparisons of project means and variances for these larger projects are summarized in Table 51. The trends indicated by these comparisons are as follows:

- Numerically, differences from target values of Caltrans test results tend to be larger than differences from target values for contractor test results. Evidence of this are the percentages of projects in column 3 of Table 51 that are all greater than 50%. A graphical illustration for asphalt content is provided in Figure 44 where 53 (65%) of the points fall in the portion of the figure that is bounded by the dashed lines of absolute equality and centered on the horizontal axis. A complete set of figures for mean differences and variances for all properties are contained in Appendix D.

Table 50. Comparisons of Caltrans Verification and Contractor QC Mix Properties

Property	n_{CAL}	n_{CONT}	$s^2_{CAL.}$	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{CAL.}$	$\overline{\Delta}_{CONT}$	Difference	p-Value
% Asphalt	1405	9258	0.087	0.042	SD	<0.001	0.036	-0.003	SD	<0.001
% Passing ¾ or ½”	1331	8553	4.863	3.319	SD	<0.001	0.951	0.719	SD	<0.001
% Passing 3/8”	1514	9585	11.082	6.478	SD	<0.001	-0.093	-0.049	NSD	0.619
% Passing #4	1514	9585	9.258	6.770	SD	<0.001	-0.517	-0.381	NSD	0.099
% Passing #8	1513	9585	8.303	5.423	SD	<0.001	-0.356	0.012	SD	<0.001
% Passing #30	1513	9585	5.363	3.203	SD	<0.001	-0.058	0.148	SD	0.001
% Passing #200	1507	9439	1.095	0.602	SD	<0.001	0.062	0.011	NSD	0.072

Table 51. Project by Project Comparisons of Caltrans Verification and Contractor QC Mix Properties Test Results

Property	Projects	Projects with Larger Caltrans $\lvert\overline{\Delta}\rvert$	Projects with SD $\overline{\Delta}$	Projects with Sig. Larger Caltrans $\lvert\overline{\Delta}\rvert$	Projects with Larger Caltrans s^2	Projects with SD s^2	Projects with Sig. Larger Caltrans s^2
% Asphalt	82	53 (65%)	26 (32%)	23 (28%)	56 (68%)	26 (32%)	25 (30%)
% Passing ¾ or ½"	77	54 (70%)	18 (23%)	16 (21%)	44 (57%)	17 (22%)	14 (18%)
% Passing 3/8"	86	61 (71%)	19 (22%)	15 (17%)	54 (63%)	17 (20%)	16 (19%)
% Passing #4	86	48 (56%)	12 (14%)	5 (6%)	61 (71%)	20 (23%)	20 (23%)
% Passing #8	86	53 (62%)	14 (16%)	11 (13%)	60 (70%)	23 (27%)	21 (24%)
% Passing #30	86	62 (72%)	13 (15%)	12 (14%)	57 (66%)	20 (23%)	18 (21%)
% Passing #200	85	52 (61%)	25 (29%)	18 (21%)	60 (71%)	31 (36%)	30 (35%)

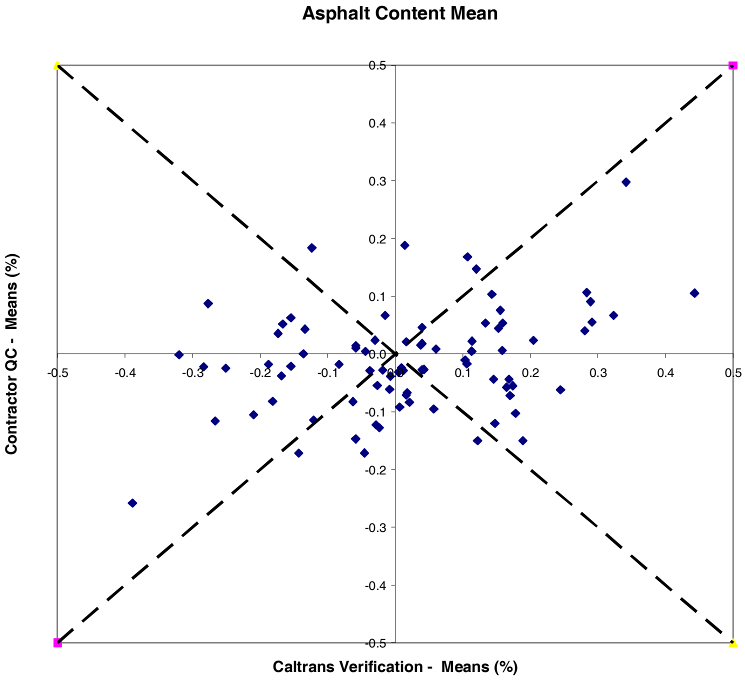


Figure 44. Project Asphalt Content Means – Caltrans Verification and Contractor QC

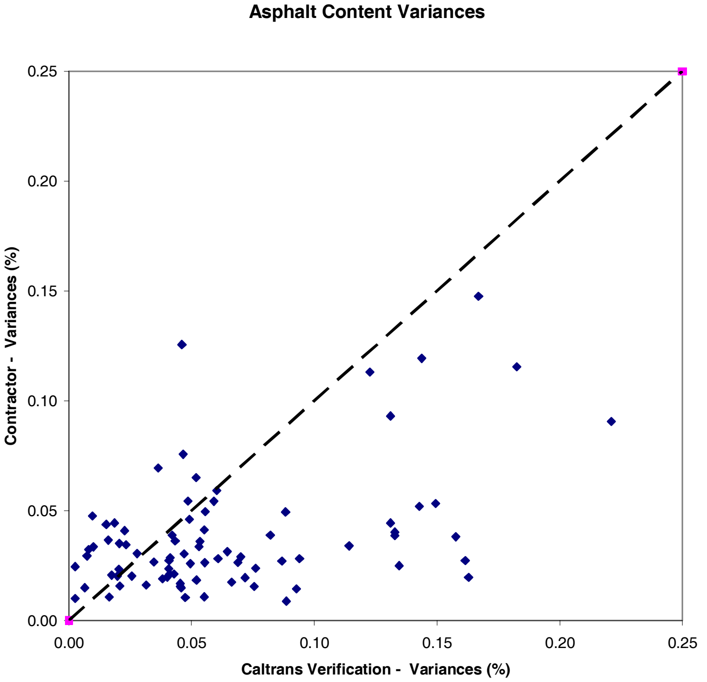


Figure 45. Project Asphalt Content Variances – Caltrans Verification and Contractor QC

- Numerically, variances of Caltrans test results are larger than variances of contractor test results. Evidence of this are the percentages of projects in column 6 that are all greater than 50%. A graphical illustration is provided in Figure 45 for asphalt content where 56 (68%) of the points plot below the line of equality.

- Except for % passing the #4 sieve, when mean differences from target values are significantly different, mean differences for Caltrans test results are likely larger. This can be confirmed by comparing numbers and percentages of projects in columns 4 and 5 which are similar.

- When variances are significantly different, variances of Caltrans test results are very likely larger. This can be confirmed by comparing numbers and percentages of projects in columns 7 and 8 which are quite similar.

Comparisons of variances and means of deviations from target values for combined data from large ($n_{CAL.} \geq 6$) projects are summarized in Table 52. Except for the #30 sieve, the comparisons for the large project data are the same as those in Table 50 for all projects. The contractor mean of differences from the #30 sieve target values is significantly larger for all projects but for large projects the means are not significantly different.

A final comparison will be between mean square deviations of Caltrans and contractor tests. The nominal is best situation is best for all properties and statistics from Table 50 were used in Equation 3 to compute the MSD_{NIB} in Table 53. The

MSD_{NIB} for contractor tests are smaller, indicating better process control (material quality).

Table 52. Comparisons of Caltrans Verification and QC Mix Properties Test Results – Large ($n_{CAL.} \geq 6$) Projects

Property	n_{CAL}	n_{CONT}	$s^2_{CAL.}$	s^2_{CONT}	Difference	p-Value	$\overline{\Delta}_{CAL.}$	$\overline{\Delta}_{CONT}$	Difference	p-Value
% Asphalt	1201	7480	0.084	0.041	SD	<0.001	0.039	-0.014	SD	<0.001
% Passing ¾ or ½"	1128	6828	5.097	3.387	SD	<0.001	1.089	0.808	SD	<0.001
% Passing 3/8"	1311	7860	11.084	6.378	SD	<0.001	-0.125	0.012	NSD	0.153
% Passing #4	1311	7860	9.389	6.619	SD	<0.001	-0.458	-0.481	NSD	0.801
% Passing #8	1310	7860	8.503	5.556	SD	<0.001	-0.281	-0.059	SD	0.009
% Passing #30	1310	7860	5.293	3.079	SD	<0.001	-0.011	0.099	NSD	0.097
% Passing #200	1304	7714	1.120	0.558	SD	<0.001	0.067	0.023	NSD	0.154

Table 53. Mean Square Deviations for Caltrans Verification and Contractor QC Tests

Property	MSD_{NIB}	
	Caltrans Verification	Contractor QC
Asphalt Content	0.088	0.042
% Passing ¾ or ½”	5.767	3.836
% Passing 3/8”	11.091	6.480
% Passing #4	9.525	6.915
% Passing #8	8.430	5.423
% Passing #30	5.366	3.225
% Passing #200	1.099	0.602

ANALYSIS OF NEW MEXICO DOT HOT MIX ASPHALT CONCRETE DATA

Limited data for HMAC were provided by the New Mexico DOT. These data included results from 3 projects with 7 mixes. Test results were not provided, rather, results from project analyses were provided. These results included target values, statistics ($\overline{X}$ and s) and pay adjustments computed with both New Mexico DOT and contractor statistics.

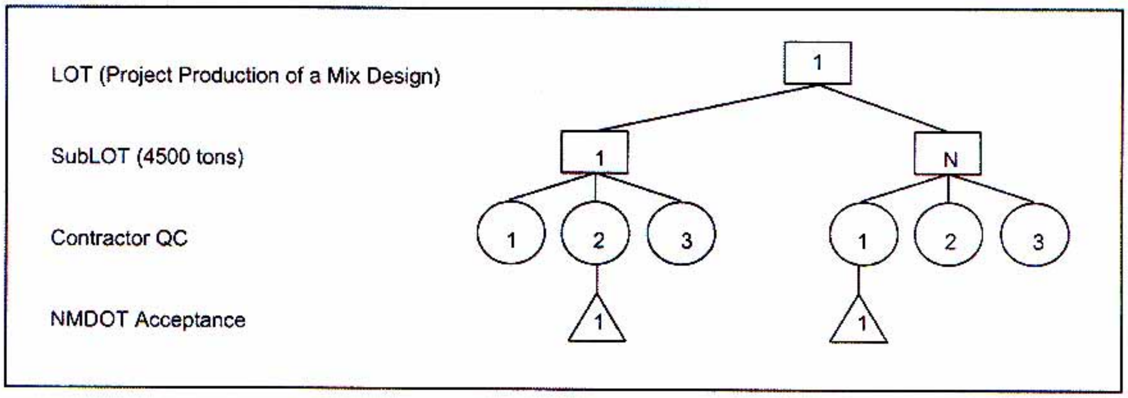
New Mexico DOT accepts HMAC on a LOT by LOT basis and a LOT is defined as the entire project production for a particular mix design. Sampling and testing requirements are illustrated in Figure 46. Contractor QC test results are plotted on control charts with applicable upper and lower specification limits. Contractor QC and New Mexico DOT acceptance test results are compared (α=0.01) with F and t tests as they are accumulated. Verification requires that both variance and mean are not significantly different. If verified, contractor QC test results are combined with New Mexico DOT acceptance test results to compute LOT pay factors. The PWL system is used to compute pay factors for the individual material properties listed in Table 54. These pay factors are combined with the weighting factors, also listed in Table 54, to compute a composite LOT pay factor as follows:

$$CPF=[f_1(PF_1) + f_2(PF_2) + \cdots f_j(PF_j)]/\sum f_j \quad (7)$$

where

f_j = weighting factors and

PF_j = pay factors for individual material properties



Notes:

1. Contractor QC test results are plotted on control charts with applicable upper and lower specification limits.
2. Contractor QC and NMDOT Acceptance testing on independent samples.
3. Contractor QC and NMDOT Acceptance test results are compared with F and t test as accumulated. Final acceptance decisions and pay factor calculations are made when production of a mix design is complete. If Contractor QC test results are validated they are combined with NMDOT Acceptance test results for final acceptance decisions and pay factor calculations.
4. Both variabilties (F test) and means (t test) at α =0.01 must be comparable for validation of contractor test results.

Figure 46. New Mexico DOT HMAC Sampling and Testing Requirements

Table 54. Properties for Computing Pay Factors and Weighting Factors

Mix Type	Properties	Weighting Factor
Dense Graded and SMA	Asphalt Content	50
	Mat Density	50
	Air Voids	50
	Nominal Max. Agg Size	10
	% Passing #8*	15
	% Passing #10*	15
	% Passing #16*	15
	% Passing #30*	15
	% Passing #40*	15
	% Passing #50*	15
	% Passing #200*	15
Open Graded Friction Course	Asphalt Content	20
	% Passing #4	6
	% Passing #10	20
	% Passing #40	6
	% Passing #200	6

* A combination of 2 to 3 sieves is used, depending on specific mix type.

An example of the type information provided by the New Mexico DOT for an open graded friction course (OGFC) mix is shown in Table 55. The test results for the example mix indicate no particular tendency for New Mexico DOT or contractor test results to be more or less variable or more or less closer to targets. This was true for all seven mixes where 30 of 60 (50%) contractor standard deviations were smaller and where 28 of 60 (47%) contractor means were closer to target values.

None of the standard deviations or means for the example mix were significantly different (α=0.01). Despite these similarities in variability and accuracy, the acceptance outcomes using New Mexico DOT and contractor test results were different. These acceptance outcomes are as follows:

New Mexico DOT CPF = 1.024
New Mexico DOT pay = $407,757

Contractor CPF = 1.045
Contractor pay = $415,994

Use of contractor test results yield $8,237 (2.02%) greater pay for the example mix.

For all seven mixes, only 6 of 60 (10%) of the standard deviations were significantly different and contractor standard deviations were smaller for 5 of 6 cases. Seven of 60 (12%) of the means were significantly different but contractor means were closer to targets for only 2 of 7 cases. Again, despite similarities for all seven mixes, the use of contractor test results gave $9,615,127 - $9,411,517 = $203,610 or 2.16% greater pay.

The similarities between New Mexico DOT and contractor test results may be a result of the verification process where F and t test are used to compare variability and

Table 55. Example New Mexico DOT Data

Property	Target	n_{DOT}	s_{DOT}	$\overline{X}_{DOT}$	PF_{DOT}	n_{CONT}	s_{CONT}	$\overline{X}_{CONT}$	PF_{CONT}
% Asphalt	6.9	14	0.085	6.864	1.050	12	0.081	6.854	1.050
% Passing #4	40.0	10	2.791	36.700	1.050	12	2.221	30.750	1.050
% Passing #10	6.0	10	1.751	10.200	0.975	12	1.557	9.333	1.035
% Passing #40	4.0	10	0.707	5.500	1.050	12	0.793	5.417	1.050
% Passing #200	2.0	10	0.200	2.300	1.050	12	0.303	2.367	1.050

Shaded values are smallest standard deviations or means that are closest to targets.

accuracy as tests are accumulated for the entire project mix design production. Tables 56 and 57 contain standard deviations and means of differences from target values for some properties from New Mexico with comparable statistics from other states studied.

The standard deviations in Table 56 are interesting for several reasons. Except for the standard deviation of contractor-tested void contents in Kansas, the standard deviations for the New Mexico DOT tests (both DOT and contractor) are always the smallest. For asphalt content, the variability is considerably smaller than any other state. As observed earlier for individual mixes, there is also no consistent indication that the variability of contractor test results is smaller than the variability of New Mexico DOT tests or that differences are significant.

The standard deviations for both New Mexico DOT and contractor asphalt content tests are 0.116 which is about two and a half times smaller than the standard deviations of asphalt content tests for any other state. However, it should be noted that the asphalt content standard deviations are for data from only three New Mexico projects and they are not unlike standard deviations for individual projects in other states. Their magnitude and closeness for contractor and New Mexico DOT data may be due to the limited size of the database compared to the other states.

The means in Table 57 illustrate no consistent trends. The means for New Mexico asphalt contents are in line with the other states and indicate that, on average, test results are quite close to target values. The New Mexico DOT voids content test results are much closer to the 4% target than test results for any of the other four states, except for the Florida DOT ISVT (independent sample verification test) test results.

Table 56. Standard Deviations of Test Results from Several States

Agency	Property Standard Deviation			
	% Asphalt	Voids Content	Mat Density	% Passing #200
ALDOT (S)	0.272*	1.025	1.470*	-
CONT. (S)	0.230*	0.863	1.175*	-
GDOT (S)	0.297**	-	-	1.066
CONT. (S)	0.200**	-	-	0.877
GDOT (I)	0.253**	-	-	1.101
FDOT (S)	0.290***	1.144	1.720++	0.701
CONT. (S)	0.250***	0.841	1.603++	0.613
FDOT (I)	0.293***	1.183	1.880++	0.693
KDOT (I)	-	0.802	1.737+++	-
CONT. (I)	-	0.564	1.294+++	-
NCDOT (S)	0.308+	1.039	1.483* 1.947++	0.875
CONT. (S)	0.243+	0.751	1.287* 1.733++	0.700
NCDOT (I)	0.286+	1.039	1.483* 2.494++	0.917
Caltrans (I)	0.295***	-	-	1.046
CONT. (I)	0.204***	-	-	0.776
NMDOT (I)	0.116***	0.750	0.858++	0.522
CONT. (I)	0.116***	0.660	1.086++	0.480

(S)	DOT and contractors test split samples
(I)	DOT and contractors test independent samples
*	Nuclear gage method
**	Solvent extraction or ignition methods but primarily ignition method
***	Ignition method
+	Optional methods but primarily ignition method
++	Core method
+++	Optional core or nuclear gage methods

Table 57. Means of Test Results from Several States

Agency	Property Mean			
	% Asphalt	Voids Content	Mat Density	% Passing #200
ALDOT (S)	-0.045*	-0.357	-1.245*	-
CONT. (S)	-0.036*	-0.281	-0.997*	-
GDOT (S)	0.005**	-	-	0.334
CONT. (S)	0.005**	-	-	0.400
GDOT (I)	0.004**	-	-	0.359
FDOT (S)	0.016***	-0.289	-0.222++	0.136
CONT. (S)	-0.012***	-0.248	-0.103++	0.072
FDOT (I)	0.000***	-0.057	-0.640++	0.132
KDOT (I)	-	0.322	1.429+++	-
CONT. (I)	-	0.262	1.642+++	-
NCDOT (S)	-0.021+	-0.212	0.695* 0.588++	0.221
CONT. (S)	-0.003+	-0.097	1.114* 1.109++	0.095
NCDOT (I)	-0.021+	-0.161	0.489* 0.674++	0.194
Caltrans (I)	0.036	-	-	0.062
CONT. (I)	-0.003	-	-	0.011
NMDOT (I)	-0.018***	0.072	-1.389++	-0.142
CONT. (I)	-0.024***	-0.050	-1.503++	-0.059

(S)	DOT and contractors test split samples
(I)	DOT and contractors test independent samples
*	Nuclear gage method
**	Solvent extraction or ignition methods but primarily ignition method
***	Ignition method
+	Optional methods but primarily ignition method
++	Core method
+++	Optional core or nuclear gage methods

Mat density means for ALDOT, FDOT and NMDOT reflect differences between measured and target values. Mat density means for KDOT and NCDOT reflect differences between measured and lower specification limits or minimum acceptable values.

This mean was much closer to the target than the mean for any other type Florida DOT test.

The means for mat density are similar to those for Alabama DOT. The mat density means for Florida indicate test results closer to targets than either Alabama DOT or New Mexico DOT. The negative values for all three states indicate that, on average, target mat density was not achieved ($\Delta = X\text{-}X_T$). Lower specification limits for Kansas DOT and North Carolina DOT were subtracted from test results and is the reason for positive values. What is different about New Mexico mat density measurements is that the DOT test results indicate better compaction, whereas, in the other four states the contractor test results indicate better compaction.

The magnitude of the means of the New Mexico DOT tests for % passing the #200 sieve are not unlike some of the means for Florida DOT, North Carolina DOT or Caltrans tests. What is different is the sign. The New Mexico DOT means indicate less than target amounts passing the #200 sieve (gradations coarser than targets), whereas, in the other states the amounts passing the #200 sieve are consistently larger than targets (gradations finer than targets).

To summarize, the statistics for the limited New Mexico DOT data are quite different from the statistics in the other five states studied. The New Mexico DOT and contractor test results appear more similar in variability and accuracy. However, acceptance outcomes are more favorable when contractor test results are used to compute pay factors. The reasons for the observed differences and similarities are not known. Possible factors include the verification and acceptance system that defines a LOT as the entire project mix production, the accumulation and comparison of DOT and contractor test results with F and t test and/or the combining of DOT and contractor test results to make acceptance decisions. While, the Caltrans system is similar to that of the New Mexico DOT, the variances for Caltrans asphalt content and % passing the #200 sieve are larger. Variances among Caltrans tests are more like variances for Alabama, Georgia, Florida, North Carolina and Kansas DOT tests than the New Mexico DOT tests.

The differences in acceptance outcomes will be considered further in Chapter 4. An analysis of acceptance outcomes computed with statistics for the other five states studied will be presented in Chapter 4, and the New Mexico outcomes will be compared with these outcomes.

ANALYSIS OF COLORADO DOT PORTLAND CEMENT CONCRETE PAVEMENT DATA

Flexural strength test results from 3 PCC pavement (PCCP) projects were provided by the Colorado DOT. Contractors can choose between acceptance processes that use either 28 day flexural or compressive strengths. With the compressive strength process, contractor test results are used only for quality control and DOT test results are used for acceptance. There is no required comparison of compressive strength test results. With the flexural strength process, contractor and Colorado DOT test results are compared with F and t tests ($\alpha=0.05$). If the contractor tests are verified, they are used for acceptance, i.e., to compute a flexural strength pay factor. Comparisons must indicate no significant difference for both variances and means for verification. Pay factors for pavement thickness and smoothness are computed with test results provided by contractors.

A LOT is the entire project production of a process; defined as consistent materials, mix design and construction method. Contractors fabricate and test a set of 3 beams per 2500m^2 of pavement or a minimum of 1 set of 3 beams per day. The Colorado DOT independently fabricates and tests a set of 3 beams per 10,000m^2 of pavements. A test result is the average flexural strength from 3 beams.

Comparisons of contractor and Colorado DOT flexural strength test results are summarized in Table 58. In order to combine data from the three projects, the analysis variable was the difference between test results and lower specification limit flexural strength (Δ=x-x_L).

The comparisons indicate no significant differences (α=0.01) between Colorado DOT and contractor flexural strength test results. The p-values for Project 3 are 0.014 and 0.084 for variance and mean comparisons, respectively. Rounded to two decimal places, Project 3 variances would be significantly different; as they would also certainly be for α=0.05 significance level.

Comparisons of PCC compressive strength test results from Kentucky and Alabama were presented in Chapter 2. These comparisons, conducted at α=0.05 significance level, indicated no significant differences in variances or means for structural PCC. There were also test results for paving PCC from Kentucky. Comparisons indicated there was no significant difference in means of the Kentucky paving PCC compressive strength, but that there was a significant difference in variances (p-value=0.002). The comparisons of the limited PCC test results indicate that, if there are significant differences between contractor and DOT test results, it is more likely these will be differences in variability.

Table 58. Comparisons of Colorado DOT and Contractor Flexural Strength Test Results

Project	n_{CDOT}	n_{CONT}	S^2_{CDOT}	S^2_{CONT}	Difference	p-Value	$\bar{\Delta}_{CDOT}$	$\bar{\Delta}_{CONT}$	Difference	p-Value
1	27	99	2367	2101	NSD	0.328	179	189	NSD	0.336
2	15	53	1639	2274	NSD	0.256	105	90	NSD	0.272
3	19	69	876	2265	NSD	0.014	59	80	NSD	0.084
Combined	61	221	4434	4963	NSD	0.329	124	131	NSD	0.461

The comparisons for the Colorado, Alabama and Kentucky PCC strength data suggests no particular tendency for contractor tests to be less variable or more favorable (larger strengths). This is contrary to the general tendencies noted for HMAC.

The overall mean differences between test results and the lower specification limit of 124 and 131 psi in Table 58 are about 22% higher than the 570 psi lower specification limit. However, the overall mean differences indicates average strength that is only about 7% higher than a 650 psi plan or design strength. Also, the Colorado DOT test mean for Project 3 of 629 psi is 3% lower than the 650 psi plan strength. These comparisons indicate a not so conservative approach to assuring adequate PCC strength as do comparisons for Alabama and Kentucky.

The means in Table 10 for structural PCC indicate compressive strengths 69 and 64% higher than minimum required for contractor and Alabama DOT tests, respectively. The means in Table 11 for Kentucky Transportation Cabinet and contractor tests indicate, respectively, structural PCC compressive strengths 62 and 53% higher than the minimum required. The means in Table 11 indicate paving PCC compressive strengths 69 and 72% higher than the minimum required.

ANALYSIS OF FHWA–WESTERN FEDERAL LANDS HIGHWAY DIVISION AGGREGATE COURSE DATA

Test results from 23 aggregate course construction projects were provided by the FHWA-Western Federal Lands Highway Division (FHWA-WFLHD). The projects involved several types of aggregate courses. Each type of aggregate course has some combination of properties for pay factor computation. For these properties both contractor and FHWA-WFLHD testing of split samples is required. FHWA-WFLHD tests are used to verify contractor tests with t or paired t tests at 1% significance level. If verified, contractor tests are used to compute LOT pay factors with the PWL method. Bonuses of up to 5% may be obtained. Pavement layers have compaction requirements, but layer compaction is accepted or rejected based on contractor density tests.

A LOT is the entire project production for a particular type aggregate course. Contractors take and test one sample per 1000 tons of aggregate placed. The FHWA-WFLHD tests a split sample from the first 3 project samples and at least 10% of the remaining project samples. The data provided for the 23 projects indicate an average contractor to FHWA-WFLHD testing ratio of about 3 to 1. However, the ratio for a particular project depends on the project quantity. The variable used for the comparisons was the difference between test results and either target values, maximum specification values or minimum specification values. Target, maximum and minimum values were subtracted from test results.

Comparisons for the entire data sets of FHWA-WFLHD and contractor tests are contained in Table 59. The differences in variability seem not so extensive as those for HMAC but the differences in means seem somewhat more extensive. The variabilities of only 5 of 12 properties were significantly different but, for these 5, the variability of FHWA-WFLHD tests were larger for 4 properties. Overall, 8 of 12 FHWA-WFLHD test property variabilities were larger. This observation of larger agency test variability is consistent with observations for hot mixed asphalt concrete tests.

Table 59. Comparisons of FHWA-WFLHD and Contractor Aggregate Course Test Results

Property	n_{FHWA}	n_{CONT}	s^2_{FHWA}	s^2_{CONT}	Difference	p-Value	$\bar{\Delta}_{FHWA}$	$\bar{\Delta}_{CONT}$	Difference	p-Value
% Passing 1”	68	216	0.042	0.211	SD	<0.001	-0.022	0.007	NSD	0.611
% Passing ¾”	30	96	3.547	4.518	NSD	0.232	0.625	0.122	NSD	0.248
% Passing ½”	148	347	4.777	3.964	NSD	0.085	1.541	-0.010	SD	<0.001
% Passing 3/8”	36	103	19.332	12.354	NSD	0.044	2.259	0.146	SD	0.004
% Passing #4	154	354	7.821	5.054	SD	0.001	-0.648	-0.119	NSD	0.024
% Passing #10	136	290	4.461	3.839	NSD	0.148	-0.371	0.060	NSD	0.040
% Passing #40	154	354	2.805	3.139	NSD	0.213	-0.012	0.151	NSD	0.330
% Passing #200	148	348	1.558	0.968	SD	<0.001	-0.022	0.065	NSD	0.408
LL	118	251	4.114	2.000	SD	<0.001	-10.534	-11.450	SD	<0.001
PI	118	251	3.281	1.863	SD	<0.001	0.034	-0.390	SD	0.013
SE/P200	13	80	0.074	0.061	NSD	0.288	0.535	0.503	NSD	0.668
% Frac. Part.	135	331	81.514	90.453	NSD	0.244	20.934	24.943	SD	<0.001

Specifications contain target values for gradation and PI, maximum values for LL and minimum values for % fractured particles and the
ratio of the sand equivalent to percent passing the #200 sieve ratio (SE/P200).

The procedure FHWA-WFLHD uses to establish gradation targets will affect consideration of the comparisons of means. Gradation targets are set as the average of contractor tests, provided the average is within specification allowable limits. For example, if the allowable range for percent passing a sieve is 20 to 30% and the average for contractor tests is 27%, the target value would be 27%. This was the case for most of the 23 projects and accounts for the low gradation mean deviations for contractor tests. As a result, comparisons of the magnitude of FHWA-WFLHD and contractor mean deviations from gradation targets are not meaningful.

The gradation means were significantly different for only 2 of 7 sieves. For the remaining properties, the FHWA-WFLHD test means were significantly different for 3 of 4 properties. The contractor means were more favorable, relative to specification limits for these 3 properties. The means for SE/P200 were not significantly different and the FHWA-WFLHD mean was slightly more favorable relative to minimum specified values.

Means of contractor and FHWA-WFLHD test from split samples were compared with paired t tests. These comparisons are summarized in Table 60. The comparisons of gradation means were the same as those for the entire contractor data set in Table 59. Means for only 2 sieves (3/4” and 1/2”) were significantly different. The comparisons of paired tests for the remaining samples were the same as the comparisons for all data, except for PI. The means for paired PI tests were not significantly different (p-Value=0.044).

Table 60. Comparisons of Paired FHWA-WFLHD and Contractor Aggregate Course Test Results

Property	n	$\bar{\Delta}_{FHWA}$	$\bar{\Delta}_{CONT}$	Difference	P-Value
% Passing 1”	68	-0.022	-0.035	NSD	0.810
% Passing ¾”	30	0.625	0.053	NSD	0.035
% Passing ½”	148	1.541	0.071	SD	<0.001
% Passing 3/8”	36	2.259	0.135	SD	0.006
% Passing #4	154	-0.648	-0.181	NSD	0.039
% Passing #10	136	-0.371	0.032	NSD	0.023
% Passing #40	154	-0.012	0.121	NSD	0.290
% Passing #200	148	-0.022	0.126	NSD	0.054
LL	118	-10.534	-11.178	SD	<0.001
PI	118	0.034	-0.246	NSD	0.029
SE/P200	13	0.535	0.425	NSD	0.044
% Frac. Part.	136	20.934	22.708	SD	0.002

The comparisons of mean differences from target values for granular base are somewhat the same as comparisons for HMAC. Means are not consistently significantly different but, when they are significantly different, contractor tests are likely more favorable (LL, PI, and % fractured particles).

Project by project comparisons were made for the 9 properties in Table 61. Percentages passing the 1" and ¾" sieves and the ratio of the sand equivalent and % passing the #200 sieve (SE/P200) were omitted because individual project data was insufficient for meaningful comparisons. Projects were included that had 5 or more FHWA-WFLHD tests. Previous project analyses defined a large project as one with 6 or more agency tests. However, this data had a number of projects with 5 FHWA-WFLHD tests and the inclusion of these projects greatly expanded the database.

The numbers and percentages of projects in column 3 of Table 61 indicates contractor gradation tests are consistently closer to targets. However, this is due to the designation of the project target percent passing as the average of contractor tests, provided this average is within specification tolerances. Figure 47 illustrates the resulting unusual distribution of project means for % passing the #200 sieve. A complete set of figures for project means and variances for all the properties in Table 61 are contained in Appendix E. The numbers and percentages of projects in column 4 indicate it is unlikely gradation means are significantly different.

Table 61. Project Comparisons of FHWA-WFLHD and Contractor Aggregate Course Test Results

Property	Projects	Proj. with Larger FHWA $\lvert\bar{\Delta}\rvert$	Proj. with SD $\lvert\bar{\Delta}\rvert$	Proj. with Sig. Larger FHWA $\lvert\bar{\Delta}\rvert$	Proj. with Larger FHWA s^2	Proj. with SD s^2	Proj. with Sig. Larger FHWA s^2
% Passing ½”	20	20 (100%)	5 (25%)	5 (25%)	11 (55%)	1 (5%)	1 (5%)
% Passing 3/8”	5	4 (80%)	0	0	0	0	0
% Passing #4	21	17 (81%)	4 (19%)	4 (19%)	18 (86%)	1 (5%)	1 (5%)
% Passing #10	19	18 (95%)	0	0	10 (53%)	0	0
% Passing #40	21	16 (76%)	1 (5%)	1 (5%)	8 (38%)	0	0
% Passing #200	20	19 (95%)	2 (10%)	2 (10%)	10 (50%)	1 (5%)	1 (5%)
LL	16	2 (12%)	4 (25%)	0	11 (69%)	2 (12%)	2 (12%)
PI	16	9 (56%)	3 (19%)	2 (12%)	14 (88%)	2 (12%)	2 (12%)
% Frac. Part.	18	7 (39%)	6 (33%)	1 (6%)	12 (67%)	2 (11%)	2 (11%)

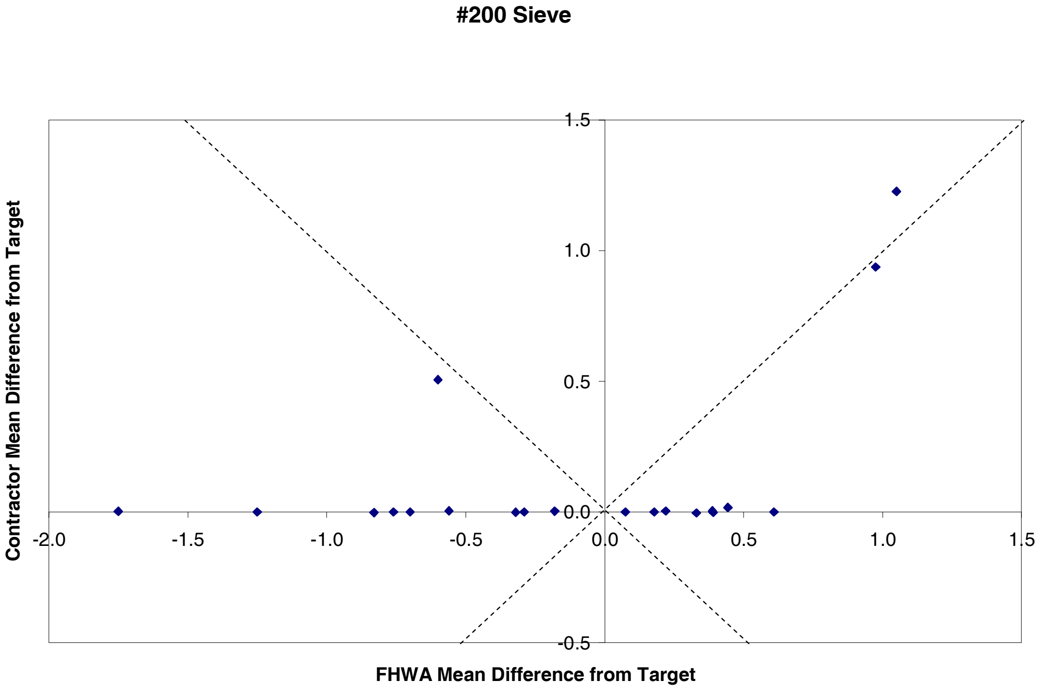


Figure 47. Project Percent Passing the #200 Sieve Means – FHWA-WFLHD Verification and Contractor QC

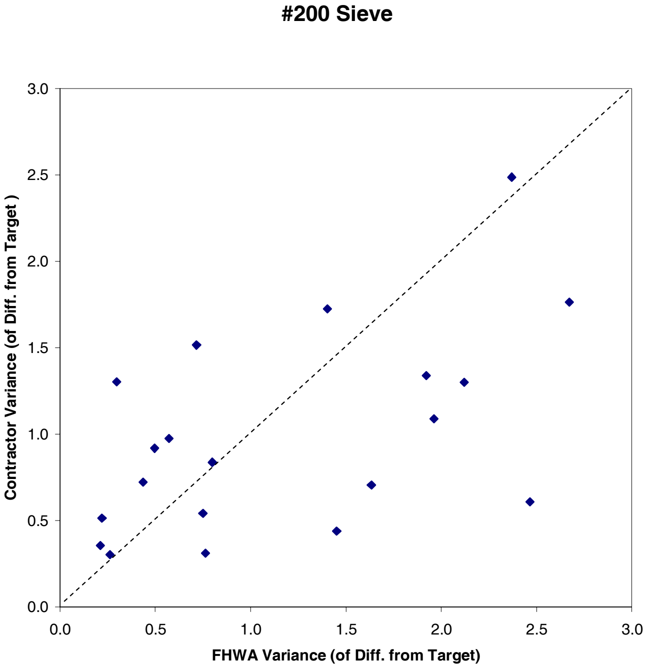


Figure 48. Project Percent Passing the #200 Sieve Variances – FHWA-WFLHD Verification and Contractor QC

The numbers and percentages of projects in column 6 indicate no particular tendency for FHWA-WFLHD or contractor gradation variances to be larger, except for % passing the #4 sieve. The numbers and percentages of projects in columns 7 and 8 indicate that variances of gradation tests are not likely significantly different, but that, if they are significantly different, the variances of FHWA-WFLHD gradation tests are always larger. These tendencies are illustrated in Figure 48 for % passing the #200 sieve.

The numbers and percentages of projects in column 3 for LL, PI and % fractured particles indicate more favorable contractor test results, relative to specification limits. The numbers and percentages of projects in columns 4 and 5 indicate some tendency for significant differences in means and that, if the means are significantly different, contractor tests are more favorable. These tendencies are illustrated in Figure 49 for LL. Upper limits for LL are specified.

The numbers and percentages of projects in column 6 for LL, PI and % fractured particles indicate larger FHWA-WFLHD test variances. The numbers and percentages in column 7 indicate no strong tendency for significant differences in variances but, if the means are significantly different, the numbers in column 8 indicate the variances for FHWA-WFLHD tests are always larger. These tendencies are illustrated in Figure 50 for LL.

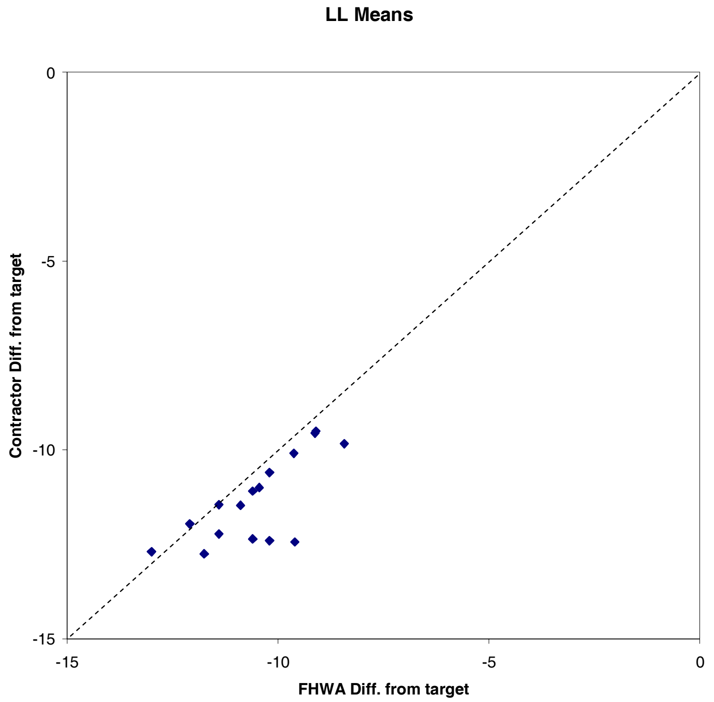


Figure 49. Project LL Means – FHWA-WFLHD Verification and Contractor QC

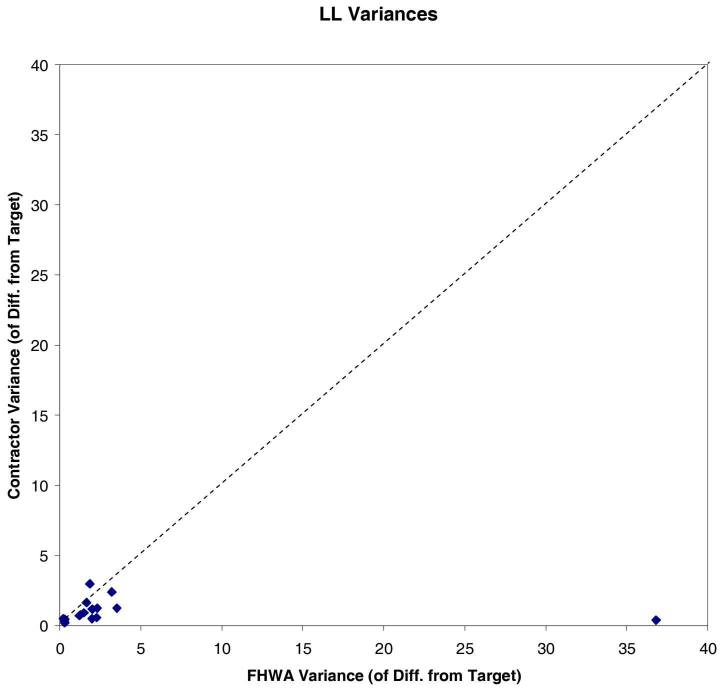


Figure 50. Project LL Variances –FHWA-WFLHD Verification and Contractor QC

CHAPTER 4: EVALUATION OF THE EFFECTS OF DIFFERENCES IN TEST RESULTS ON ACCEPTANCE OUTCOMES

The extensive statistical comparisons in Chapter 3 indicate contractor and state DOT tests of HMAC properties are likely different. These comparisons indicate that it is highly likely that variability of state DOT tests are significantly (α=0.01) larger than the variability of contractor tests. These comparisons also indicate deviations of state DOT test results from target values or specification limits are likely larger than deviations of contractor test results. However, it is less likely that differences between state DOT and contractor deviations from target values are statistically significant.

To provide an assessment of the effects of these observed differences between state DOT and contractor tests, evaluations of acceptance outcomes using HMAC statistics for Georgia, Florida, Kansas, North Carolina and California were conducted. Statistics for contractor and state test results were applied to acceptance procedures to compute theoretical outcomes. These outcomes were compared and differences computed. The results from these computations are summarized in Table 62. Details for all the acceptance outcome computations are contained in Appendix F and illustrated in Table 63 for Kansas computations.

Table 62. Comparison of Acceptance Outcomes with DOT and Contractor Test Results

Property	% Greater Chance of				
	PF<100% with Georgia DOT Statistics	Exceeding Spec. Limits with Florida DOT Statistics	Exceeding Spec. Limits with Kansas DOT Statistics	Exceeding Min. Spec. Limits with North Carolina DOT Statistics	Exceeding Spec. Limits with Caltrans Statistics
% Asphalt	0.8	6.0	-	-	7.8
% Passing 1/2" Sieve	0.1	-	-	-	2.7
% Passing 3/8" Sieve	0.3	-	-	-	5.4
% Passing #4 Sieve	2.7	-	-	-	1.5
% Passing #8 Sieve	12.3	7.6	-	-	5.6
% Passing #30 Sieve	-	-	-	-	5.9
% Passing #200 Sieve	-	5.7	-	-	4.7
Void Content	-	12.5	13.9	-	-
Mat Density (% G_{mm})	-	3.6 Coarse Mix 4.2 Fine Mix	10.3	12.6* 9.1**	-

* Contractor and NCDOT Retest – Nuclear Gage
** Contractor and NCDOT Comparison - Cores

Table 63. Kansas DOT Acceptance Outcomes Computation

Voids Content

Statistics

s^2_{DOT} = 0.643 $s^2_{CONT.}$ = 0.318 s^2 are SD

$\overline{\Delta}_{DOT}$ = 0.322% $\overline{\Delta}_{CONT.}$ = 0.262% $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 1% from 4% target

Probability = 24.9% with DOT statistics
Probability = 11.0% with contractor statistics

13.9% greater chance of exceeding specification limits with DOT statistics

Mat Density

Statistics*

s^2_{DOT} = 3.016 $s^2_{CONT.}$ = 1.674 s^2 are SD

$\overline{\Delta}_{DOT}$ = 1.429% $\overline{\Delta}_{CONT.}$ = 1.642% $\overline{\Delta}$ are SD

Probability of exceeding lower* specification limits (LSL)

LSL = 92% of G_{mm} for mainline paving > 2 inches thick
LSL = 91% of G_{mm} for mainline paving $\leq$ 2 inches thick
LSL = 90% of G_{mm} for shoulder paving

Probability = 20.5% with DOT statistics
Probability = 10.2% with contractor statistics

10.3% greater chance of exceeding LSL with DOT statistics

* Mat density is controlled with one sided limits, ie, only a minimum or lower limit is specified. Data from three types of paving were combined by using the variable Δ = X-LSL.

Statistics ($\overline{\Delta}$ and s^2) were selected from the largest available data bases for each state. For example, the following statistics were selected from Table 22 for Florida, and used for the computation of acceptance outcomes for asphalt content:

$$s^2_{FDOT} = 0.084$$

$$s^2_{CONT} = 0.062$$

$$\overline{\Delta}_{FDOT} = 0.016\%$$

$$\overline{\Delta}_{CONT} = -0.012\%$$

Statistics were applied to each state DOT's acceptance procedures to compute the probability of certain outcomes. The DOT's in Florida and Kansas and California use the percent within limits (PWL) procedure, and the outcomes computed were probabilities that upper and lower (two-sided) or lower (one-sided) specification limits would be exceeded.

As shown in Table 63, the Kansas DOT specification limits for voids content are ± 1% from the 4% target. The probabilities that the upper or lower specification limits might be exceeded were computed as 24.9 and 11.0%, respectively, using Kansas DOT and contractor statistics. Therefore, there is a 13.9% greater chance of exceeding specification limits with Kansas DOT statistics. Mat density has a one-sided or lower limit. There is a 10.3% greater chance of exceeding the lower specification limit with Kansas DOT statistics. Similar computations were used for the Florida and North Carolina DOT's and Caltrans. The North Carolina DOT specifies a minimum of 92% G_{mm} mat density, below which a pay reduction is assessed. The North Carolina DOT allows the use of nuclear gages or cores to measure mat density and computations are included for both.

Computations for the Georgia DOT are different. Pay adjustments are applied based on average absolute differences from target values. Limits for pay adjustments, both reductions and bonuses, are a function of the number of test results for a LOT: typically 2 to 6. For comparisons, probabilities for pay factors less than 100% were computed with criteria for numbers of tests equal to 3. The absolute value distributions and computation procedures suggested in Parker, et al (18) were used for these computations.

For asphalt content, a LOT pay reduction (PF<100%) will be applied by the Georgia DOT if the average absolute deviation from a target value of the average of 3 tests exceeds 0.46%. With Georgia DOT and contractor statistics the probabilities that a pay reduction will be applied are 0.9 and 0.1%. Therefore, there is an 0.8% greater chance of getting a pay reduction for asphalt content with DOT statistics.

The percentages in Table 62 indicate that outcomes with contractor DOT test results are always more favorable. More favorable outcomes with contractor statistics are expected since contractor test results are, typically, closer to targets and significantly less variable. However, apparent differences in test results may not be necessary for difference in pay. As presented in Chapter 3, contractor and New Mexico DOT statistics are quite similar, but acceptance outcomes using contractor statistics were more favorable (approximately 2% greater pay). The range of percent chances in Table 62 is 0.1 to 13.9%.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The basic premise for this research was that contractor-performed tests can be effectively used in quality assurance if they provide the same results as state DOT-performed tests. Considerable effort was devoted to comparing contractor and state DOT test results that might be influenced by a variety of verification and validation procedures. These comparisons consistently indicated that contractors and state DOT test results for HMAC are statistically significantly different ($\alpha = 0.01$). Furthermore, these comparisons consistently indicate less variable and more favorable contractor test results, relative to specification limits, that give more favorable acceptance outcomes. Details of quality assurance processes (sampling and testing frequencies, verification procedures and acceptance procedures) seem to have little if any effect on these comparisons.

HMAC data was analyzed from state DOTs that use verification procedures ranging from simple one to one comparisons to statistically robust F and t tests. All these procedures indicated that state DOT and contractor-performed tests do not provide the same measures of HMAC quality.

Consistent statistically significant differences between contractor and state DOT performed tests, which lead to consistently more favorable acceptance outcomes with contractor-performed tests, are reasons to use only state DOT-performed tests for HMAC acceptance.

There has been limited application of statistically based quality assurance procedures for PCC. As a result, only limited data were available for analysis. Comparisons indicated no particular differences between state DOT and contractor test results. This may be due to the limited data available for comparisons, the nature of PCC sampling and testing, or the inclusion of a separate material supplier in the construction process.

At this time there are no compelling reasons to not use contractor-performed PCC tests for quality assurance. There is the obvious benefit of direct process or product quality control. For acceptance, there are no indications of substantial differences between contractor and state DOT-performed test results and the use of contractor-performed tests can reduce required state DOT resources for sampling and testing. However, considerably more data collection and analysis should be conducted before contractor-performed tests are routinely used for the acceptance of PCC.

The use of statistically based quality assurance procedures for granular base is even more limited than for PCC. The limited comparisons conducted as part of this study suggest there may be differences between contractor and agency-performed tests. No recommendation for using contractor-performed tests for granular base quality assurance is warranted at this time. A prudent approach would seem to be the approach that has been followed for HMAC, i.e., trial projects with model specifications, collection and analysis of test results, and modification of specifications over time.

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APPENDICES

APPENDIX A

PLOTS OF GEORGIA DOT AND CONTRACTOR HOT MIXED ASPHALT CONCRETE PROJECT MEANS AND VARIANCES

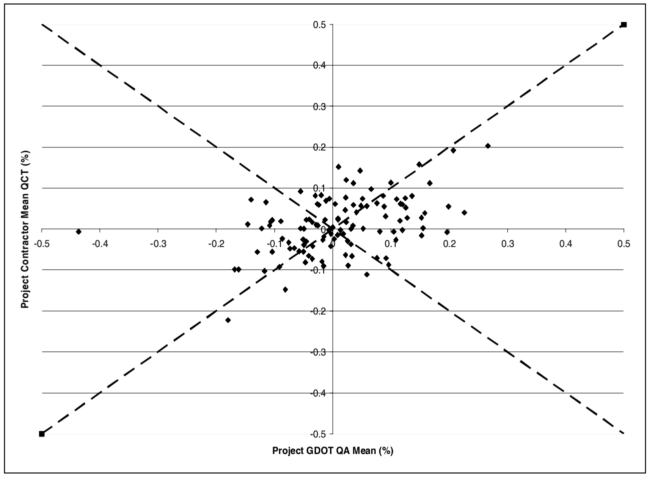


Figure A.1. Asphalt Content Project Means – Georgia DOT QA and Contractor QC

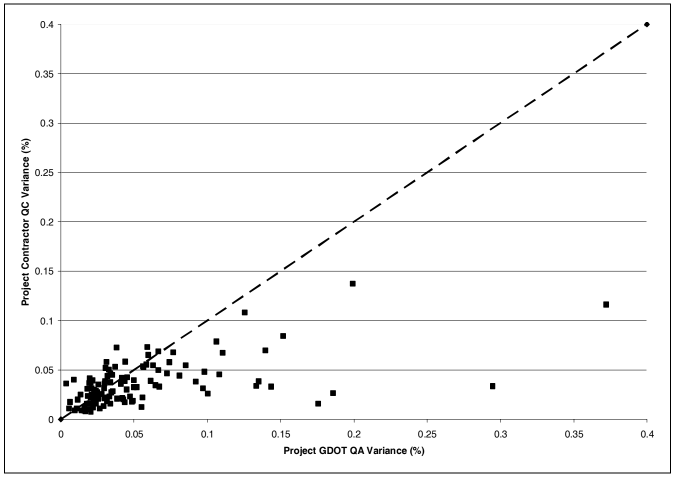


Figure A.2. Asphalt Content Project Variances – Georgia DOT QA and Contractor QC

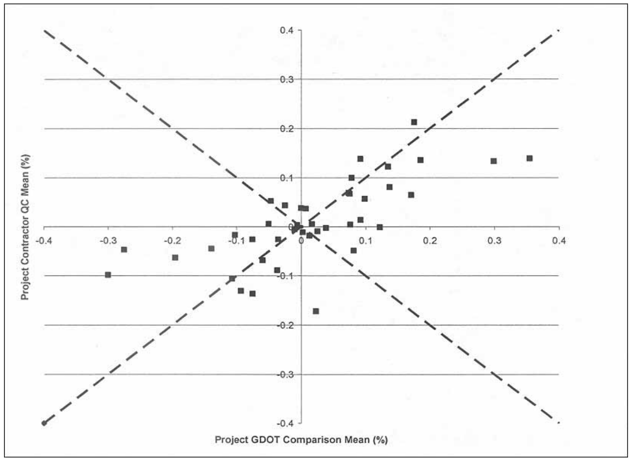


Figure A.3. Asphalt Content Project Means – Paired Georgia DOT Comparison and Contractor QC.

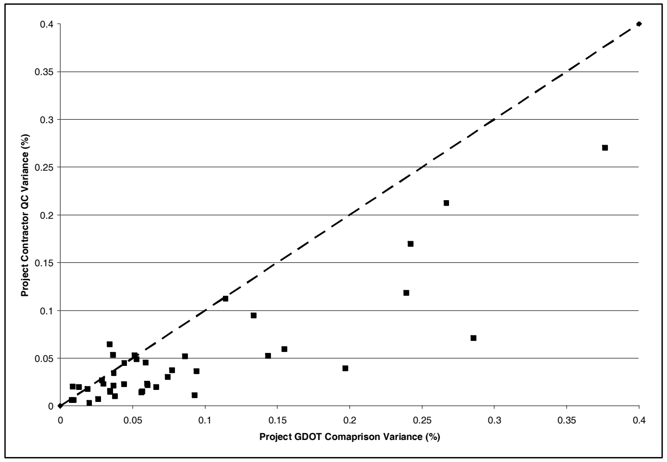


Figure A.4. Asphalt Content Project Variances – Paired Georgia DOT Comparison and Contractor QC.

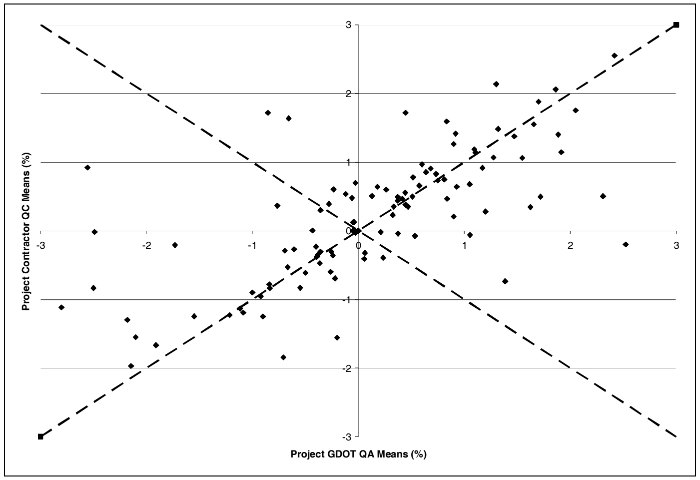


Figure A.5. Percent Passing the ½" Sieve Project Means – Georgia DOT QA and Contractor QC.

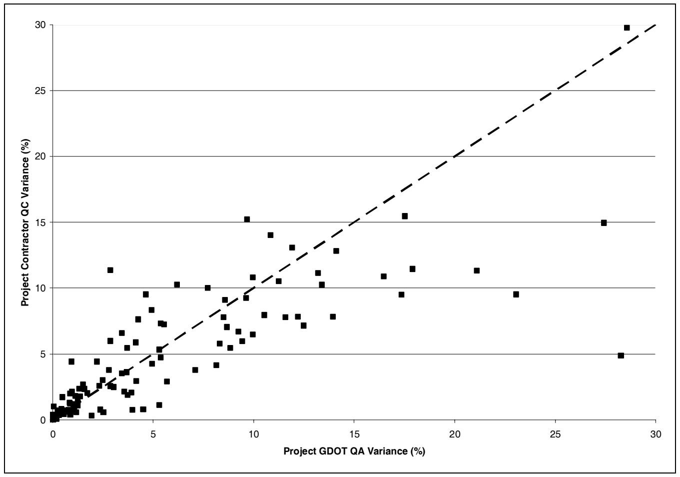


Figure A.6. Percent Passing the ½" Sieve Project Variances – Georgia DOT QA and Contractor QC.

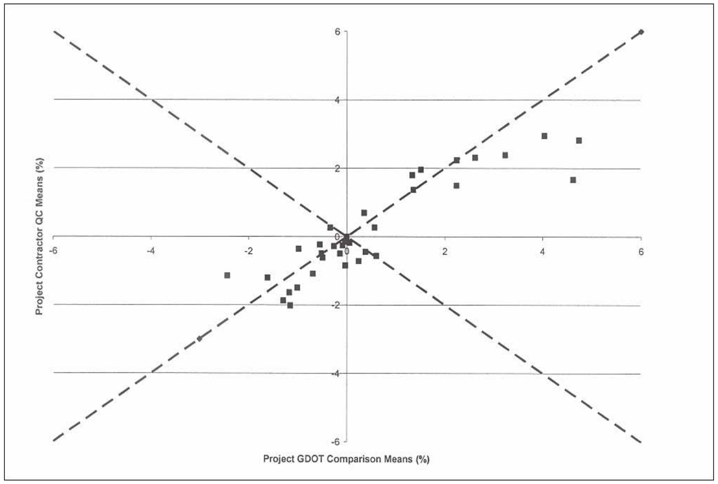


Figure A.7. Percent Passing the ½" Sieve Project Means - Paired Georgia DOT Comparison and Contractor QC

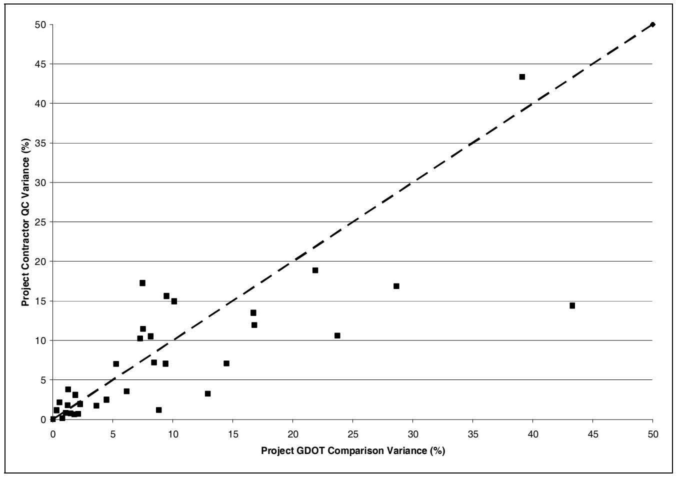


Figure A.8. Percent Passing the ½" Sieve Project Variances - Paired Georgia DOT Comparison and Paired Contractor QC.

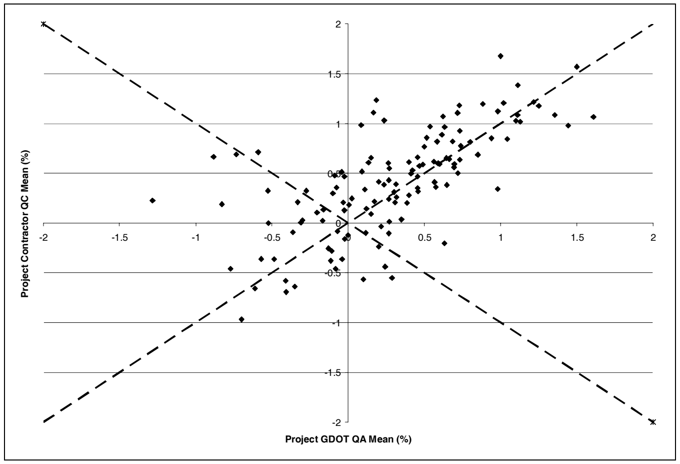


Figure A.9. Percent Passing the #200 Sieve Project Means – Georgia QA and Contractor QC.

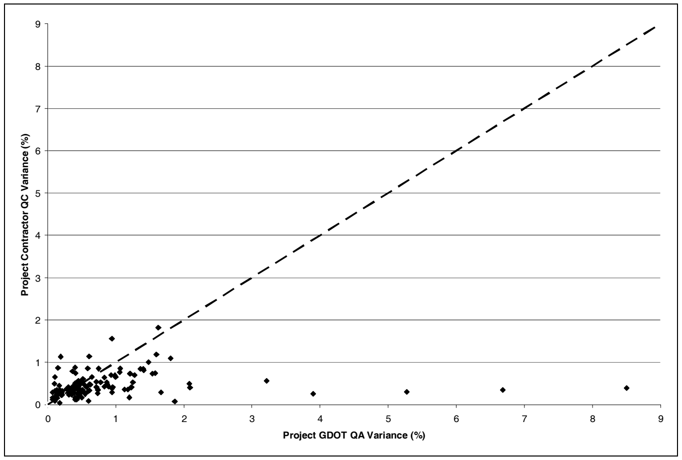


Figure A.10. Percent Passing the #200 Sieve Project Variances – Georgia QA and Contractor QC.

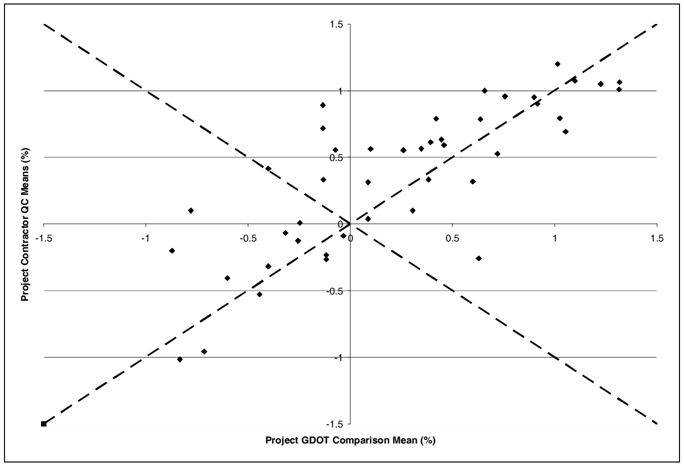


Figure A.11. Percent Passing the #200 Sieve Project Means - Georgia DOT Paired Comparison and Contractor QC

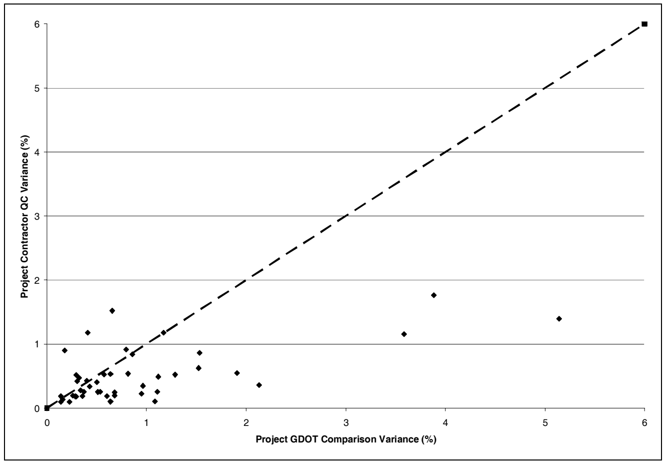


Figure A.12. Percent Passing the #200 Sieve Project Variances - Georgia DOT Paired Comparison and Contractor QC

APPENDIX B

PLOTS OF FLORIDA DOT AND CONTRACTOR HOT MIXED ASPHALT CONCRETE PROJECT MEANS AND VARIANCES

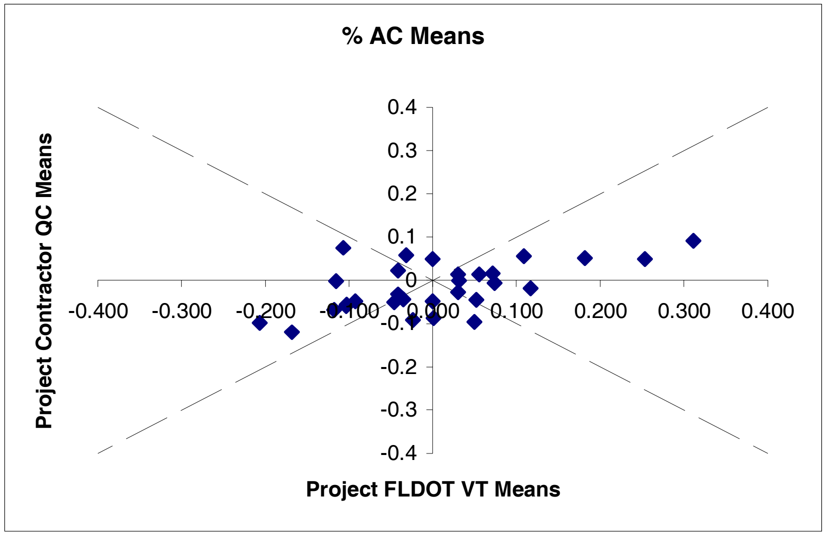


Figure B.1. Asphalt Content Project Means – Florida DOT VT and Contractor QC

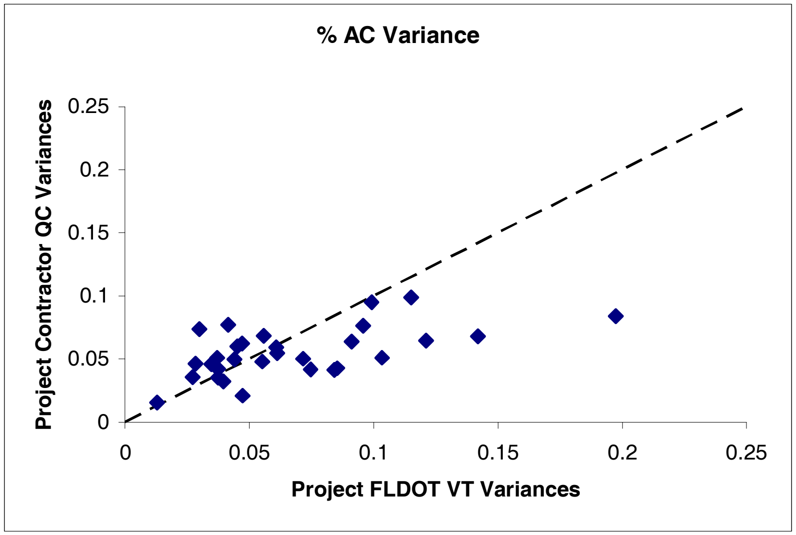


Figure B.2. Asphalt Content Project Variances – Florida DOT VT and Contractor QC

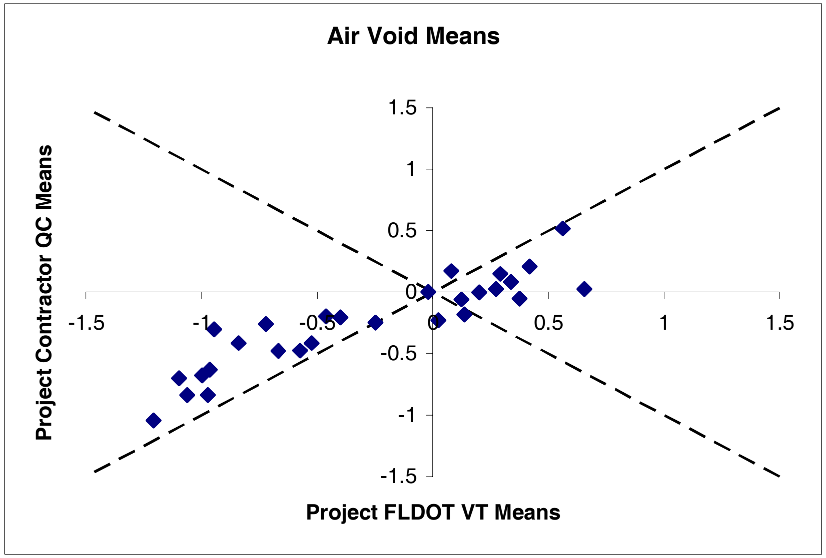


Figure B.3. Air Void Project Means – Florida DOT VT and Contractor QC

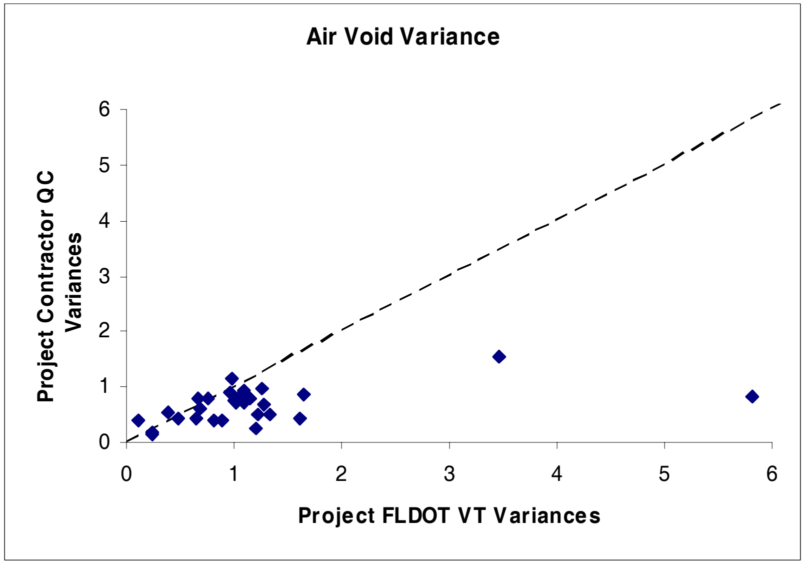


Figure B.4. Air Void Project Variances – Florida DOT VT and Contractor QC

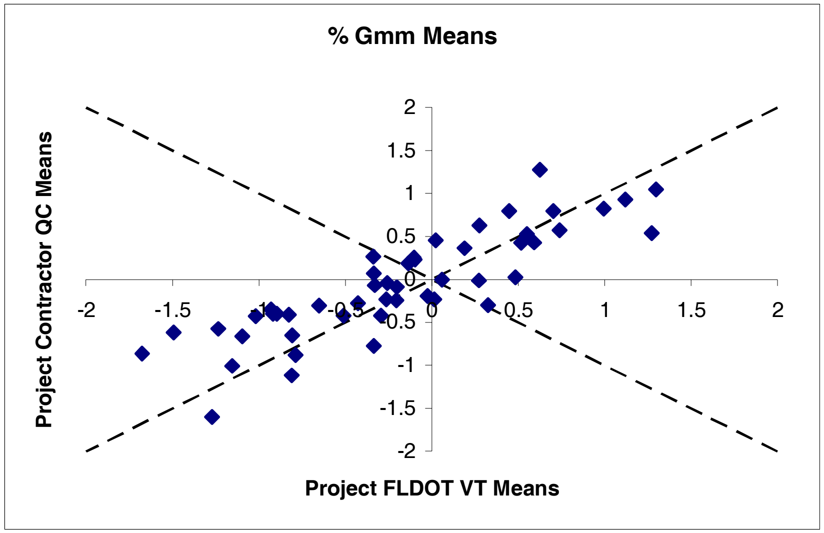


Figure B.5. % G_{mm} Project Means –
Florida DOT VT and Contractor QC

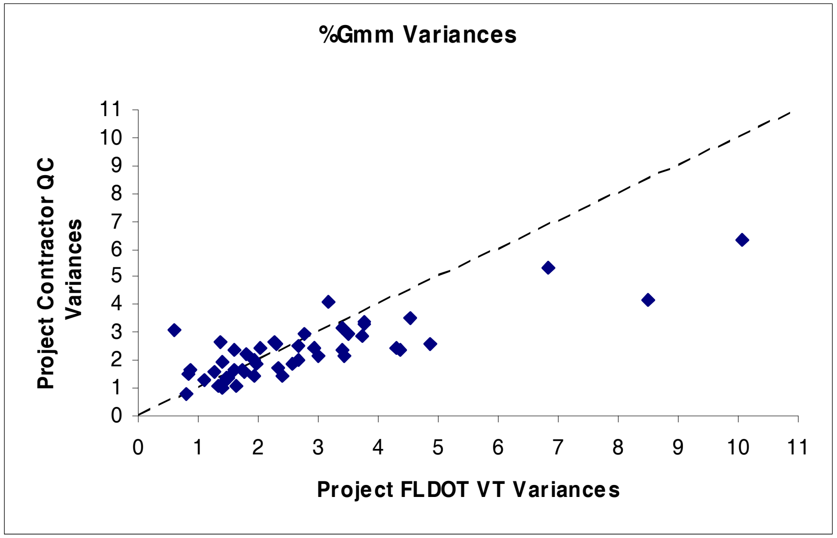


Figure B.6. % G_{mm} Project Variances –
Florida DOT VT and Contractor QC

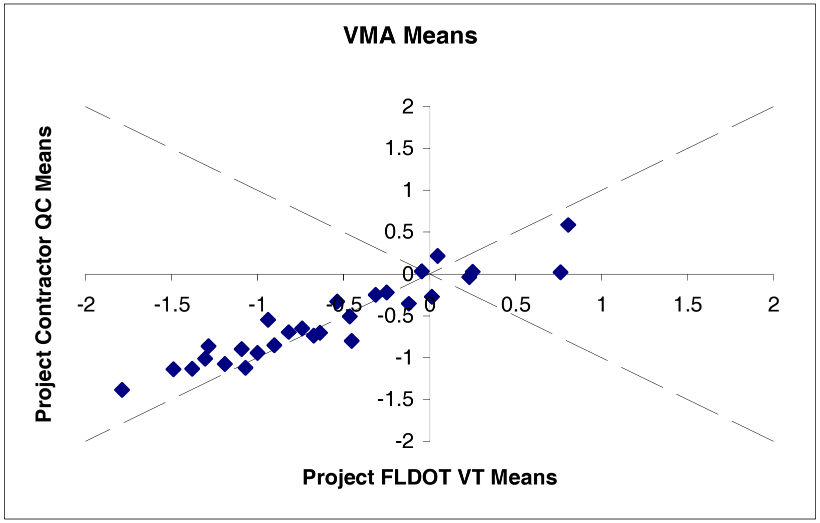


Figure B.7. VMA Project Means –
Florida DOT VT and Contractor QC

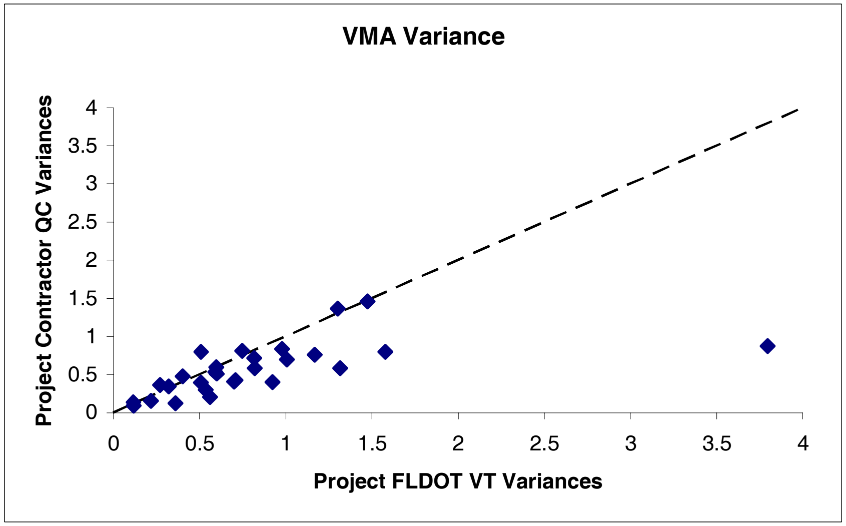


Figure B.8. VMA Project Variance –
Florida DOT VT and Contractor QC

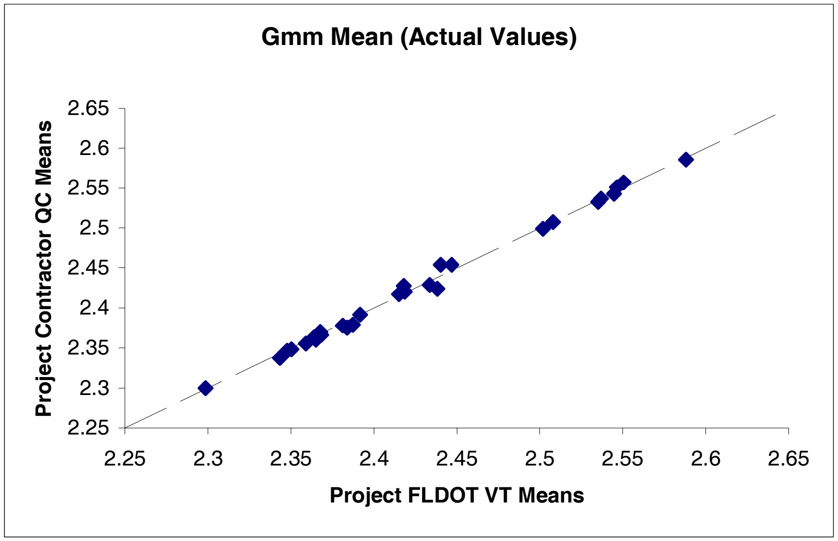


Figure B.9. G_{mm} Project Means –
Florida DOT VT and Contractor QC

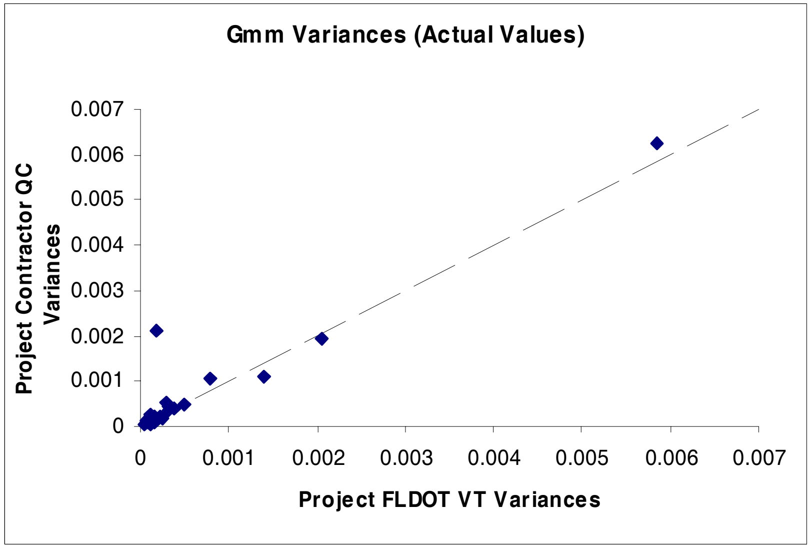


Figure B.10. G_{mm} Project Variances –
Florida DOT VT and Contractor QC

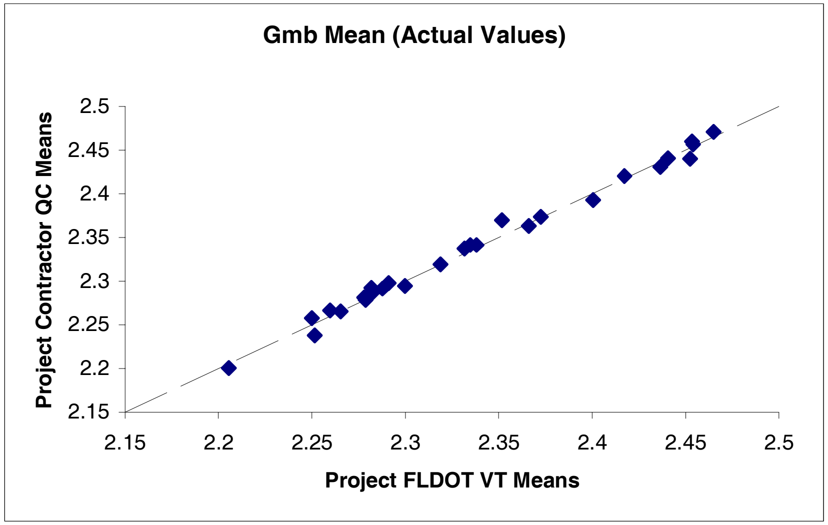


Figure B.11. G_{mb} Project Means -
Florida DOT VT and Contractor QC

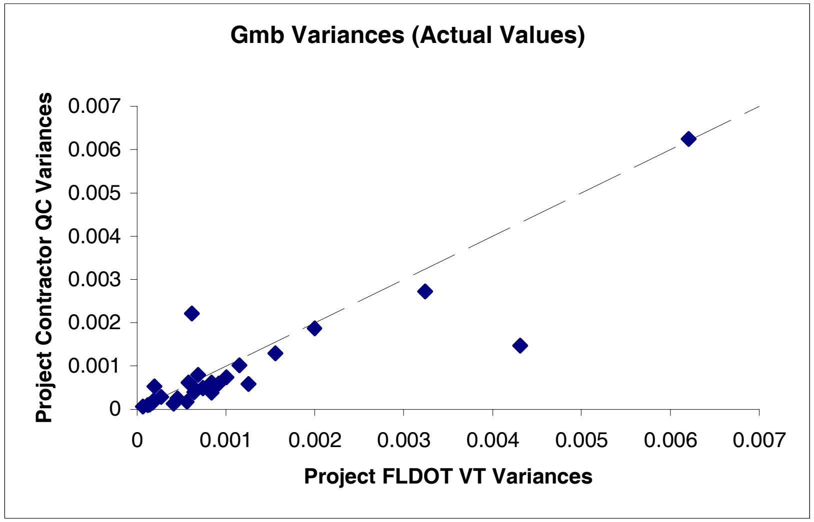


Figure B.12. G_{mb} Project Variances –
Florida DOT VT and Contractor QC

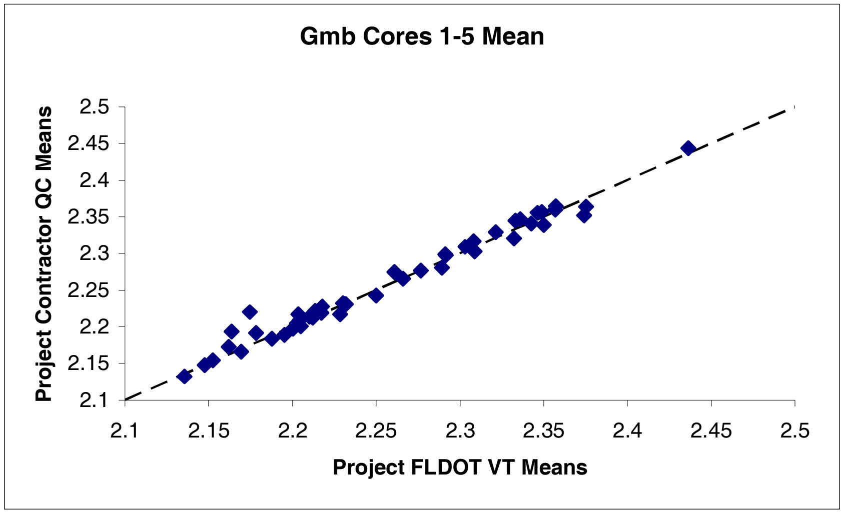


Figure B.13. G_{mb} Cores 1-5 Project Means – Florida DOT VT and Contractor QC

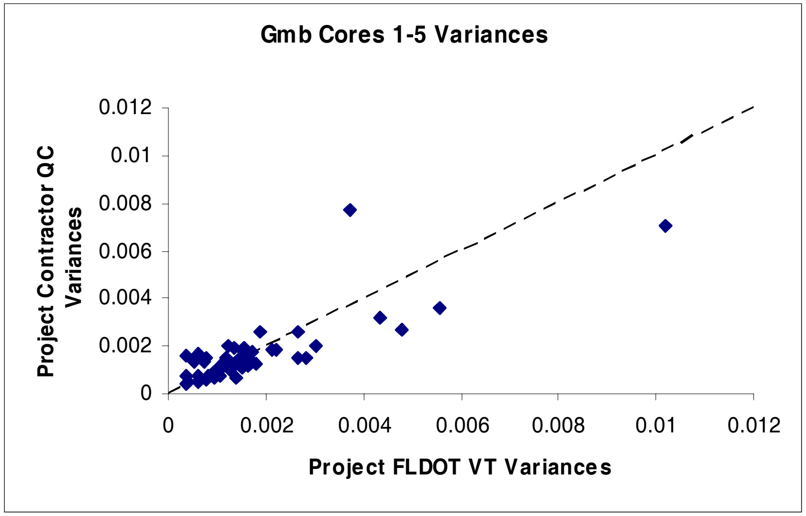


Figure B.14. G_{mb} Cores 1-5 Project Variances – Florida DOT VT and Contractor QC

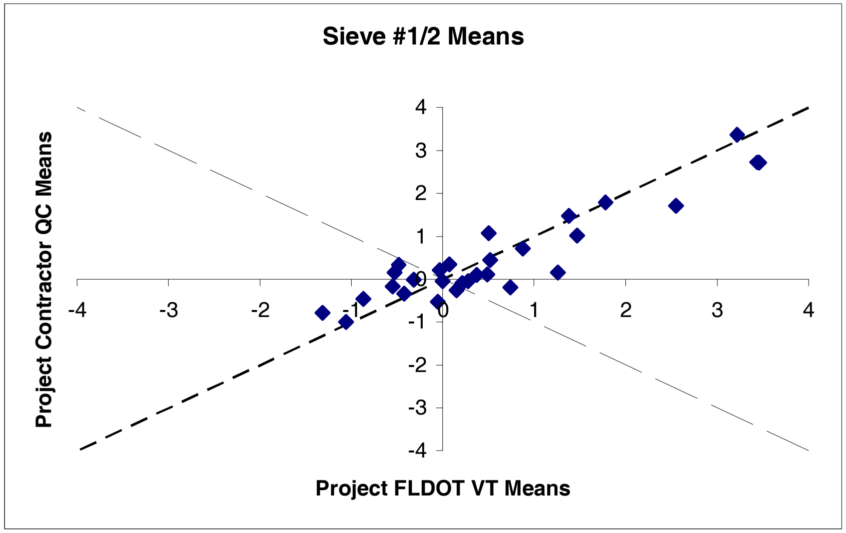


Figure B.15. Sieve #1/2 Project Means – Florida DOT VT and Contractor QC

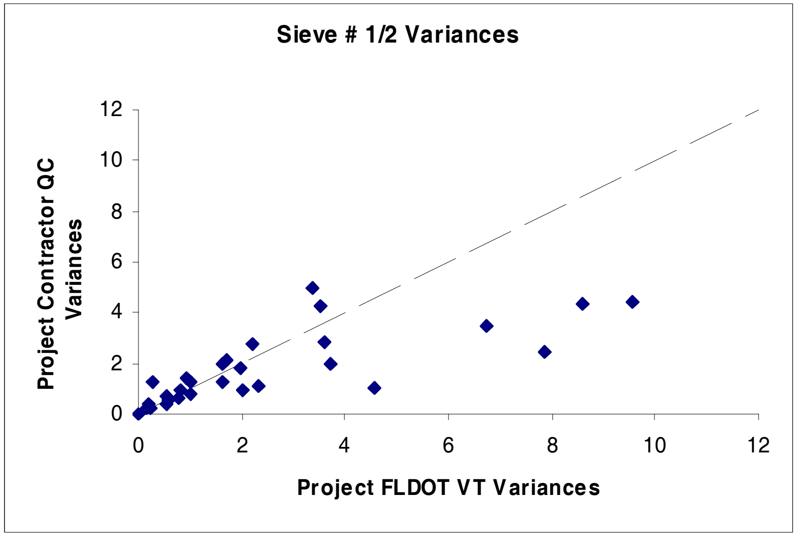


Figure B.16. Sieve #1/2 Project Variances – Florida DOT VT and Contractor QC

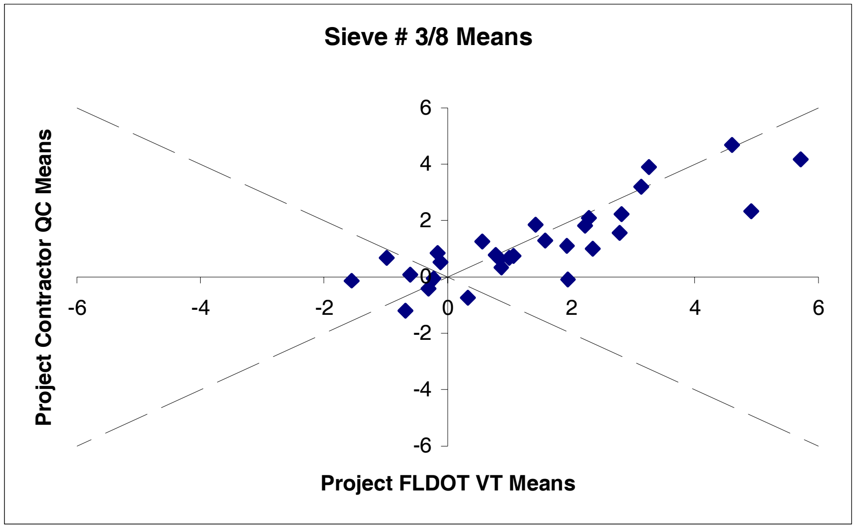


Figure B.17. Sieve #3/8 Project Means –
Florida DOT VT and Contractor QC

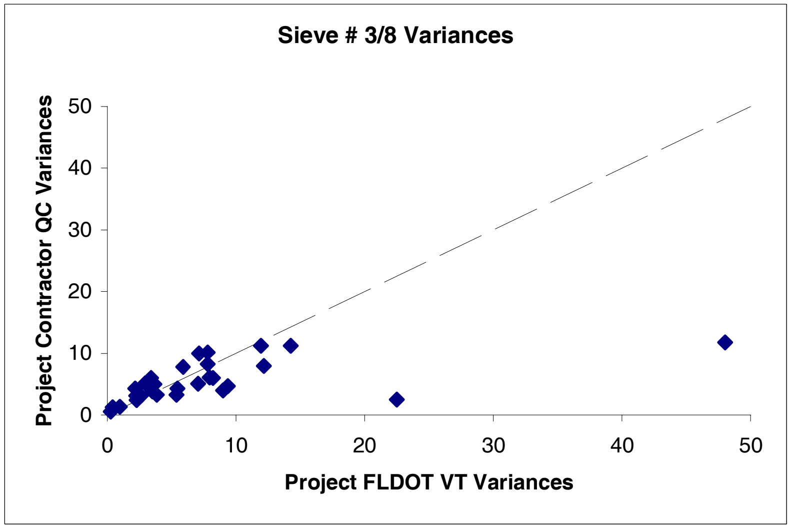


Figure B.18. Sieve #3/8 Project Variances –
Florida DOT VT and Contractor QC

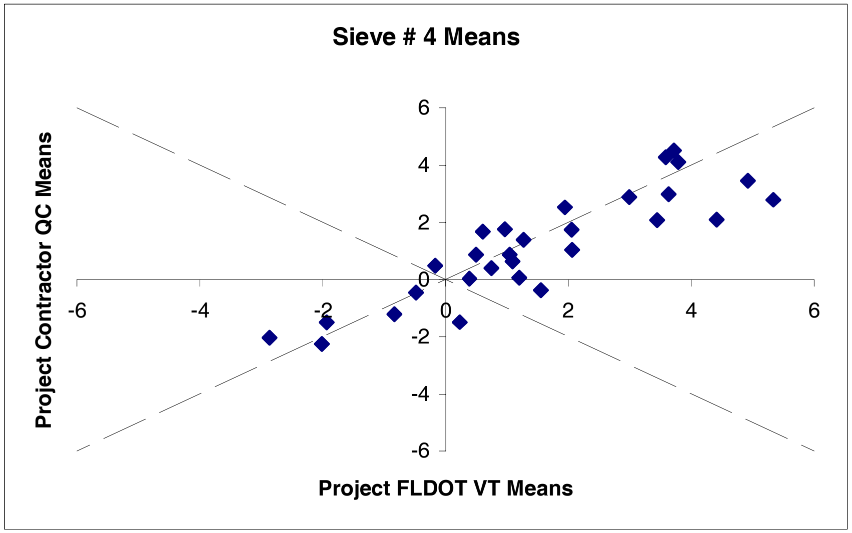


Figure B.19. Sieve #4 Project Means –
Florida DOT VT and Contractor QC

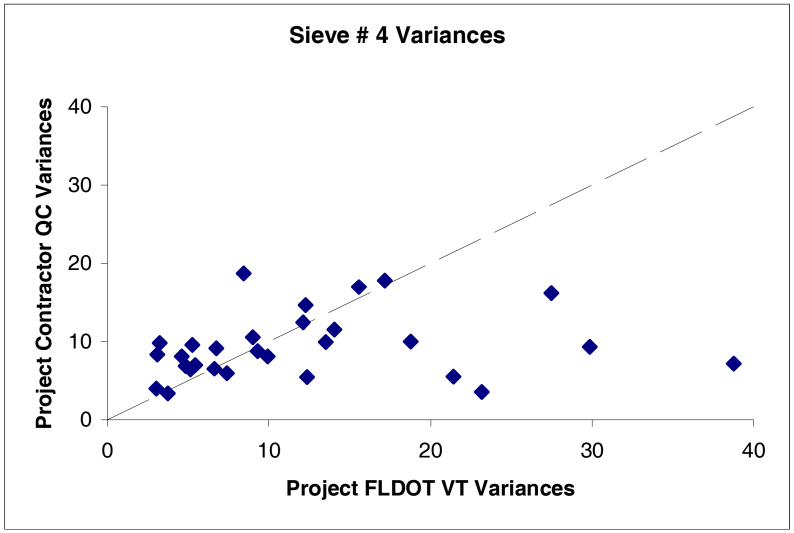


Figure B.20. Sieve #4 Project Variances –
Florida DOT VT and Contractor QC

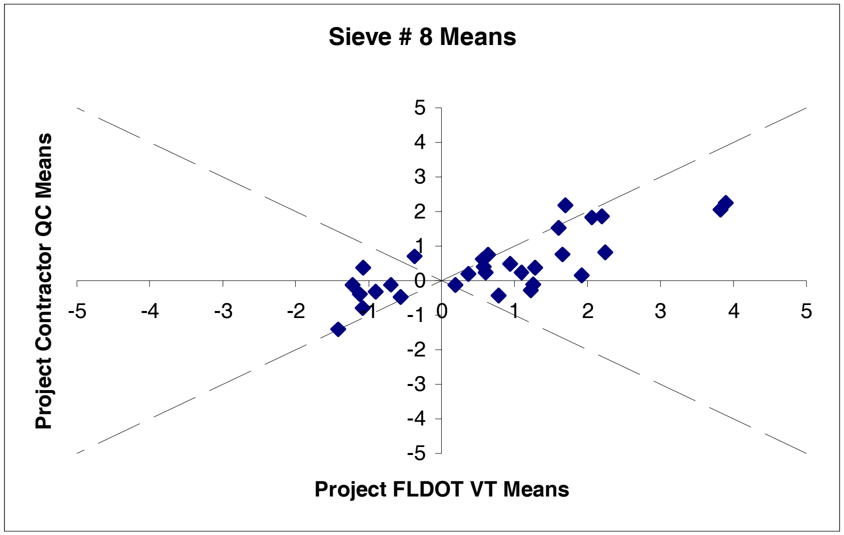


Figure B.21. Sieve #8 Project Means –
Florida DOT VT and Contractor QC

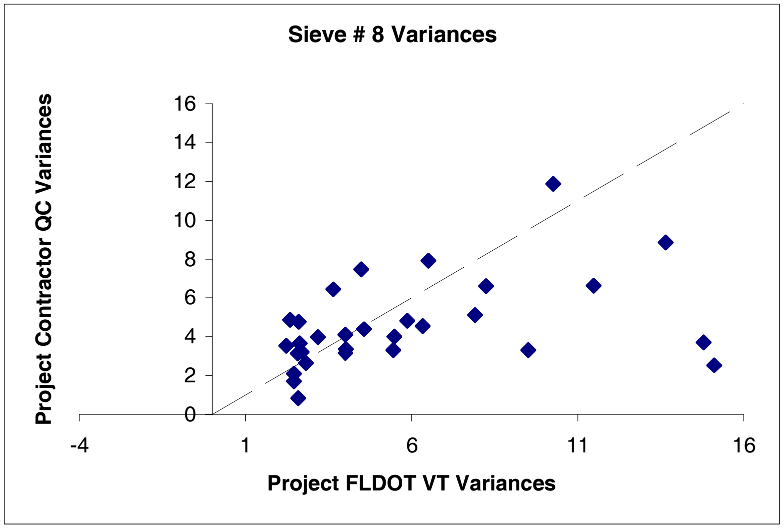


Figure B.22. Sieve #8 Project Variances –
Florida DOT VT and Contractor QC

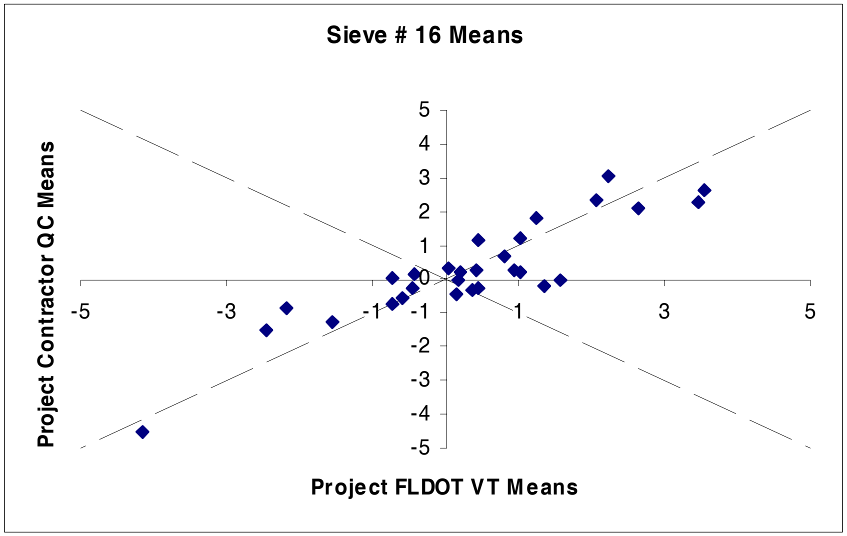


Figure B.23. Sieve #16 Project Means –
Florida DOT VT and Contractor QC

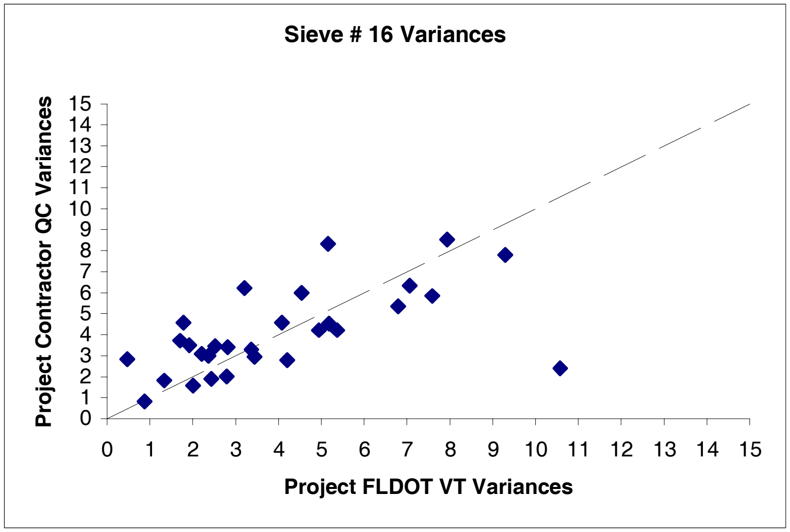


Figure B.24. Sieve #16 Project Variances –
Florida DOT VT and Contractor QC

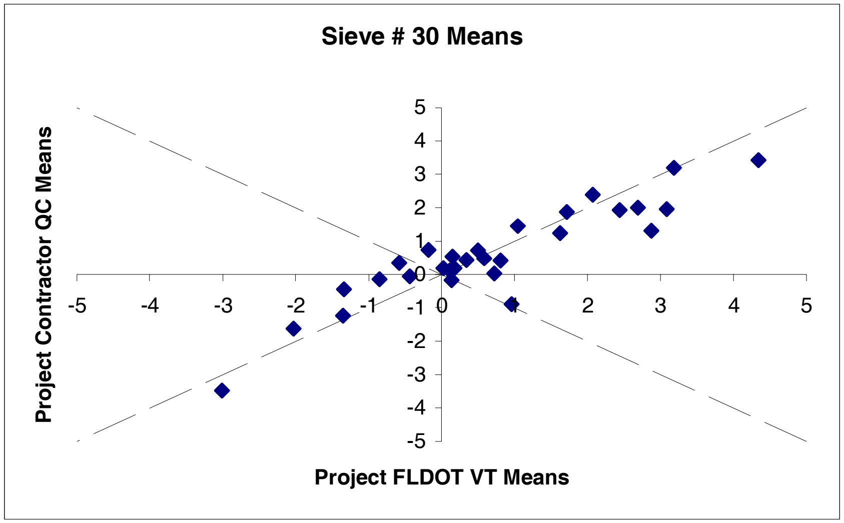


Figure B.25. Sieve #30 Project Means –
Florida DOT VT and Contractor QC

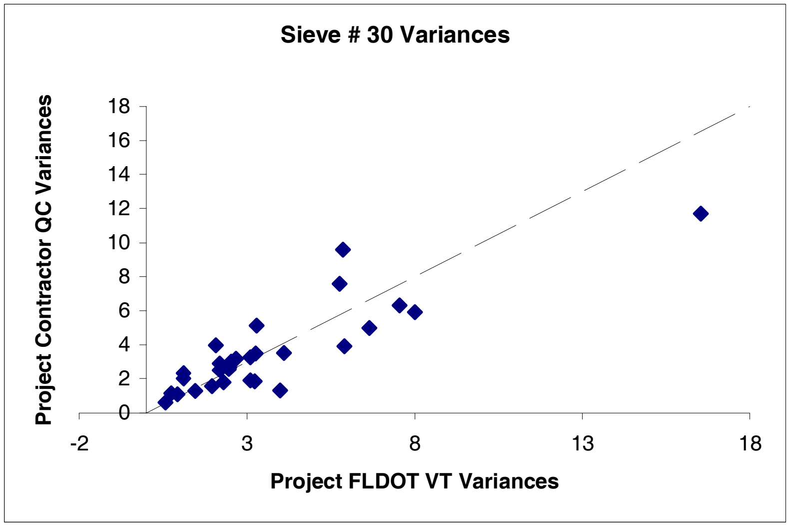


Figure B.26. Sieve #30 Project Variances –
Florida DOT VT and Contractor QC

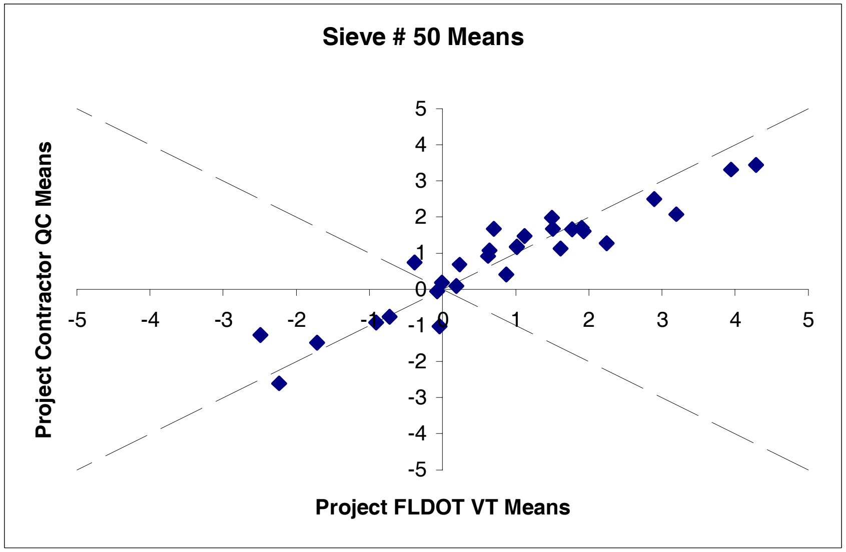


Figure B.27. Sieve #50 Project Means –
Florida DOT VT and Contractor QC

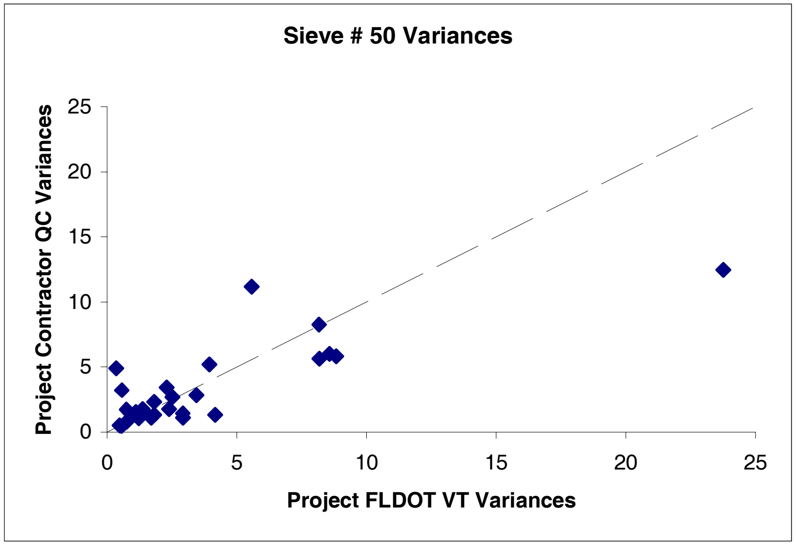


Figure B.28. Sieve #50 Project Variances –
Florida DOT VT and Contractor QC

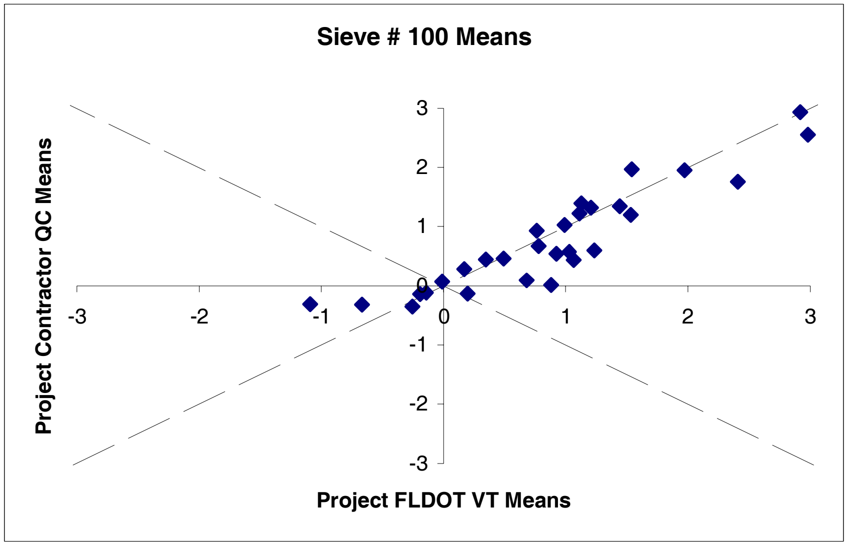


Figure B.29. Sieve #100 Project Means –
Florida DOT VT and Contractor QC

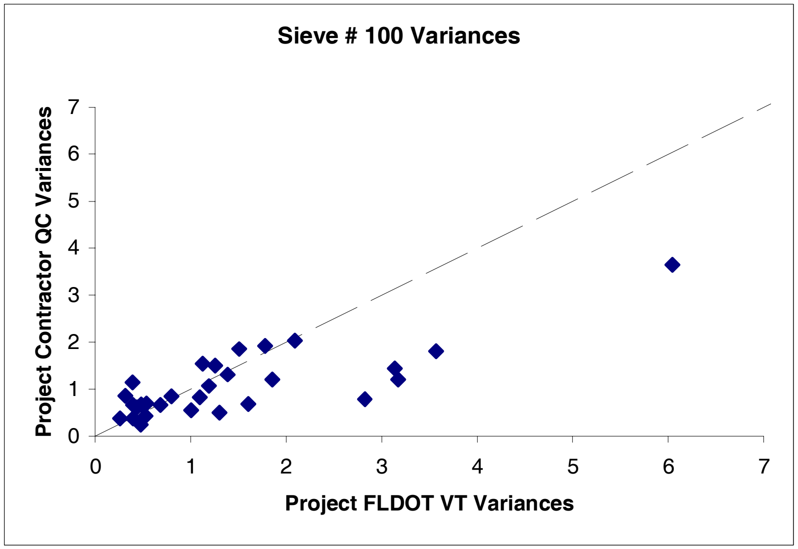


Figure B.30. Sieve #100 Project Variances –
Florida DOT VT and Contractor QC

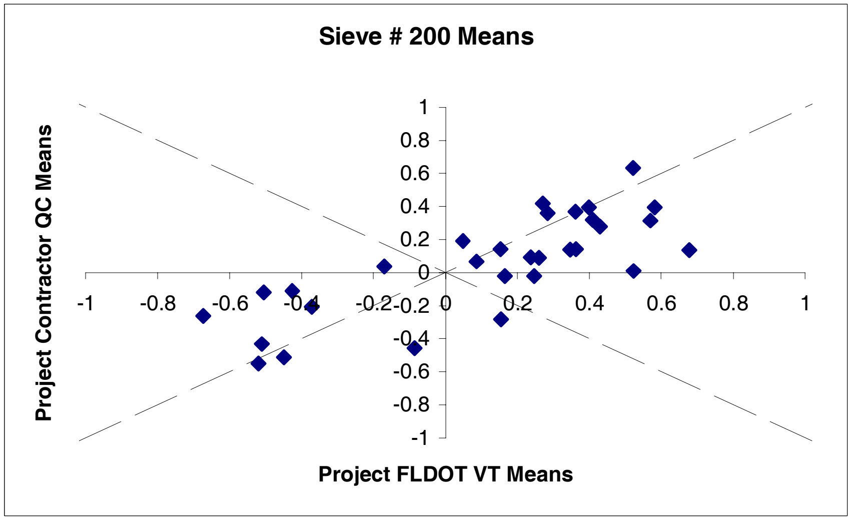


Figure B.31. Sieve #200 Project Means –
Florida DOT VT and Contractor QC

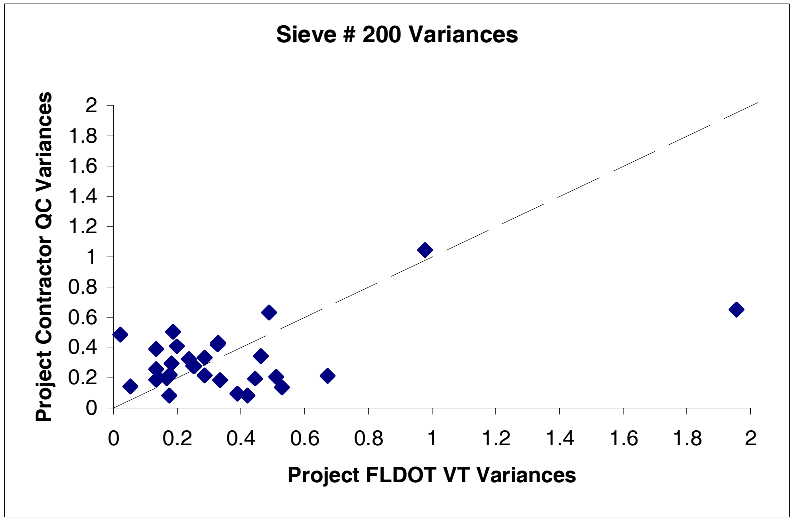


Figure B.32. Sieve #200 Project Variances –
Florida DOT VT and Contractor QC

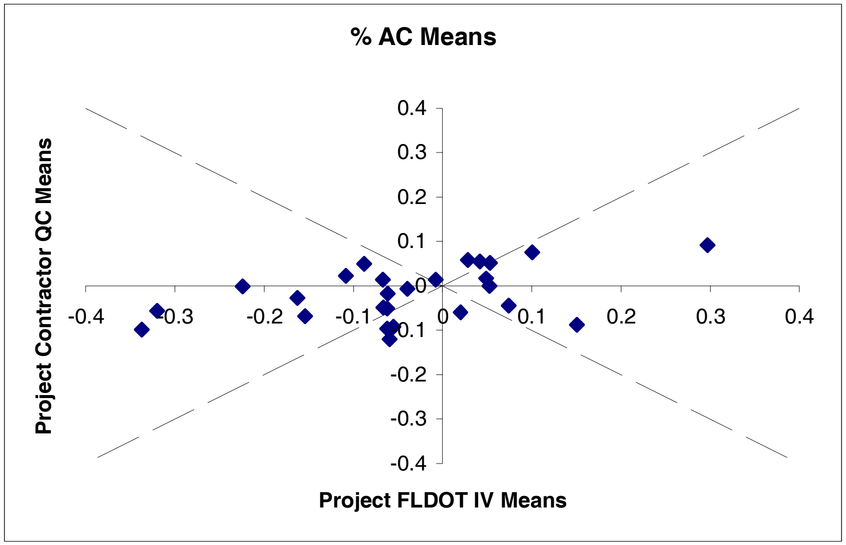


Figure B.33. Asphalt Content Project Means – Florida DOT IV and Contractor QC

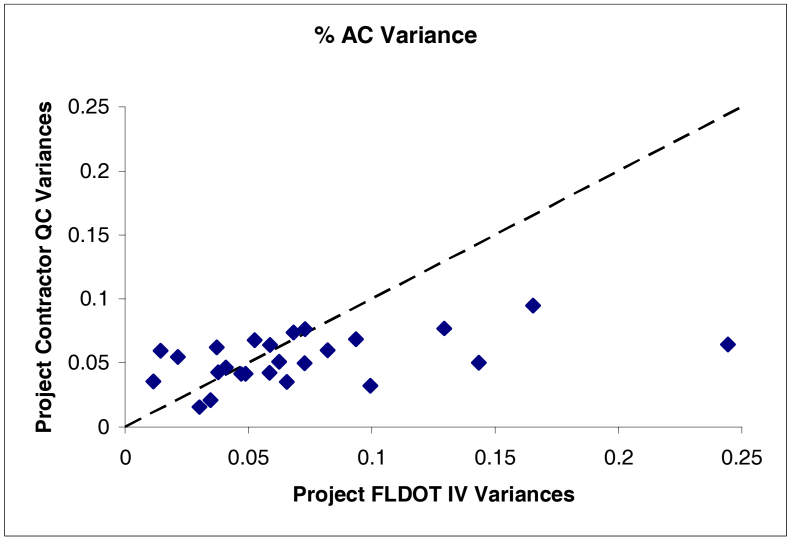


Figure B.34. Asphalt Content Project Variances – Florida DOT IV and Contractor QC

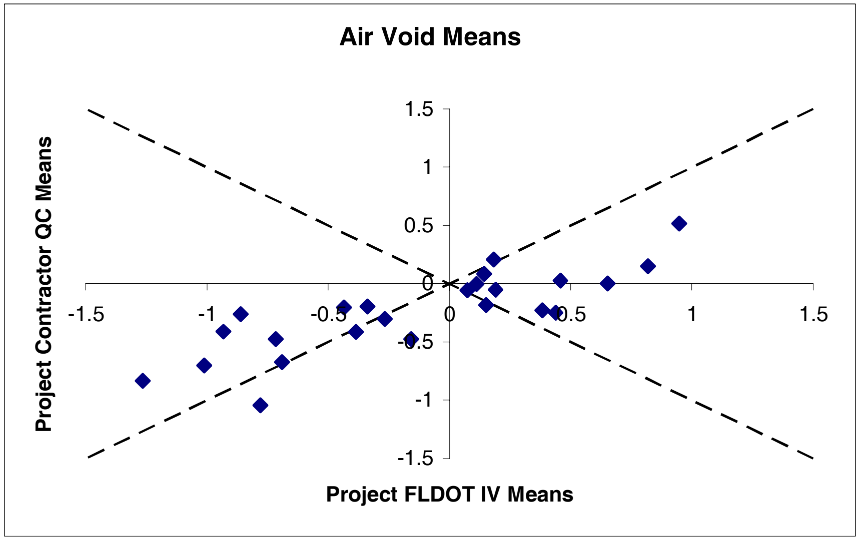


Figure B.35. Air Void Project Means – Florida DOT IV and contractor QC

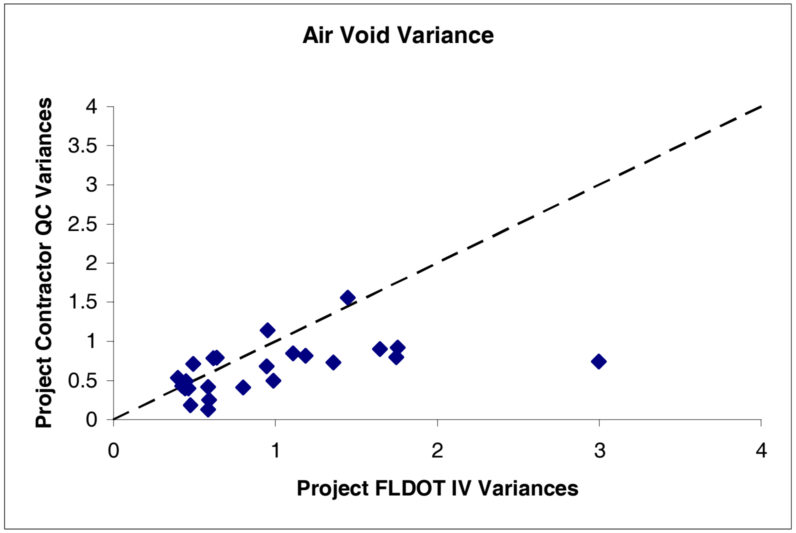


Figure B.36. Air Void Project Variances – Florida DOT IV and Contractor QC

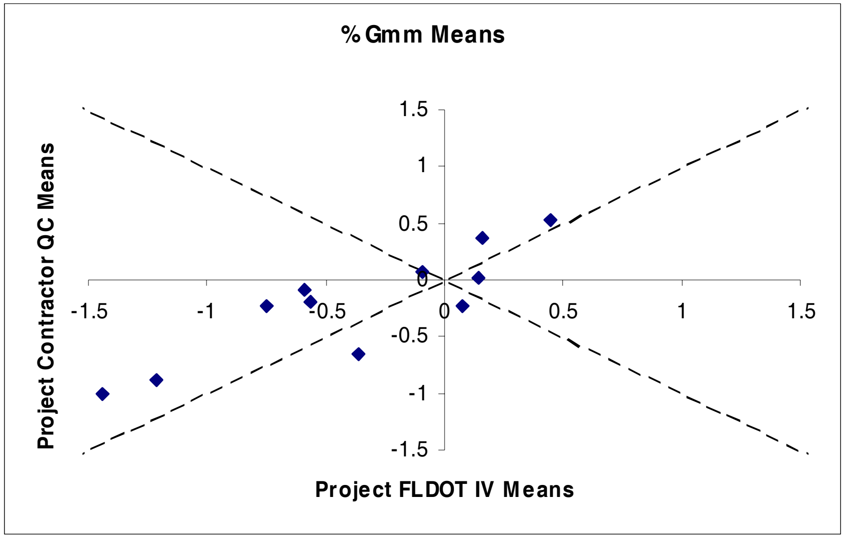


Figure B.37. % G_{mm} Project Means – Florida DOT IV and Contractor QC

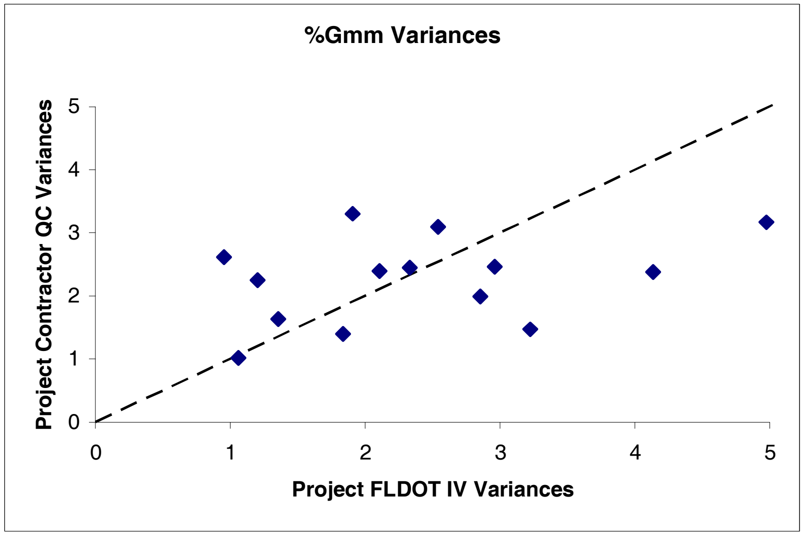


Figure B.38. % G_{mm} Project Variances – Florida DOT IV and Contractor QC

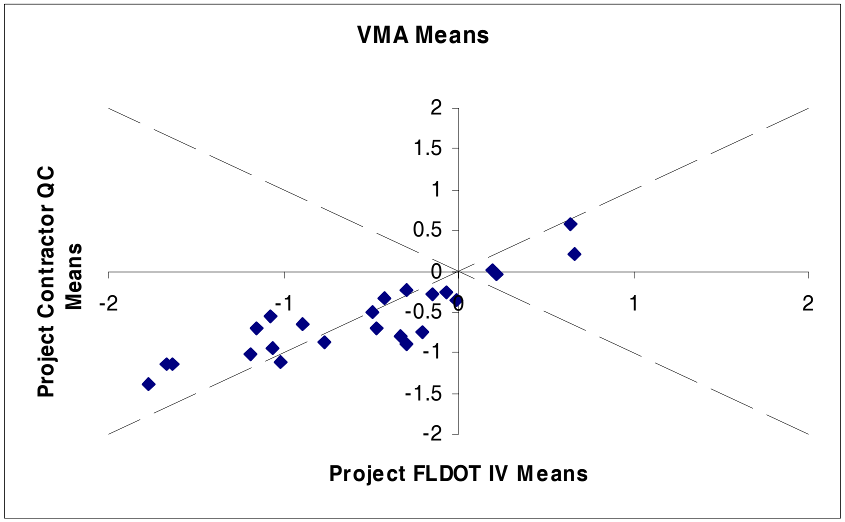


Figure B.39. VMA Project Means – Florida DOT IV and Contractor QC

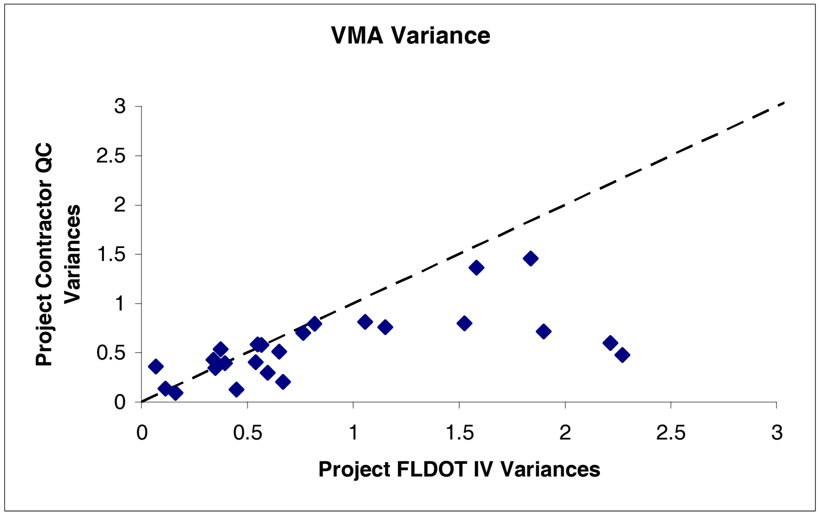


Figure B.40. VMA Project Variances Florida DOT IV and Contractor QC

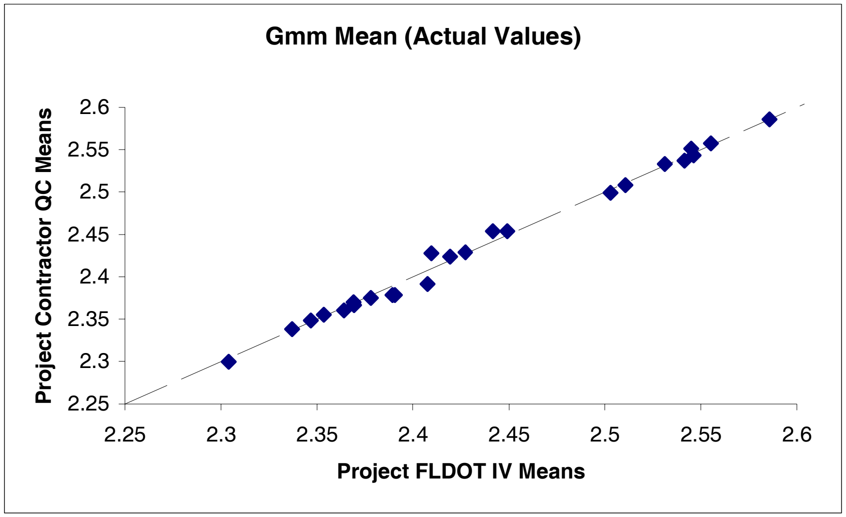


Figure B.41. G_{mm} Project Means – Florida DOT IV and Contractor QC

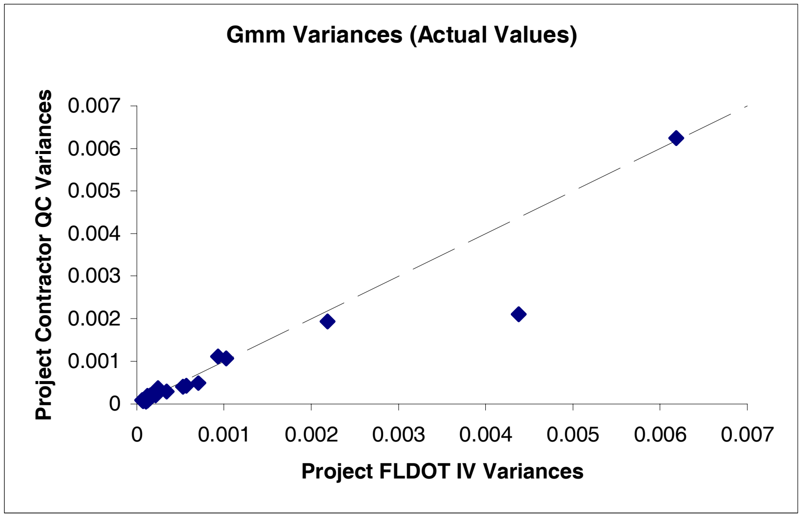


Figure B.42. G_{mm} Project Variances – Florida DOT IV and Contractor QC

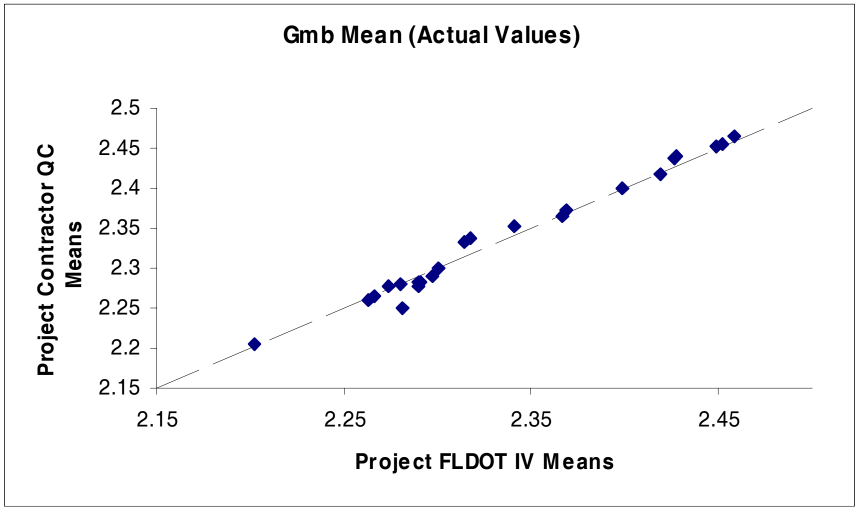


Figure B.43. G_{mb} Project Means – Florida DOT IV and Contractor QC

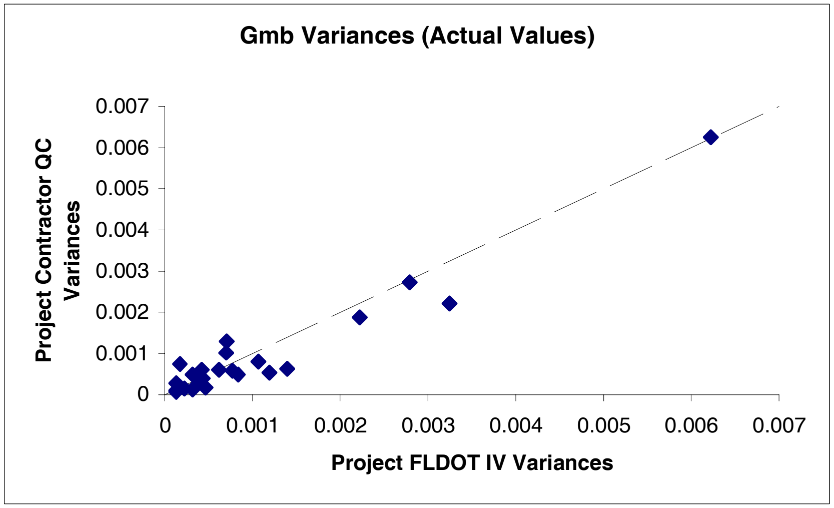


Figure B.44. G_{mb} Project Variances – Florida DOT IV and Contractor QC

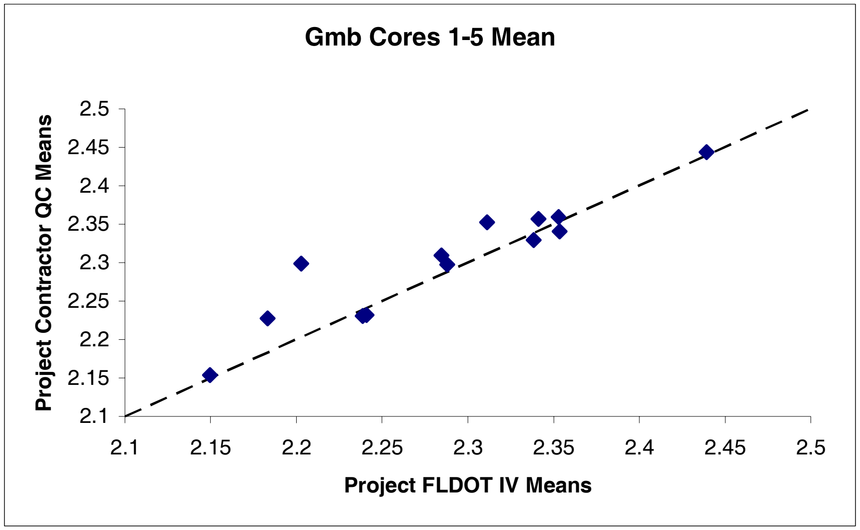


Figure B.45. G_{mb} Cores 1-5 Project Means – Florida DOT IV and Contractor QC

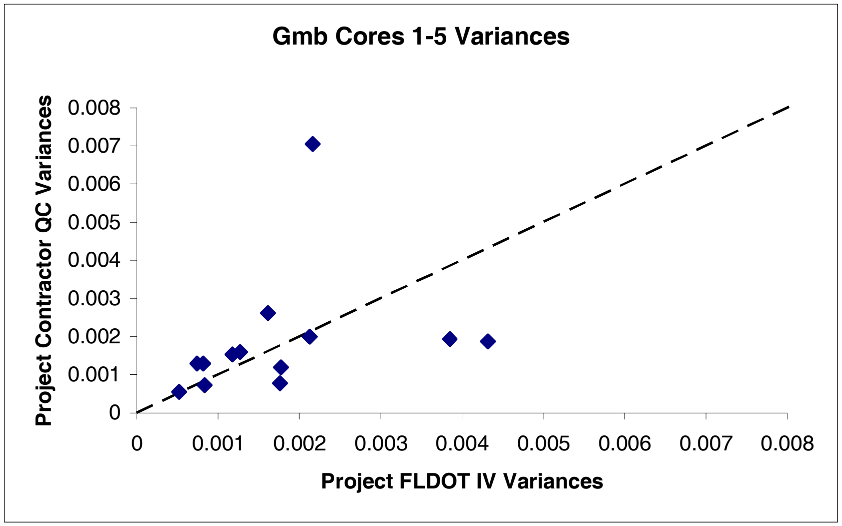


Figure B.46. G_{mb} Cores 1-5 Project Variances – Florida DOT IV and Contractor QC

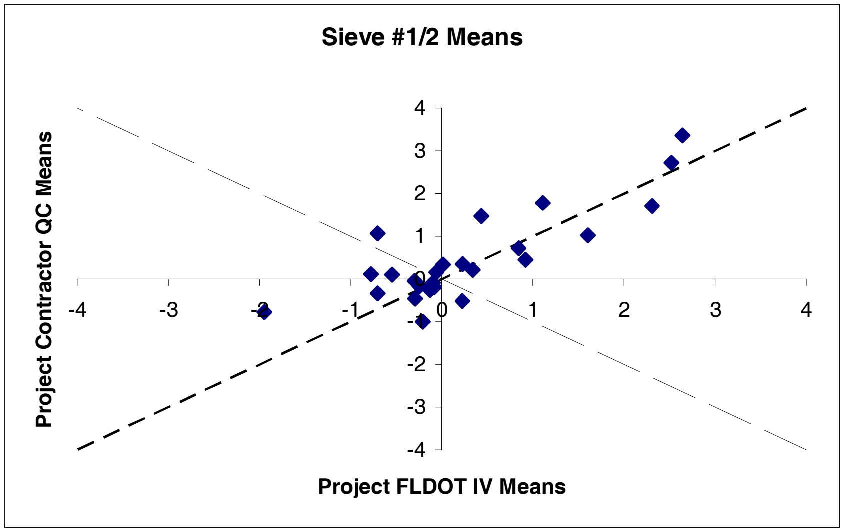


Figure B.47. Sieve #1/2 Project Means – Florida DOT IV and Contractor QC

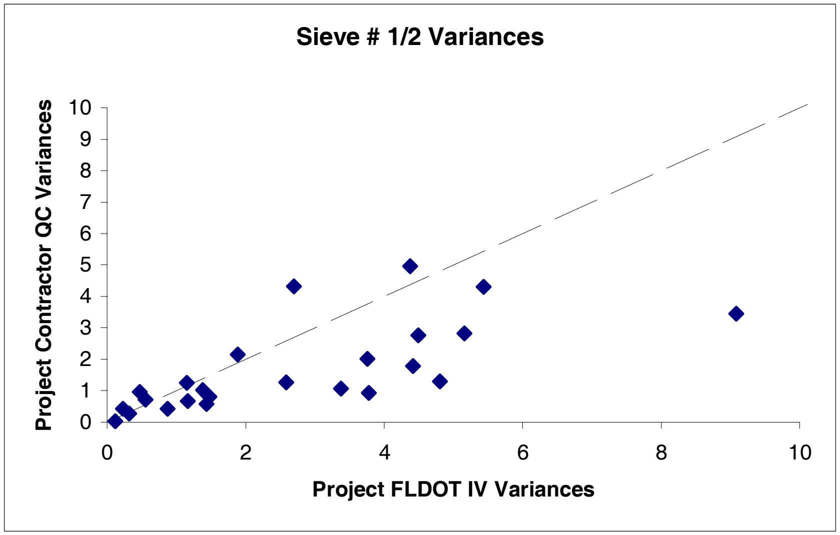


Figure B.48. Sieve #1/2 Project Variances – Florida DOT IV and Contractor QC

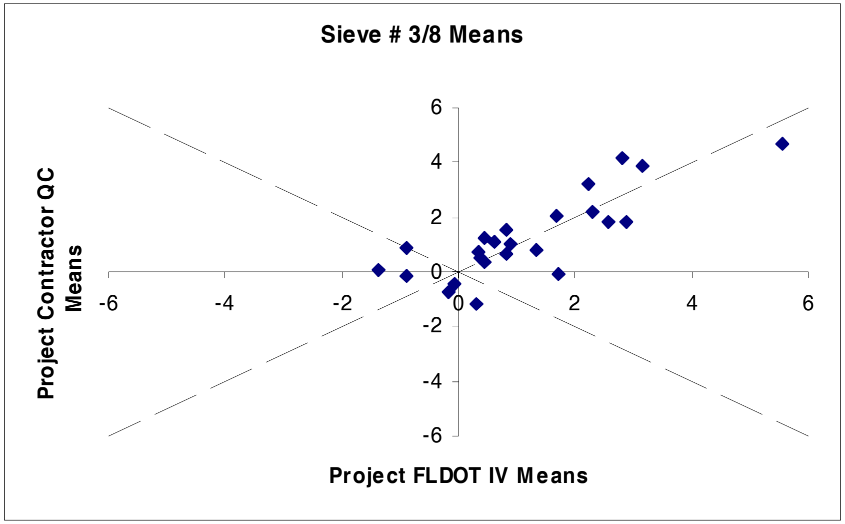


Figure B.49. Sieve #3/8 Project Means – Florida DOT IV and Contractor QC

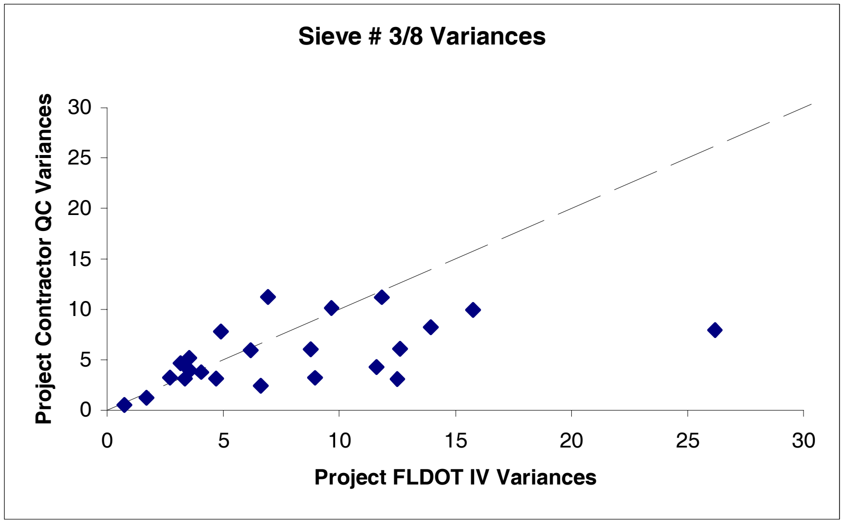


Figure B.50. Sieve #3/8 Project Variances – Florida DOT IV and Contractor QC

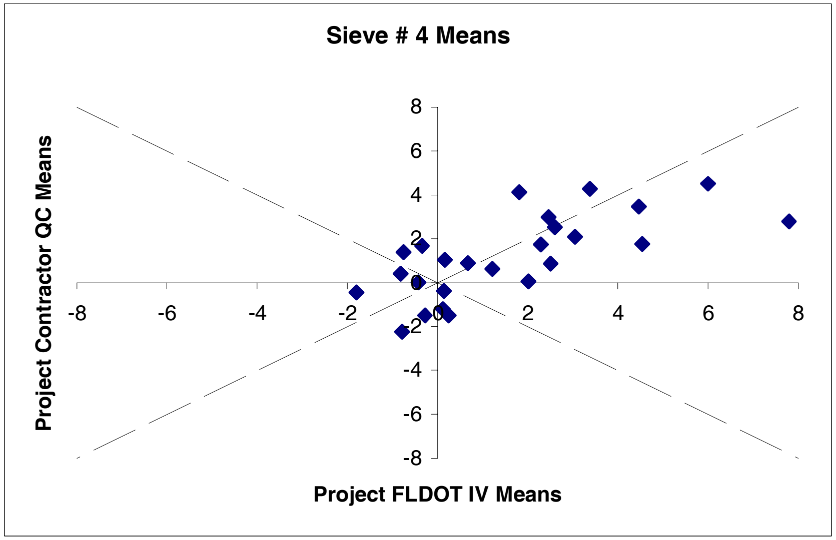


Figure B.51. Sieve #4 Project Means – Florida DOT IV and Contractor QC

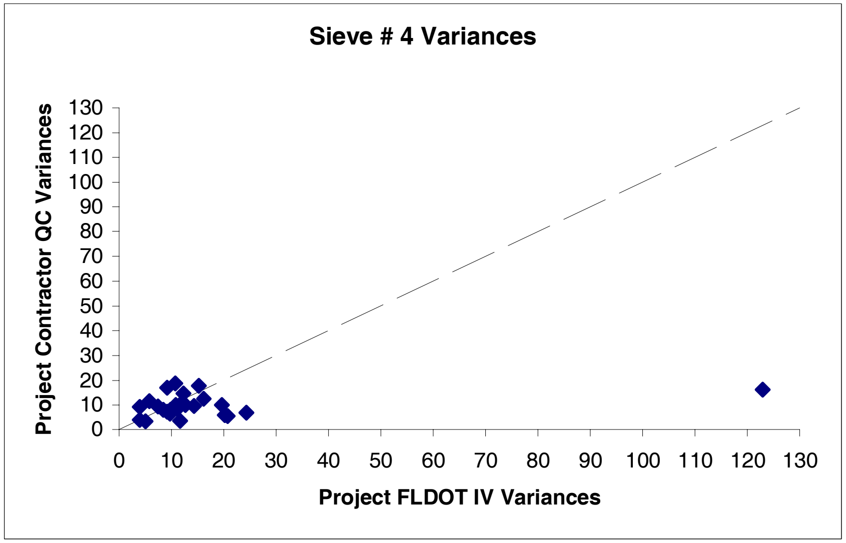


Figure B.52. Sieve #4 Project Variances – Florida DOT IV and Contractor QC

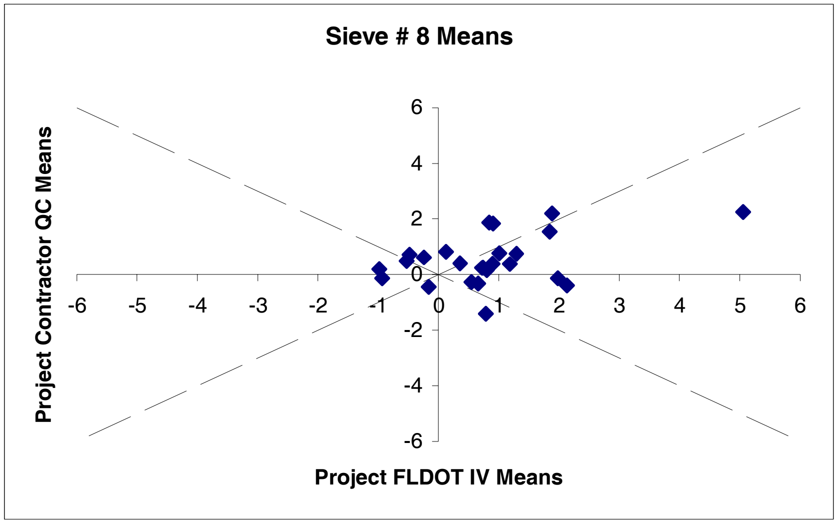


Figure B.53. Sieve #8 Project Means – Florida DOT IV and Contractor QC

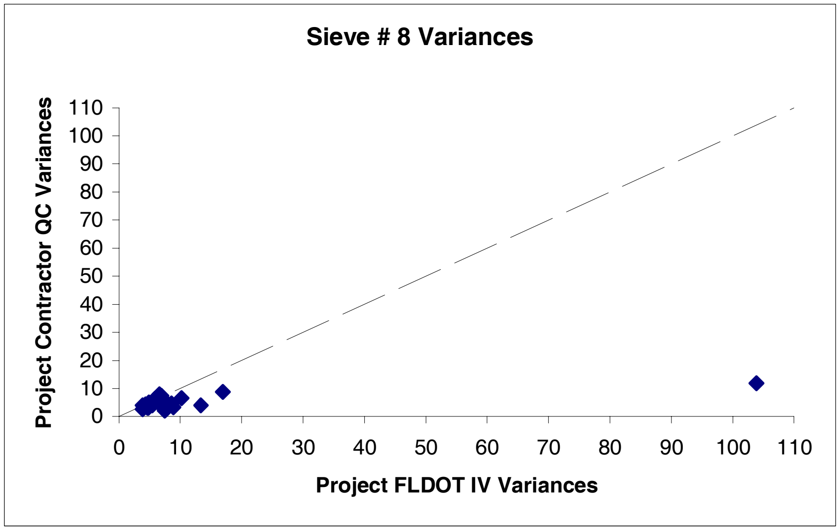


Figure B.54. Sieve #8 Project Variances – Florida DOT IV and Contractor QC

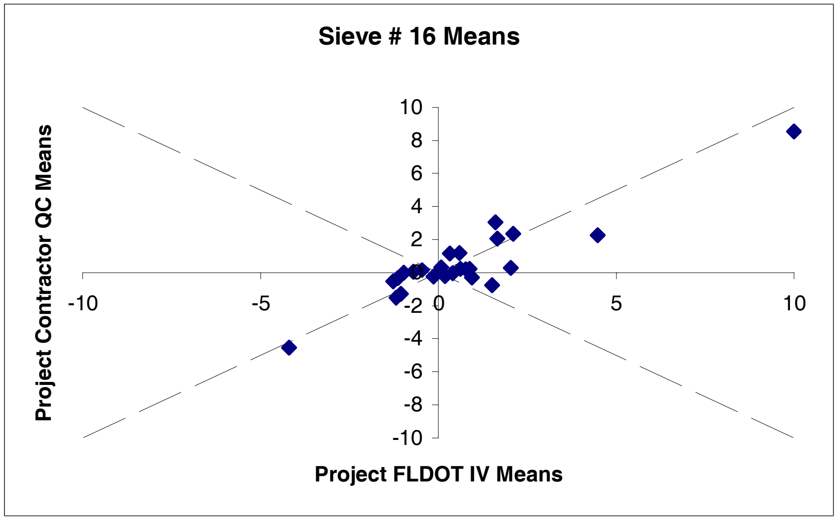


Figure B.55. Sieve #16 Project Means – Florida DOT IV and Contractor Qc

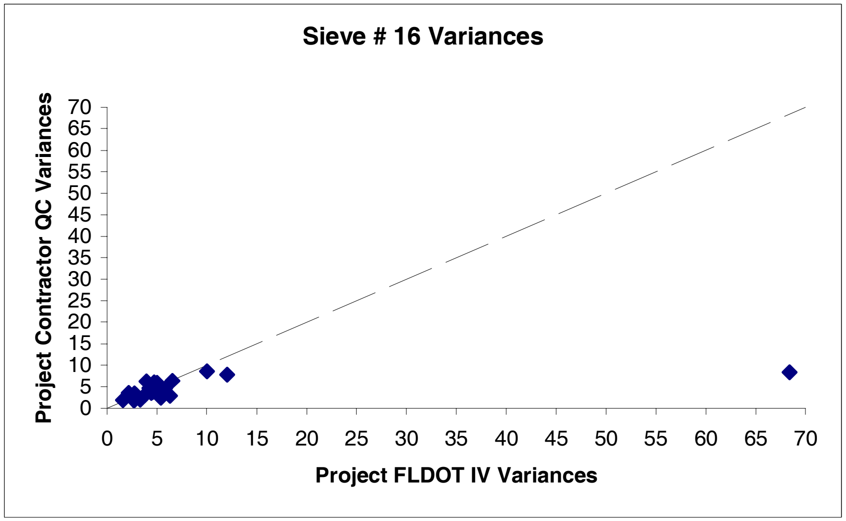


Figure B.56. Sieve #16 Project Variances – Florida DOT IV and Contractor QC

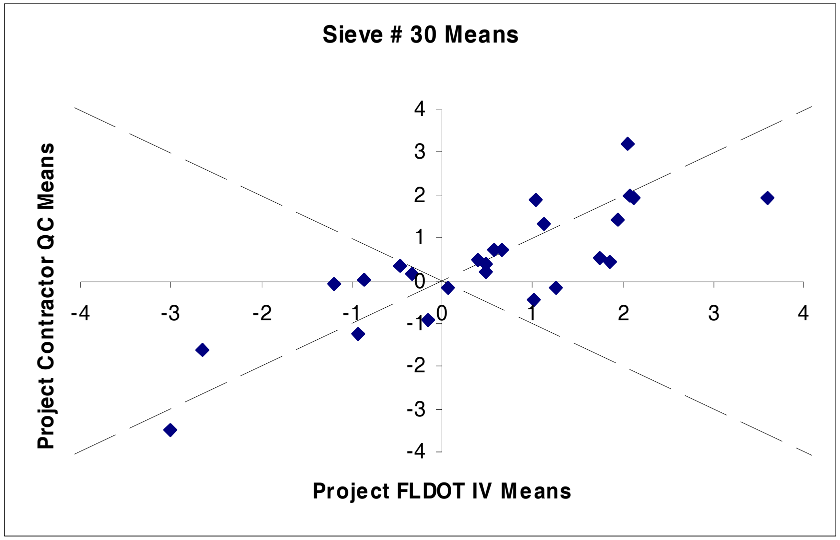


Figure B.57. Sieve #30 Project Means –
Florida DOT IV and Contractor QC

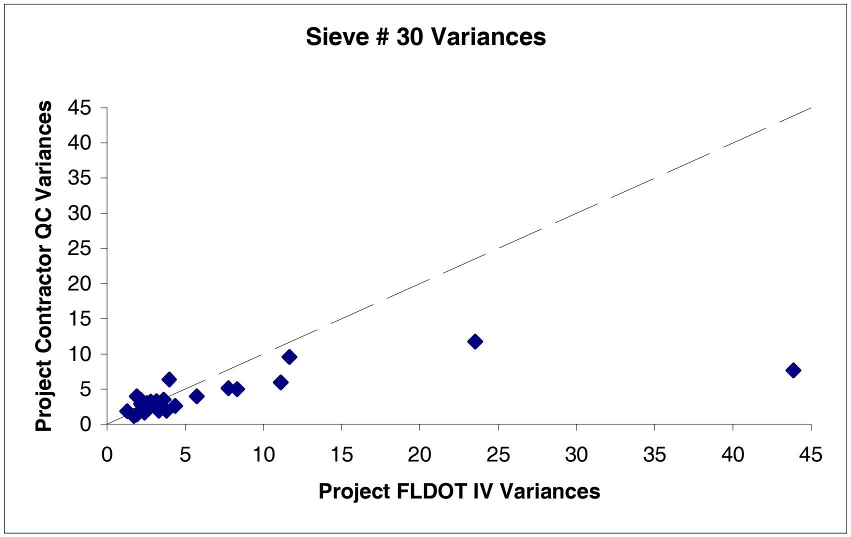


Figure B.58. Sieve #30 Project Variances –
Florida DOT IV and Contractor QC

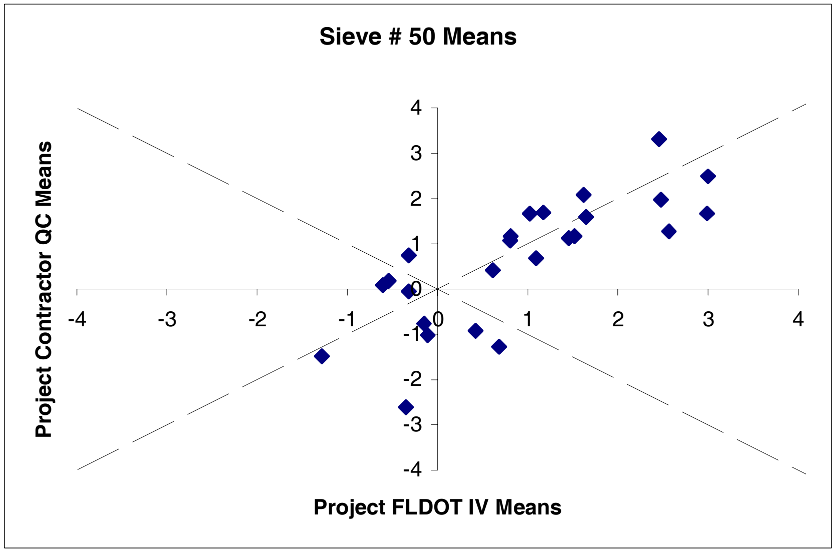


Figure B.59. Sieve #50 Project Means –
Florida DOT IV and Contractor QC

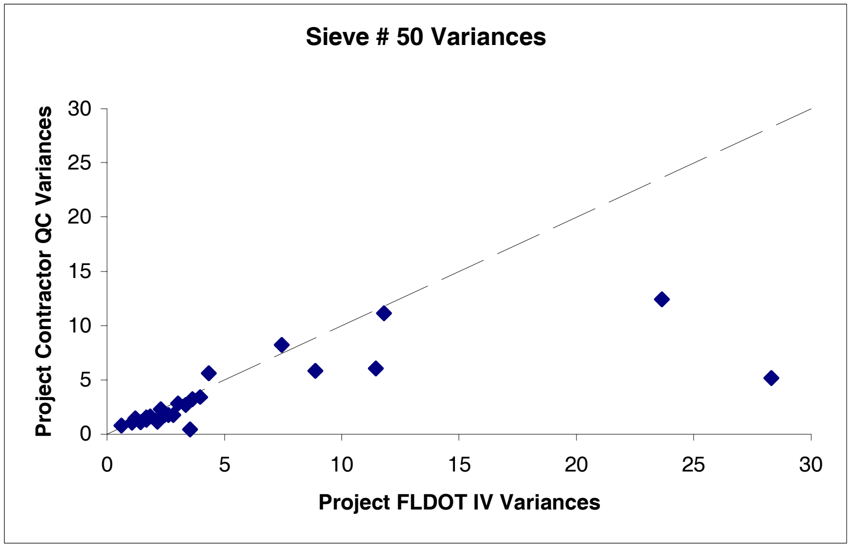


Figure B.60. Sieve #50 Project Variances –
Florida DOT IV and Contractor QC

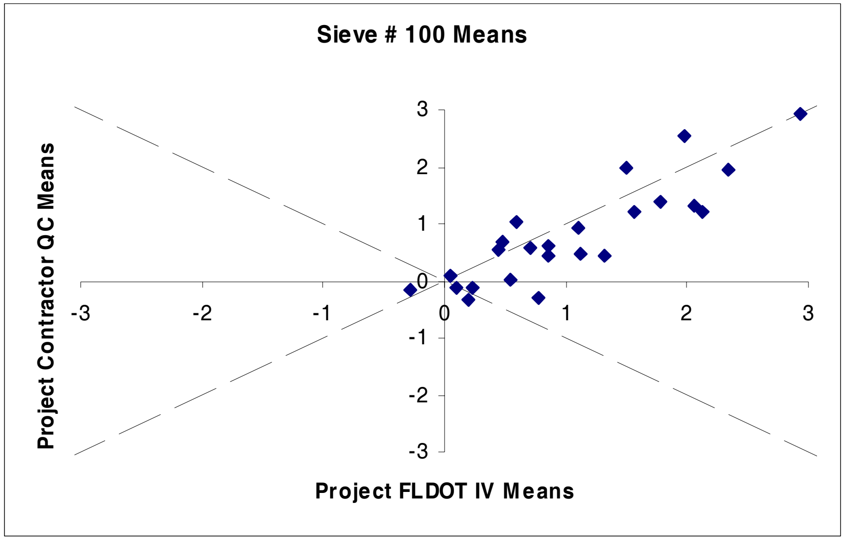


Figure B.61. Sieve #100 Project Means – Florida DOT IV and Contractor QC

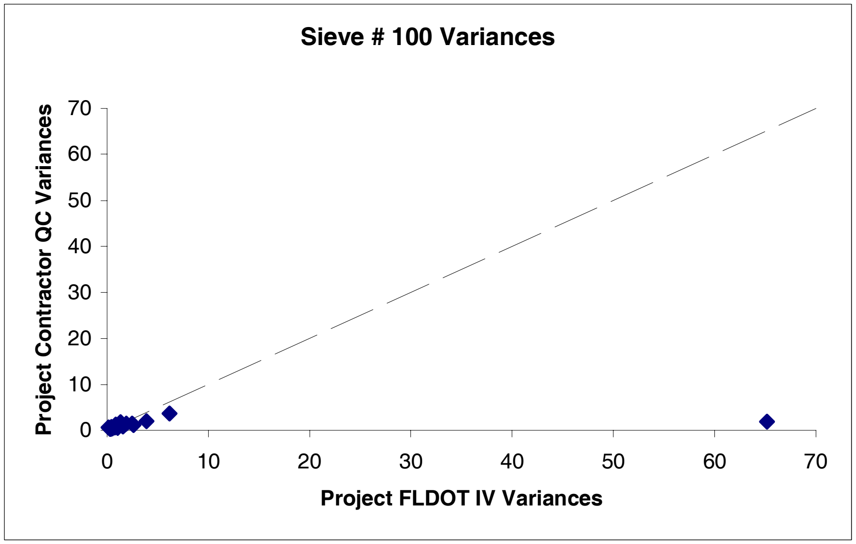
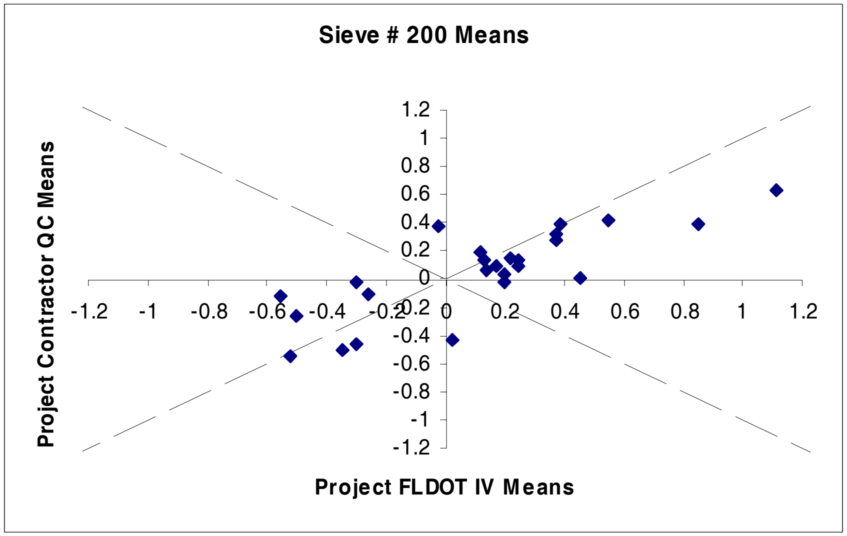


Figure B.62. Sieve #100 Project Variances – Florida DOT IV and Contractor QC



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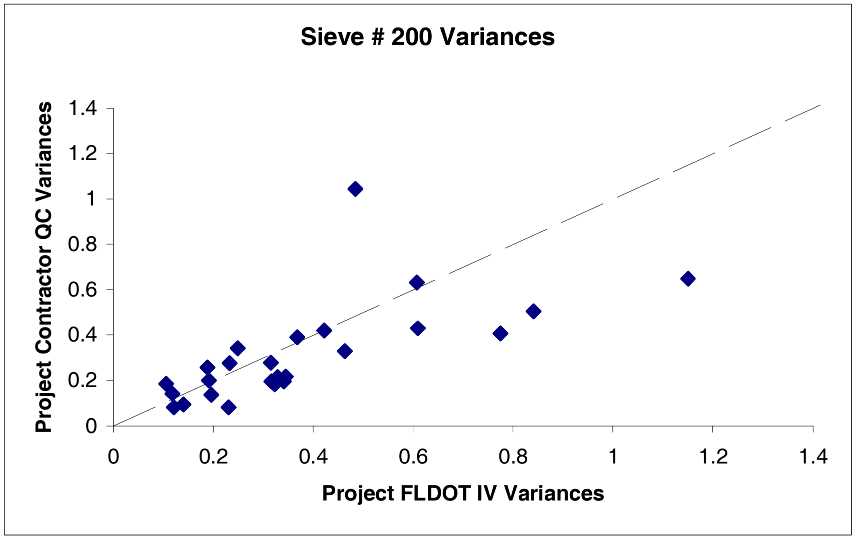

Figure B.64. Sieve #200 Project Variances – Florida DOT IV and Contractor QC

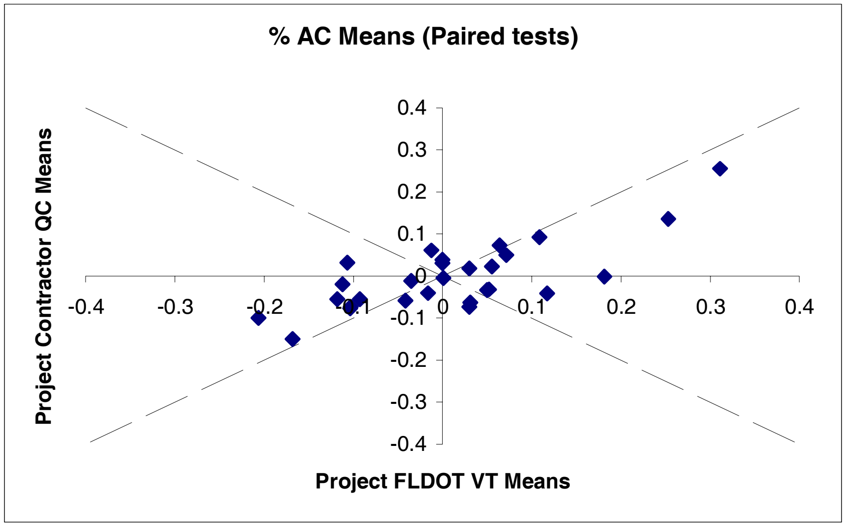

Figure B.65. Asphalt Content Project Means – Paired Florida DOT VT and Contractor QC

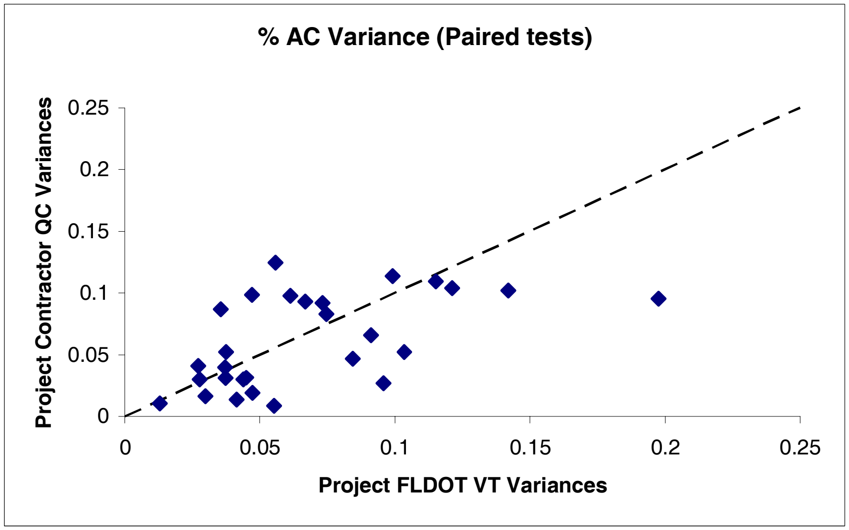

Figure B.66. Asphalt Content Project Variances – Paired Florida DOT VT and Contractor QC

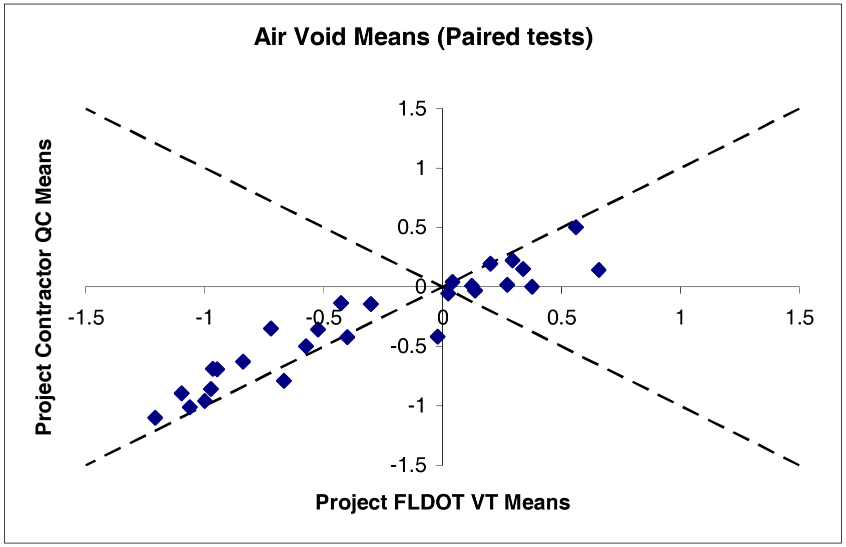

Figure B.67. Air Void Project Means – Paired Florida DOT VT and Contractor QC

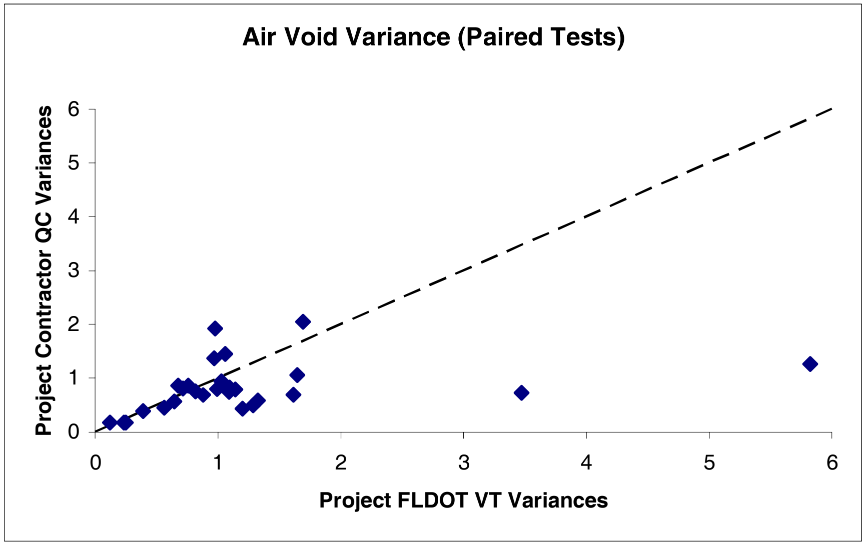

Figure B.68. Air Void Project Variances – Paired Florida DOT VT and Contractor QC

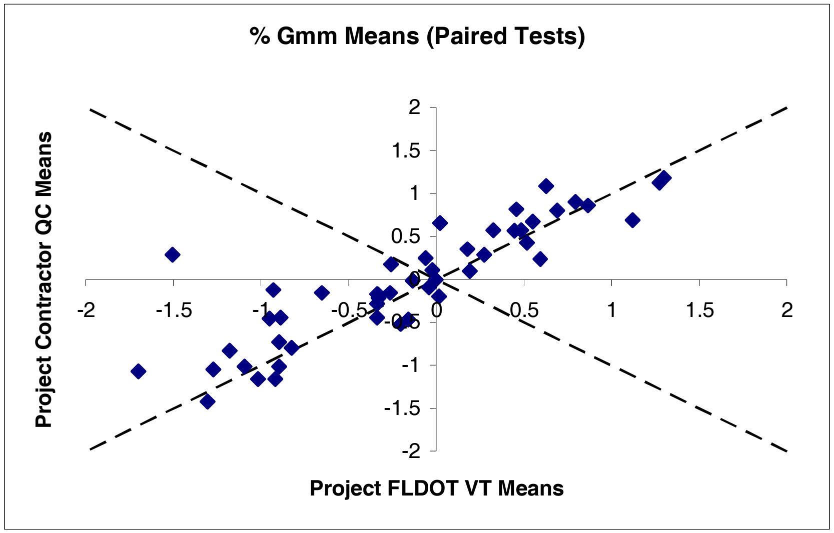

Figure B.69. % G_{mm} Project Means – Paired Florida DOT VT and Contractor QC

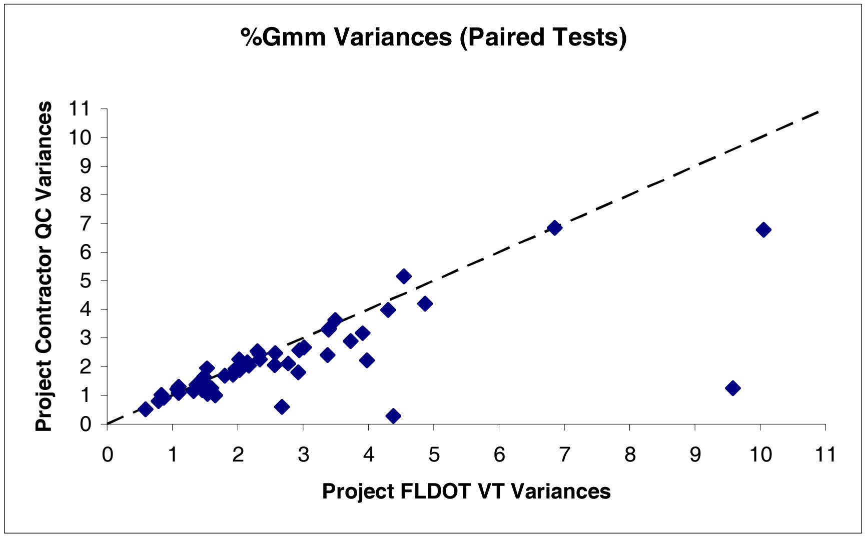

Figure B.70. % G_{mm} Project Variances – Paired Florida DOT VT and Contractor QC

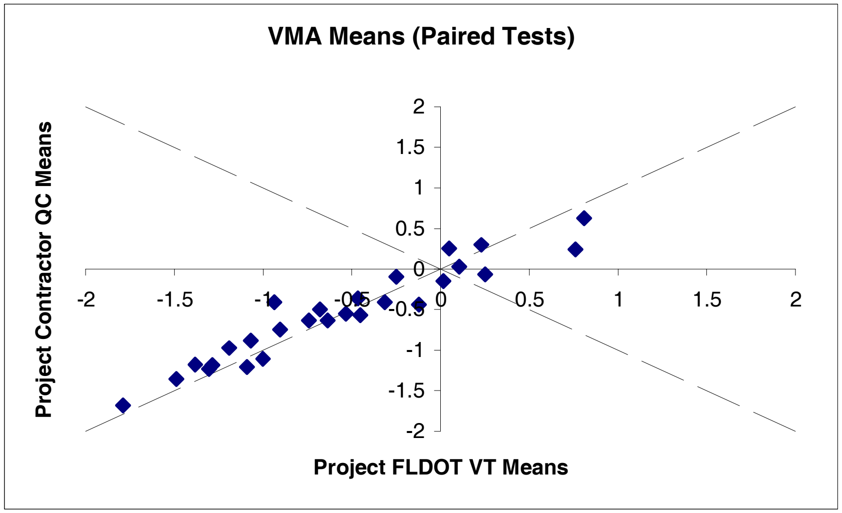

Figure B.71. VMA Project Means – Paired Florida DOT VT and Contractor QC

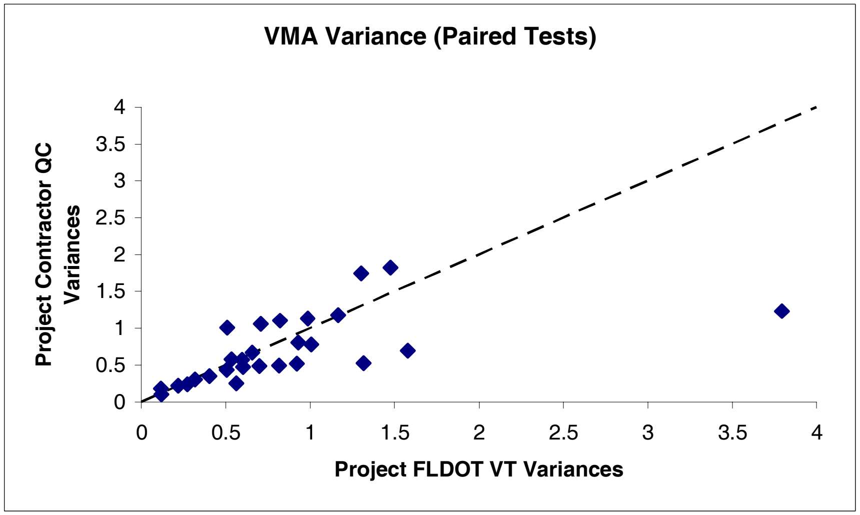

Figure B.72. VMA Project Variances – Paired Florida DOT VT and Contractor QC

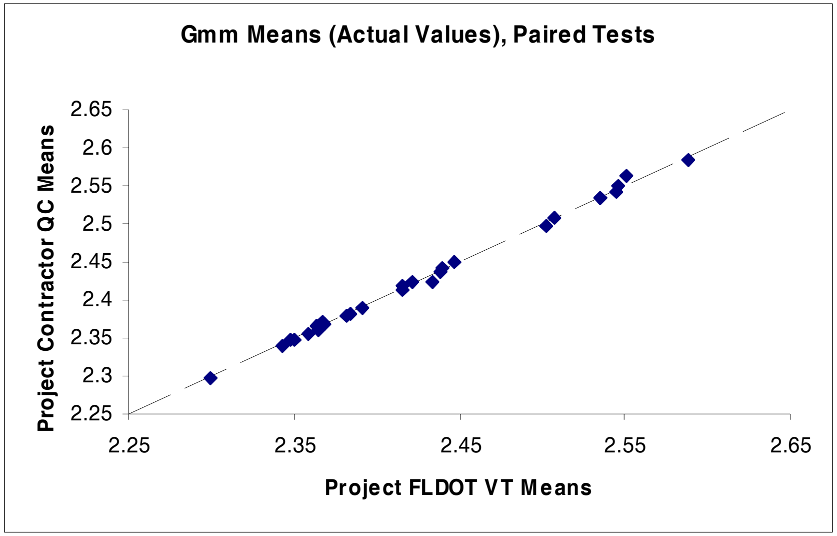

Figure B.73. G_{mm} Project Means –
Paired Florida DOT VT and Contractor QC

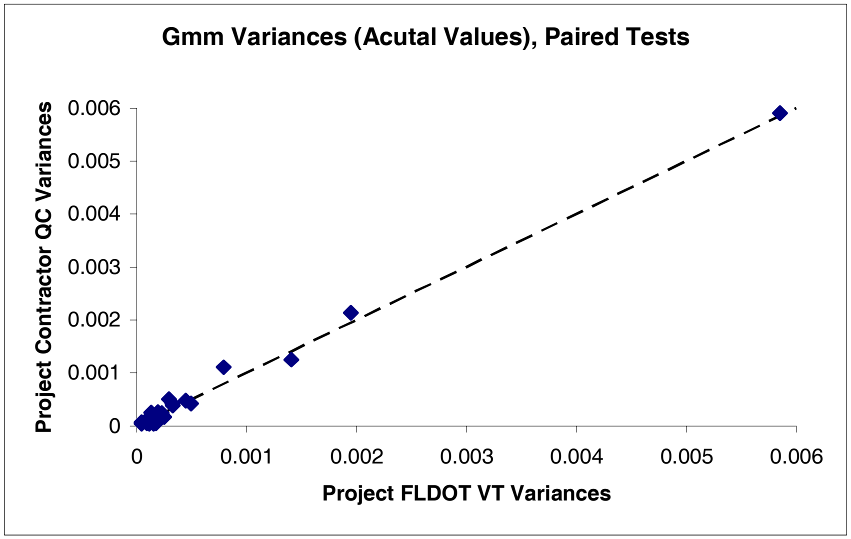

Figure B.74. G_{mm} Project Variances –
Paired Florida DOT VT and Contractor QC

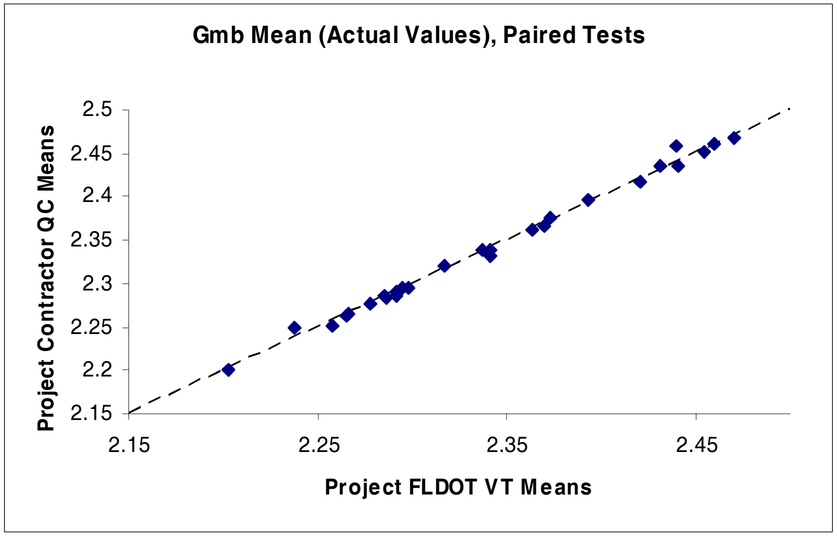

Figure B.75. G_{mb} Project Means –
Paired Florida DOT VT and Contractor QC

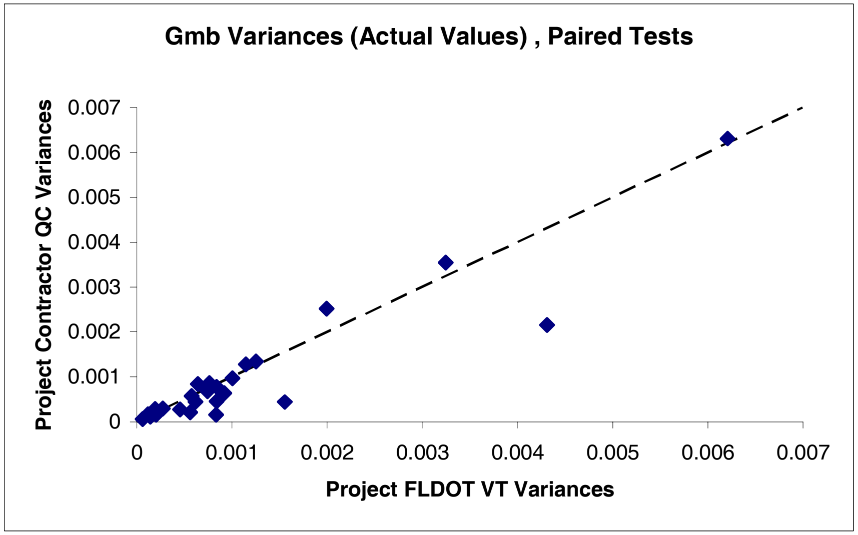

Figure B.76. G_{mb} Project Variances –
Paired Florida DOT VT and Contractor QC

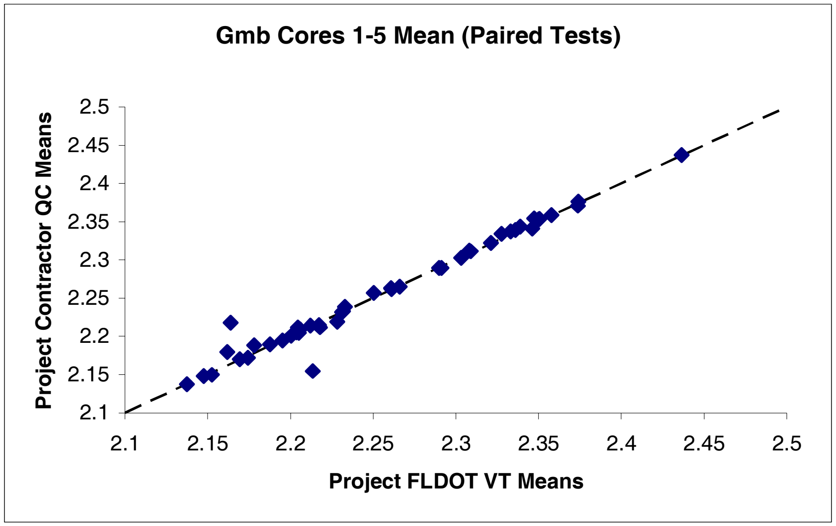

Figure B.77. G_{mb} Cores 1-5 Project Means – Paired Florida DOT VT and Contractor QC

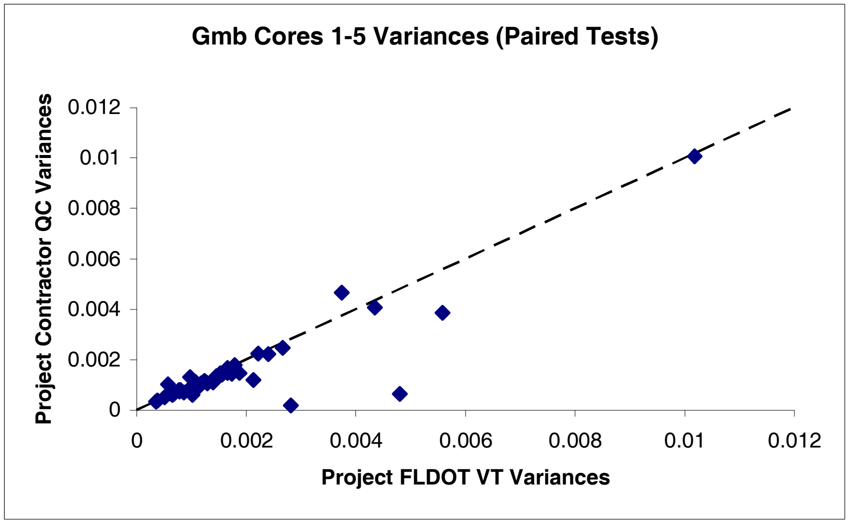

Figure B.78. G_{mb} Cores 1-5 Project Variances – Florida DOT VT and Contractor QC

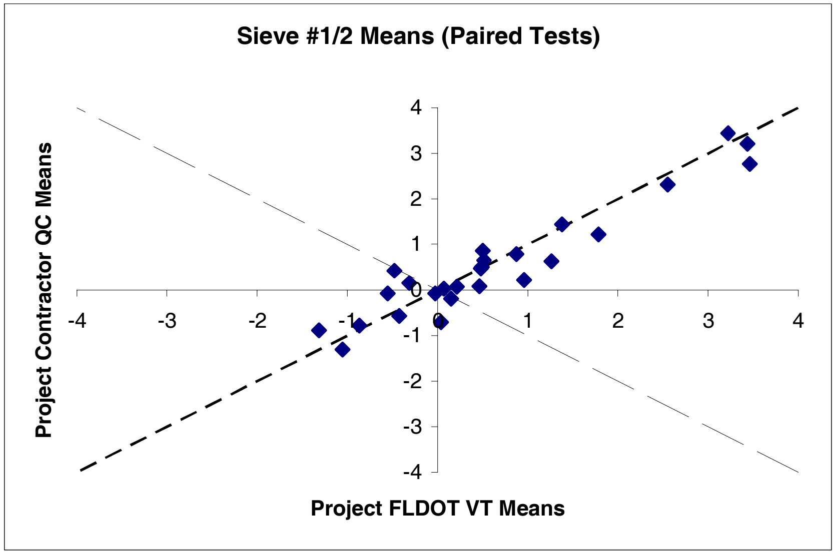

Figure B.79. Sieve #1/2 Project Means – Paired Florida DOT VT and Contractor QC

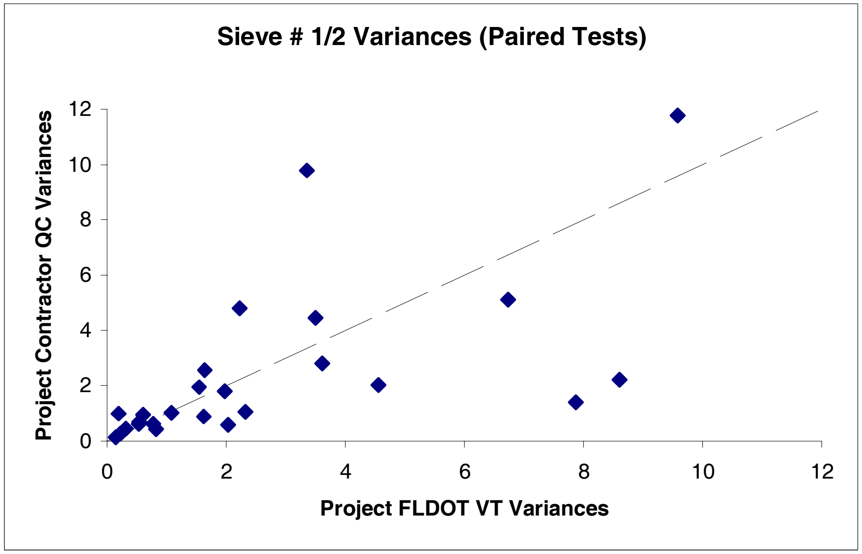

Figure B.80. Sieve #1/2 Project Variances – Paired Florida DOT VT and Contractor QC

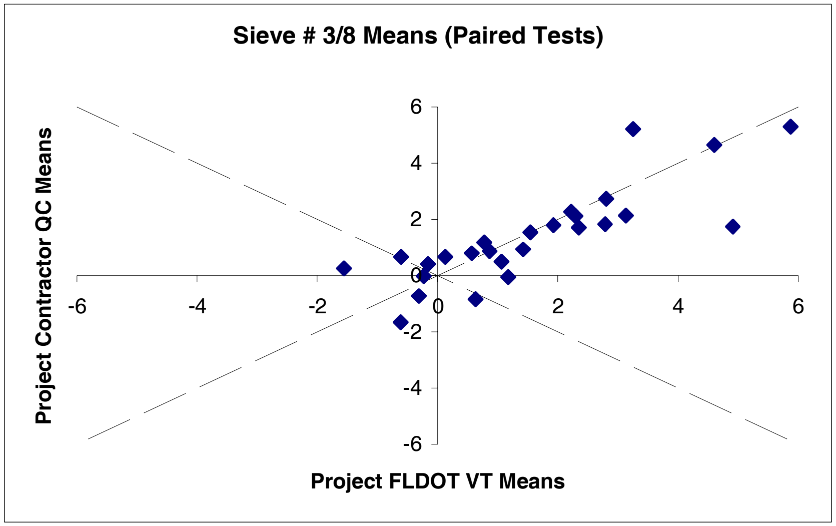

Figure B.81. Sieve #3/8 Project Means – Paired Florida DOT VT and Contractor QC

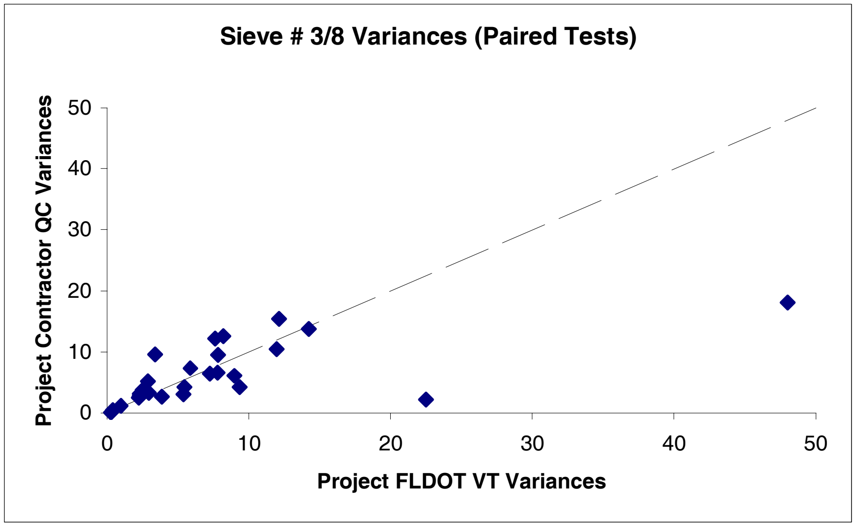

Figure B.82. Sieve #3/8 Project Variances – Paired Florida DOT VT and Contractor QC

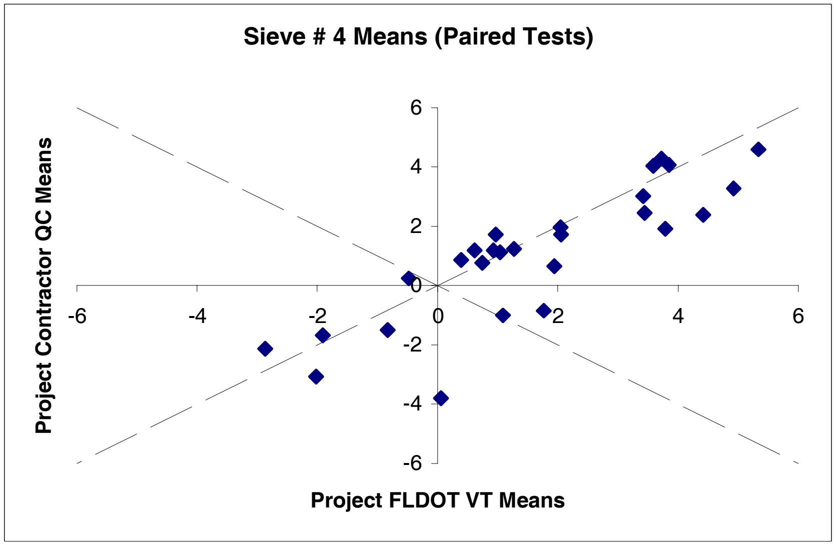

Figure B.83. Sieve #4 Project Means – Paired Florida DOT VT and Contractor QC

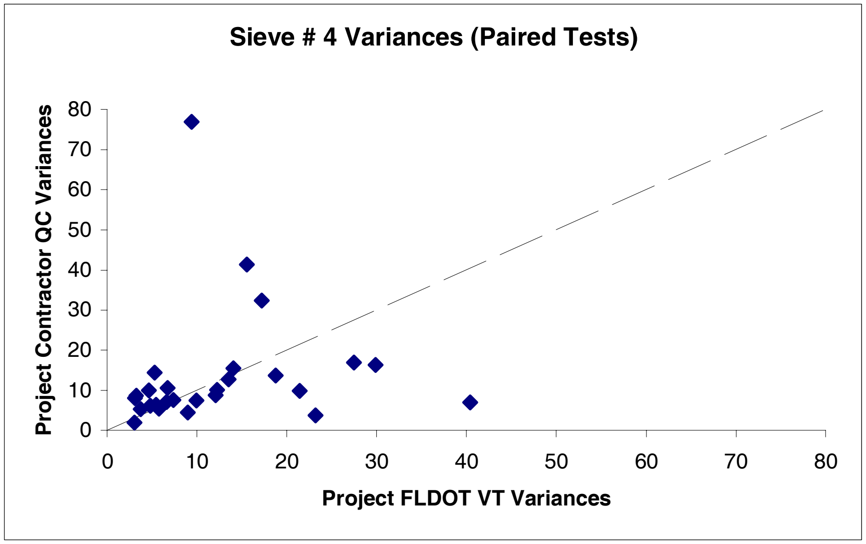

Figure B.84. Sieve #4 Project Variances – Paired Florida DOT VT and Contractor QC

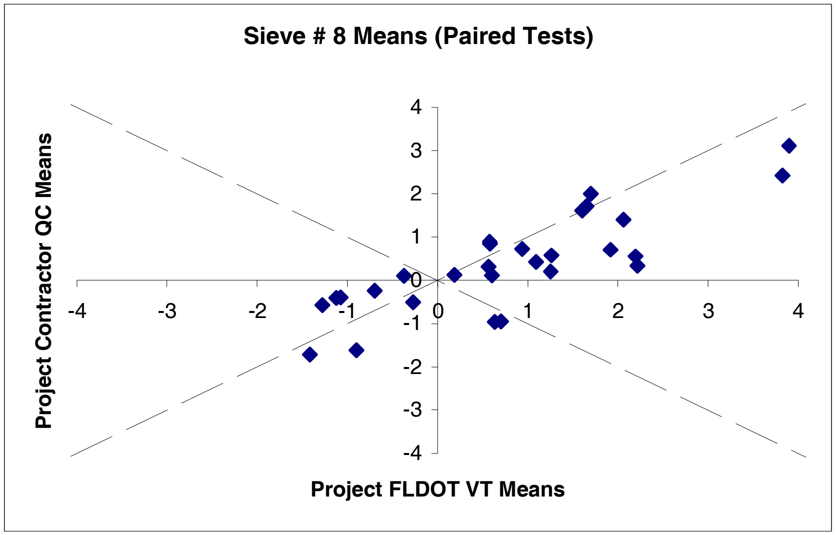

Figure B.85. Sieve #8 Project Means – Paired Florida DOT VT and Contractor QC

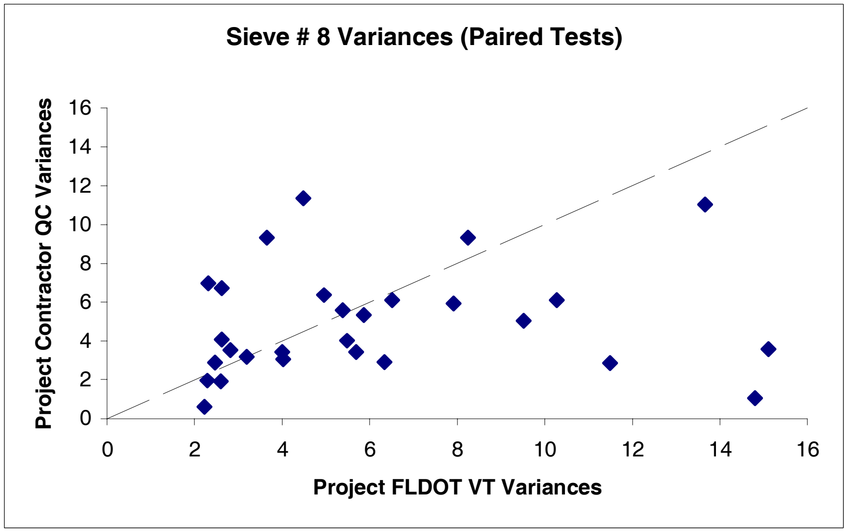

Figure B.86. Sieve #8 Project Variances – Paired Florida DOT VT and Contractor QC

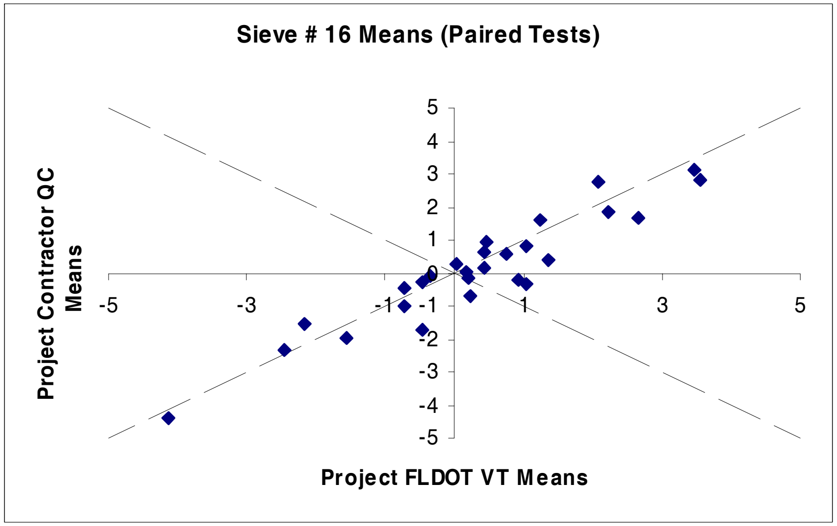

Figure B.87. Sieve #16 Project Means – Paired Florida DOT VT and Contractor QC

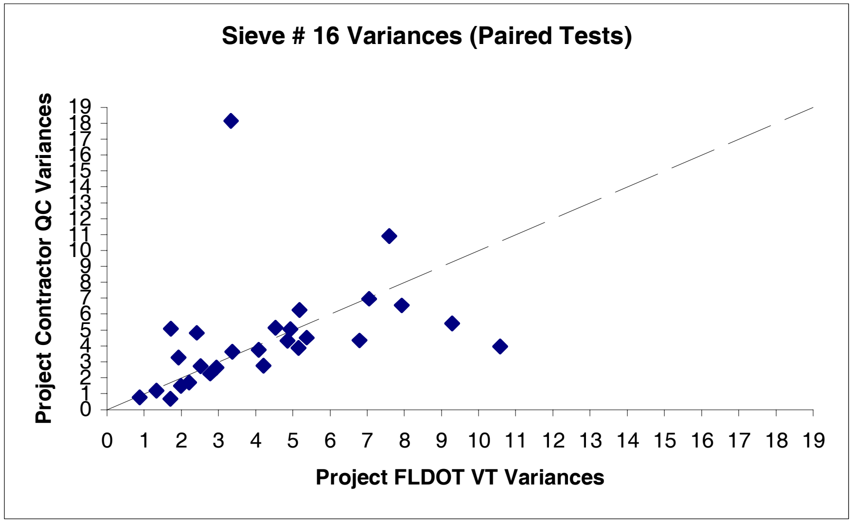

Figure B.88. Sieve #16 Project Variances – Paired Florida DOT VT and Contractor QC

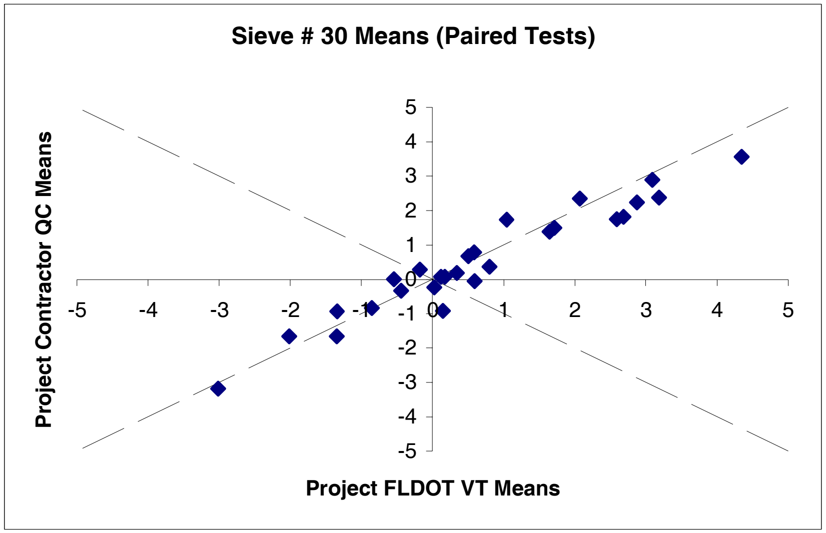

Figure B.89. Sieve #30 Project Means – Paired Florida DOT VT and Contractor QC

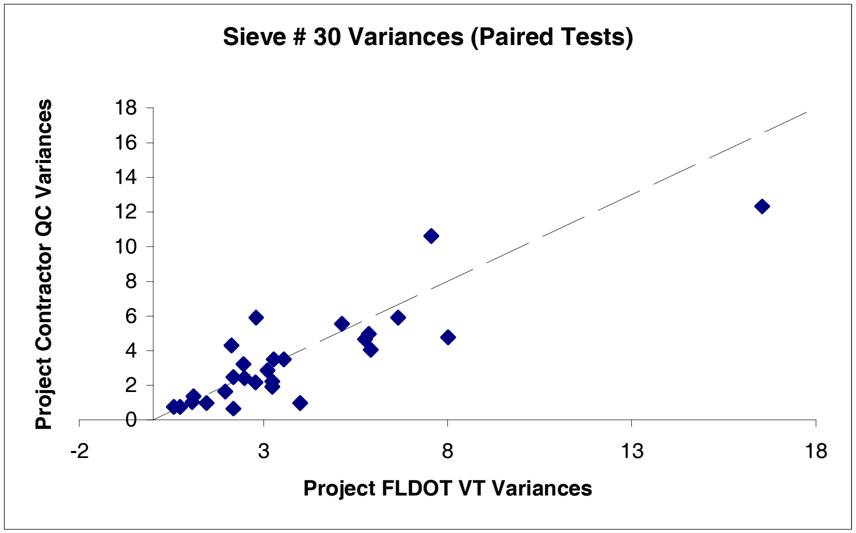

Figure B.90. Sieve #30 Project Variances – Paired Florida DOT VT and Contractor QC

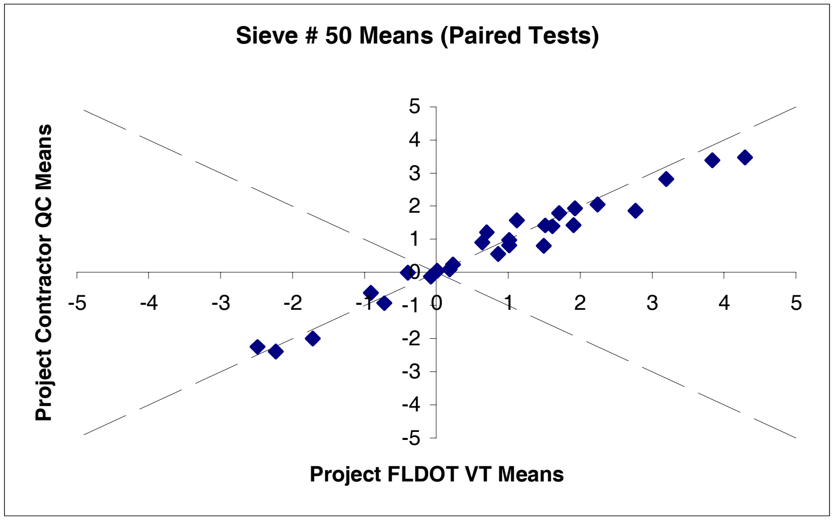

Figure B.91. Sieve #50 Project Means – Paired Florida DOT VT and Contractor QC

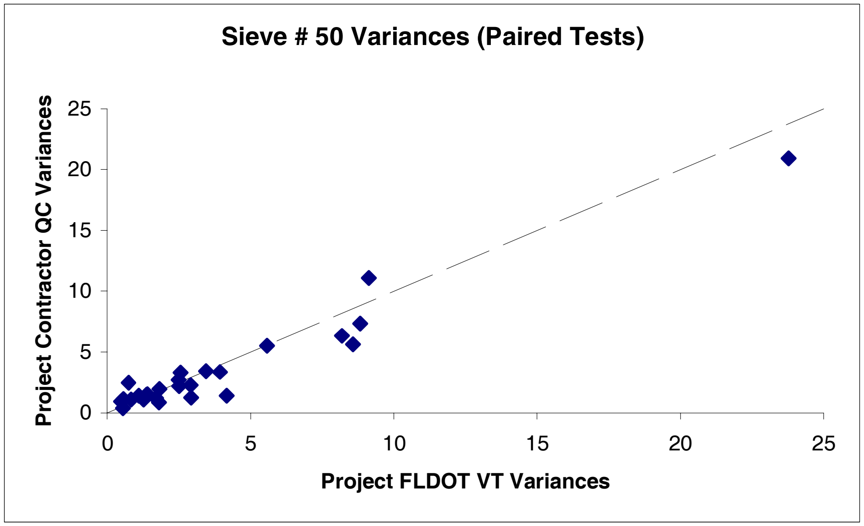

Figure B.92. Sieve #50 Project Variances – Paired Florida DOT VT and Contractor QC

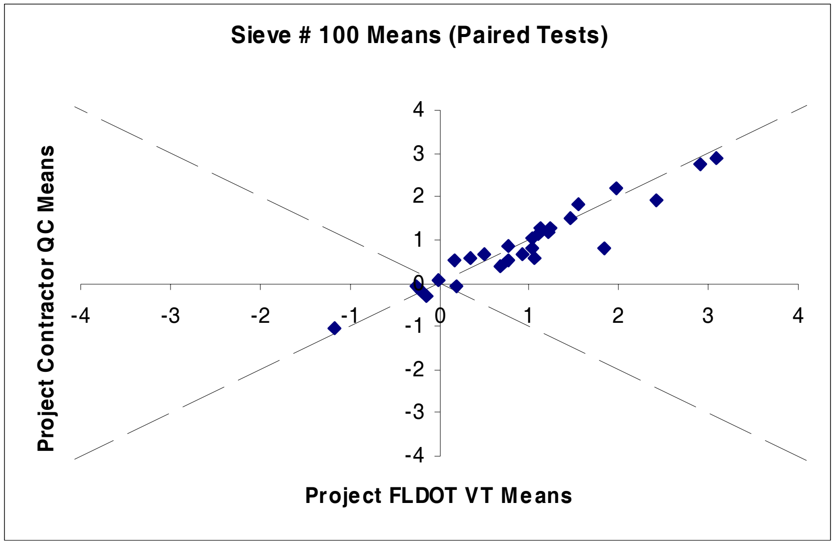

Figure B.93. Sieve #100 Project Means – Paired Florida DOT VT and Contractor QC

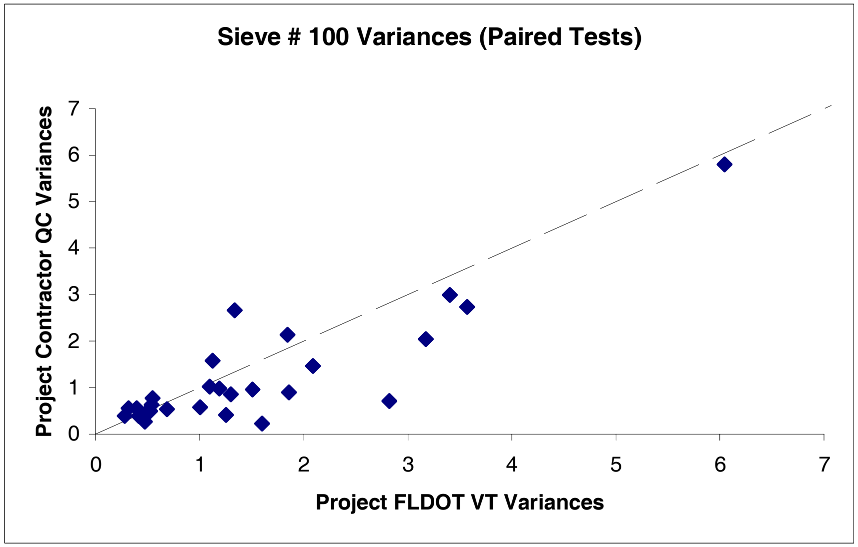

Figure B.94. Sieve #100 Project Variances – Paired Florida DOT VT and Contractor QC

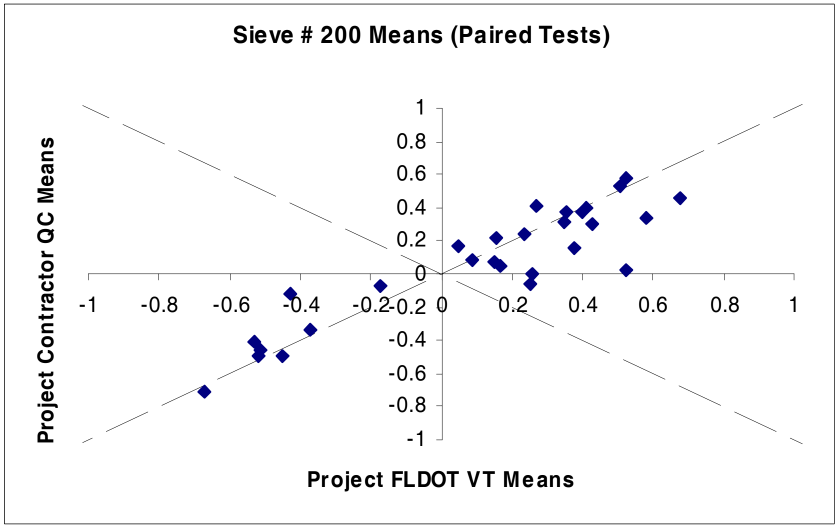

Figure B.95. Sieve #200 Project Means – Paired Florida DOT VT and Contractor QC

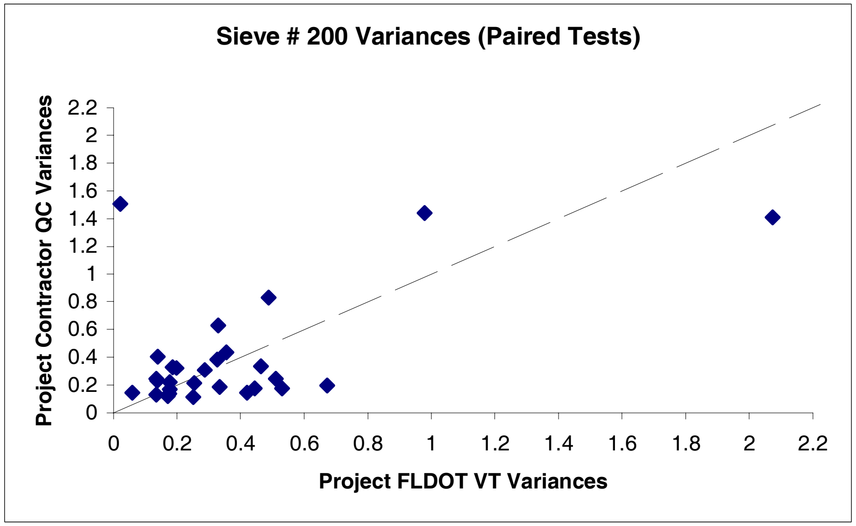

Figure B.96. Sieve #200 Project Variances – Paired Florida DOT VT and Contractor QC

APPENDIX C

PLOTS OF NORTH CAROLINA DOT AND CONTRACTOR HOT MIXED ASPHALT CONCRETE JOB MIX FORMULA MEANS AND VARIANCES

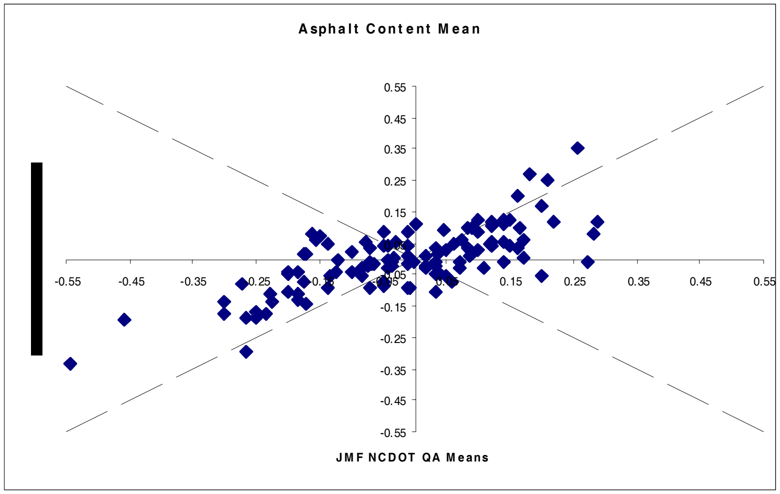

Figure C.1. Asphalt Content JMF Means –
North Carolina DOT QA and Contractor QC

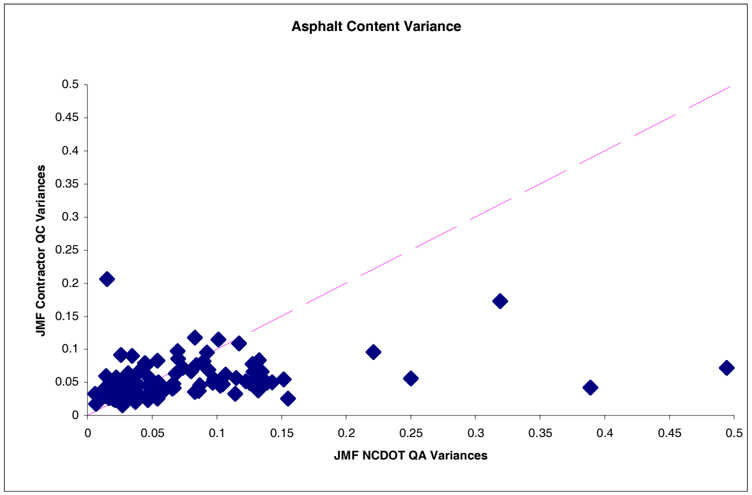

Figure C.2. Asphalt Content JMF Variances –
North Carolina DOT QA and Contractor QC

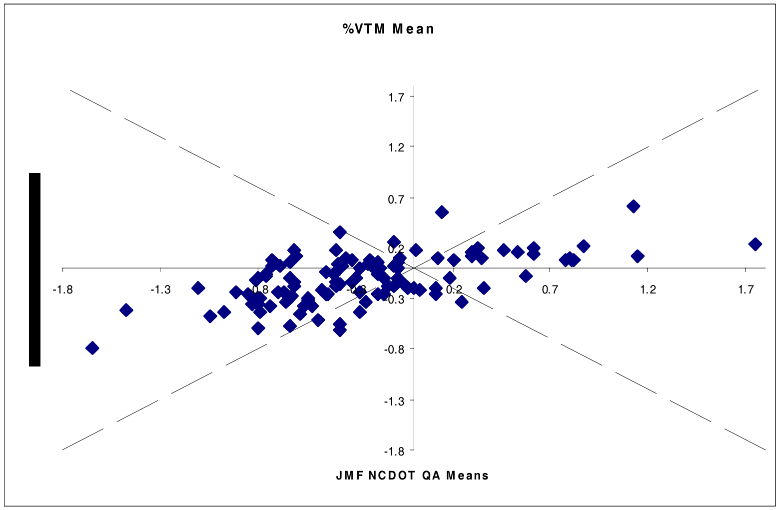

Figure C.3. % VTM JMF Means –
North Carolina DOT QA and Contractor QC

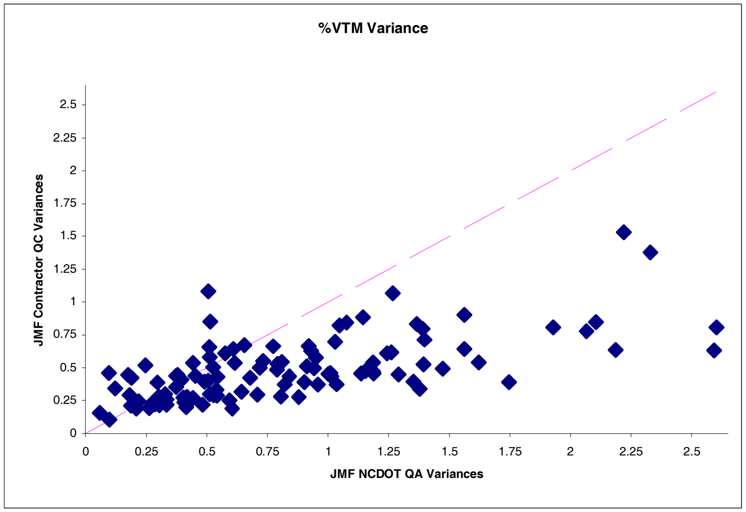

Figure C.4. % VTM JMF Variances –
North Carolina DOT QA and Contractor QC

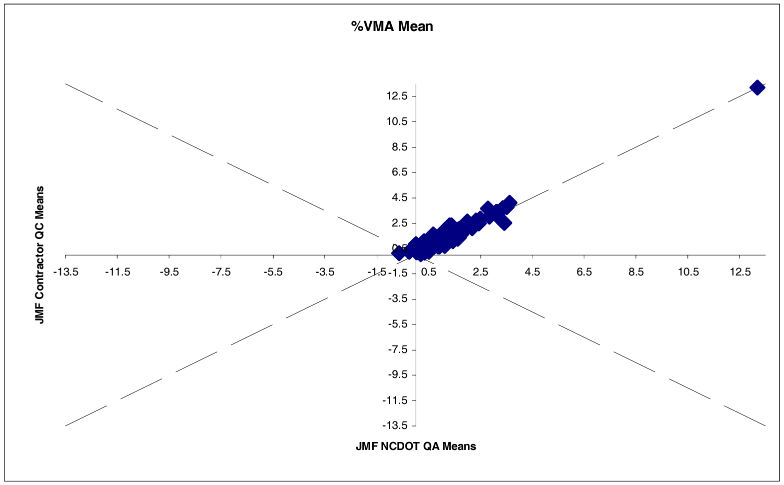

Figure C.5. % VMA JMF Means –
North Carolina DOT QA and Contractor QC

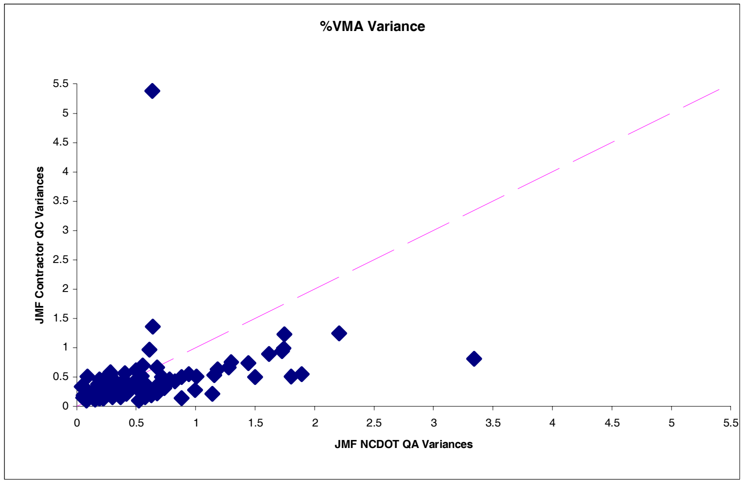

Figure C.6. % VMA JMF Variances –
North Carolina DOT QA and Contractor QC

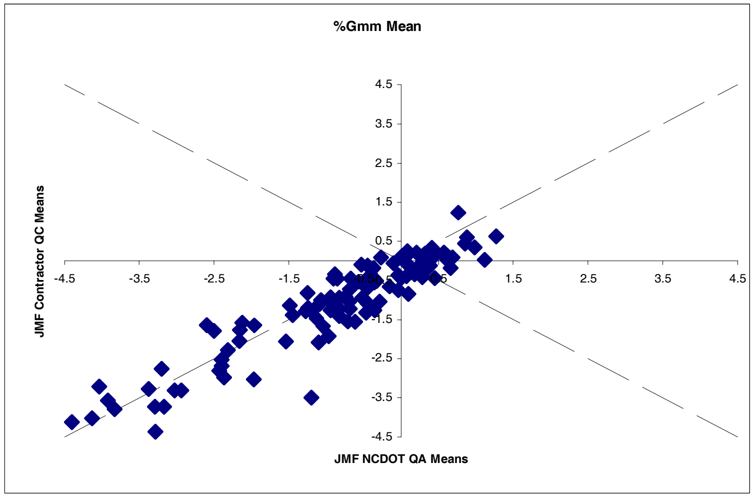

Figure C.7. % G_{mm} JMF Means –
North Carolina DOT QA and Contractor QC

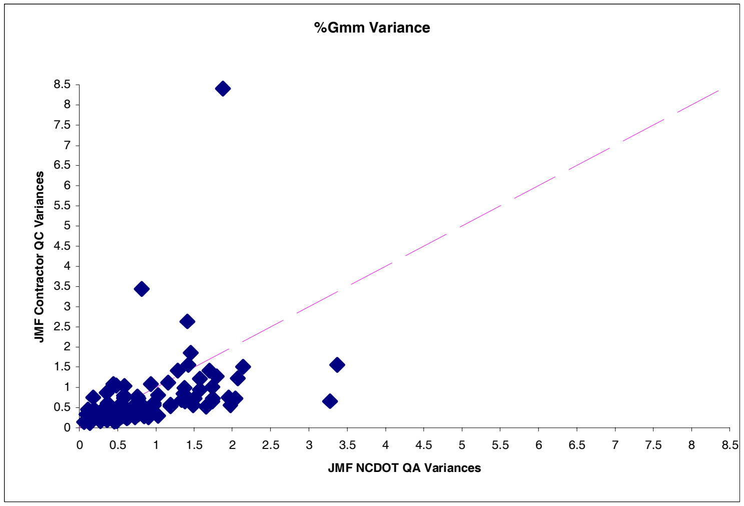

Figure C.8. % G_{mm} JMF Variances –
North Carolina QA and Contractor QC

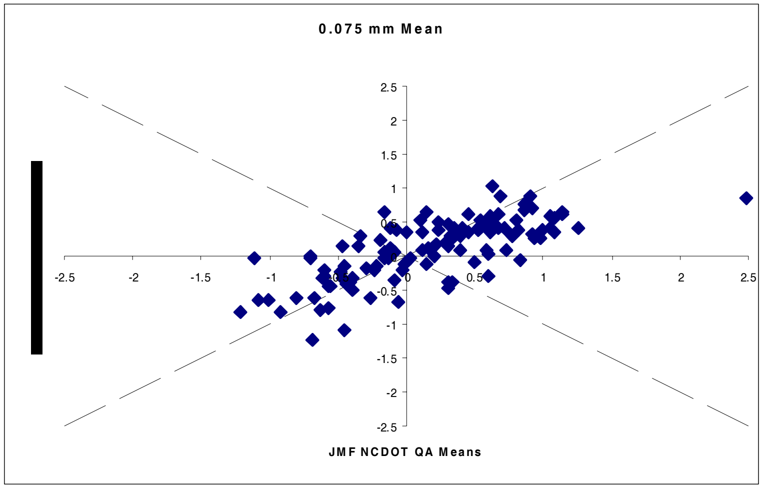

Figure C.9. 0.075 mm JMF Means –
North Carolina DOT QA and Contractor QC

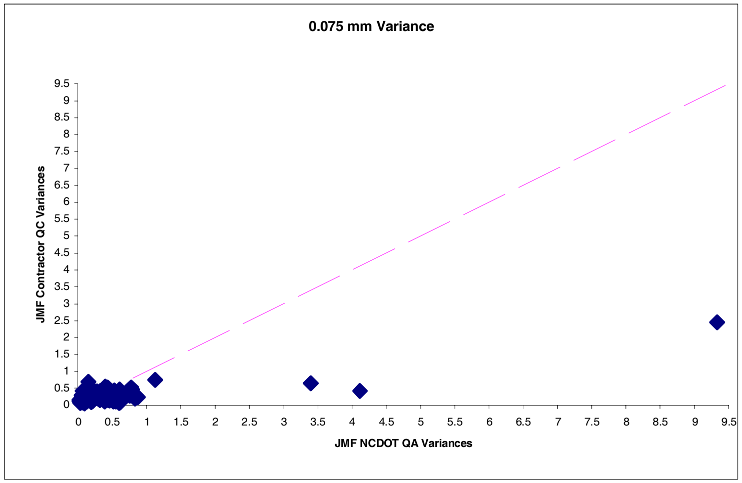

Figure C.10. 0.075 mm JMF Variances –
North Carolina DOT QA and Contractor QC

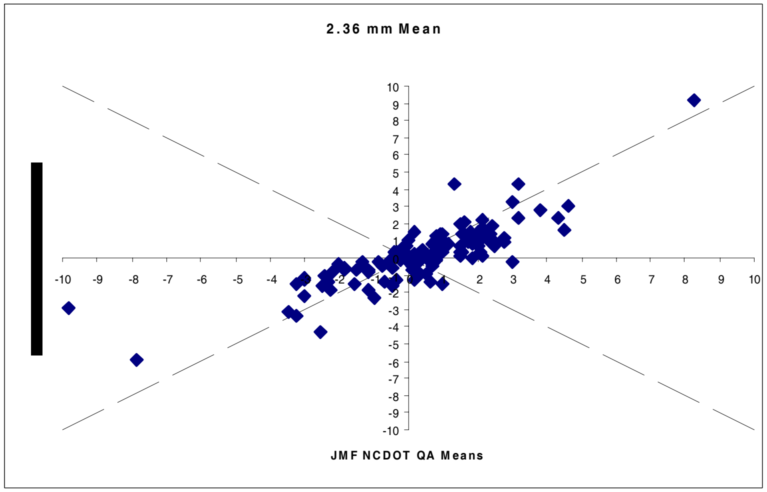

Figure C.11. 2.36 mm JMF Means –
North Carolina DOT QA and Contractor QC

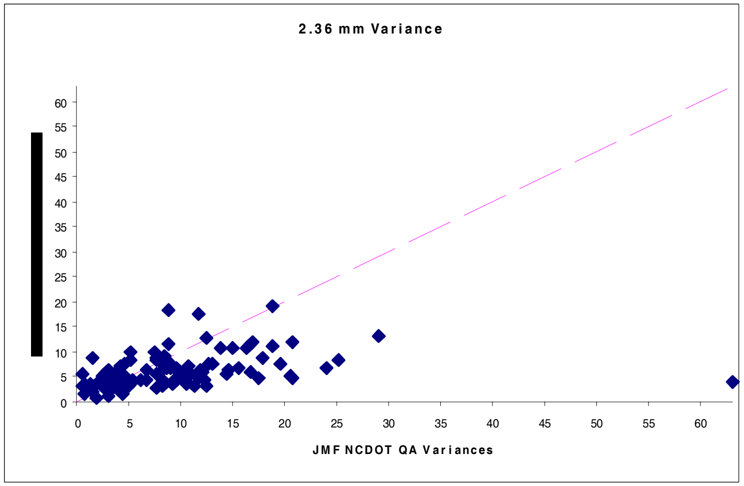

Figure C.12. 2.36 mm JMF Variances –
North Carolina DOT QA and Contractor QC

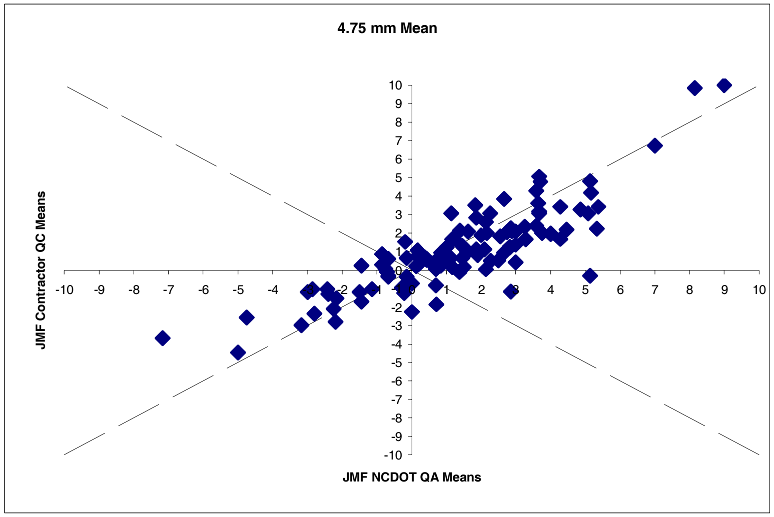

Figure C.13. 4.75 mm JMF Means –
North Carolina DOT QA and Contractor QC

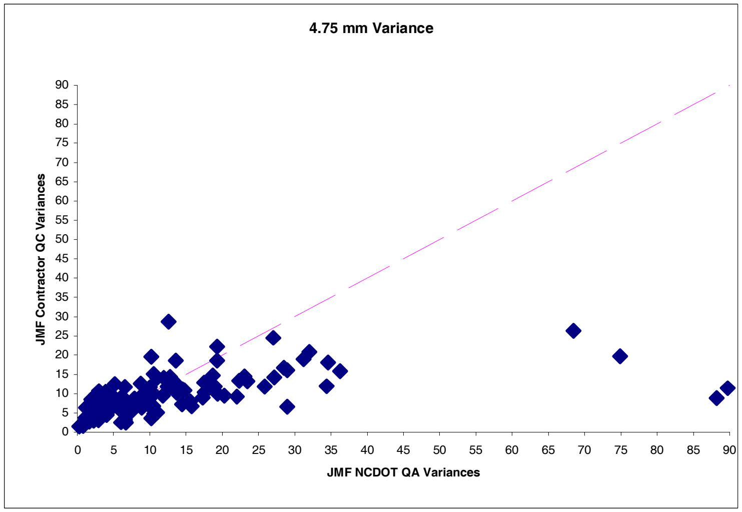

Figure C.14. 4.75 mm JMF Variances –
North Carolina DOT QA and Contractor QC

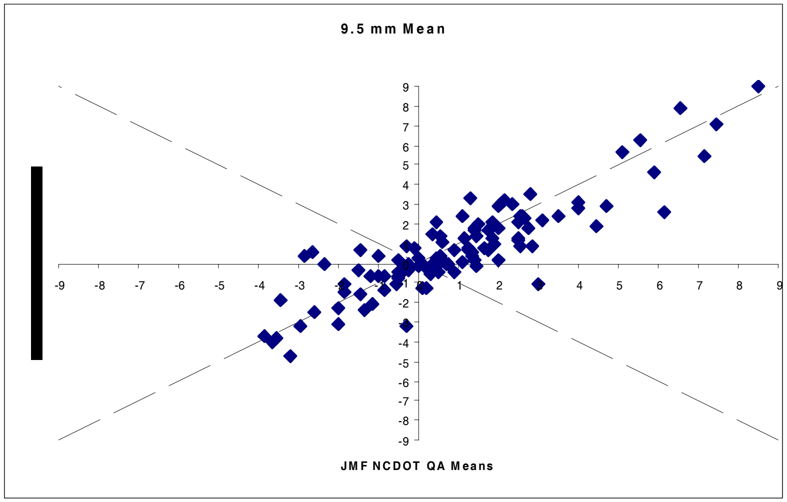

Figure C.15. 9.5 mm JMF Means –
North Carolina DOT QA and Contractor QC

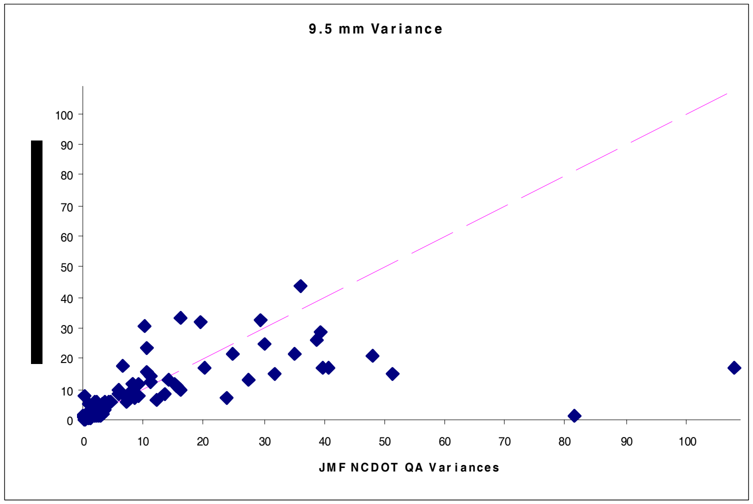

Figure C.16. 9.5 mm JMF Variances –
North Carolina DOT QA and Contractor QC

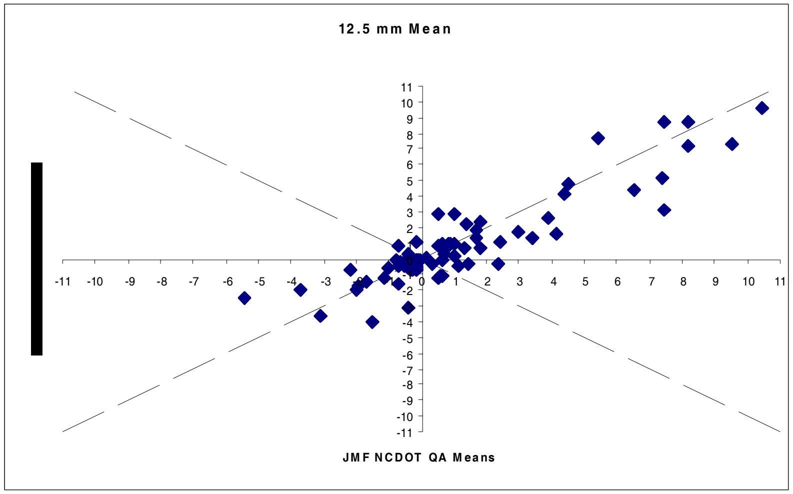

Figure C.17. 12.5 mm JMF Means –
North Carolina DOT QA and Contractor QC

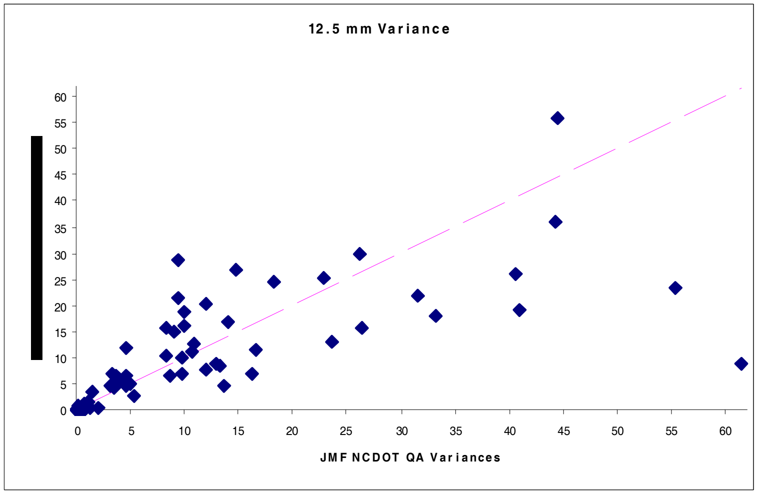

Figure C.18. 12.5 mm JMF Variances –
North Carolina DOT QA and Contractor QC

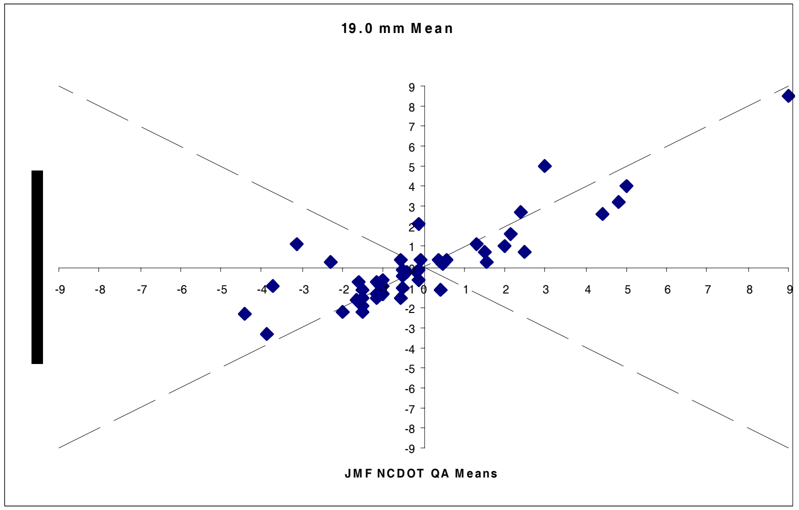

Figure C.19. 19.0 mm JMF Means –
North Carolina DOT QA and Contractor QC

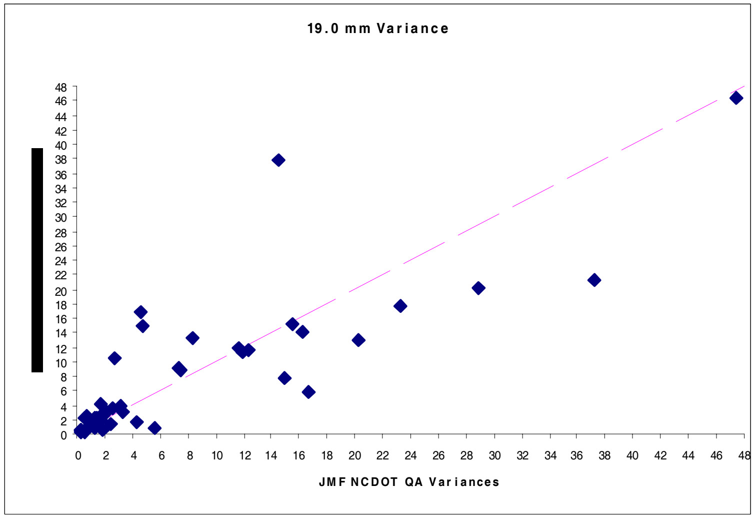

Figure C.20. 19.0 mm JMF Variances –
North Carolina DOT QA and Contractor QC

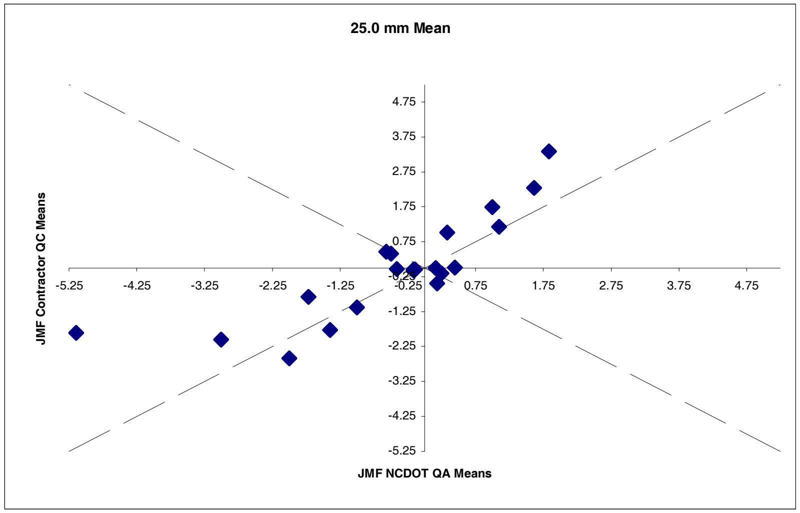

Figure C.21. 25.0 mm JMF Means –
North Carolina DOT QA and Contractor QC

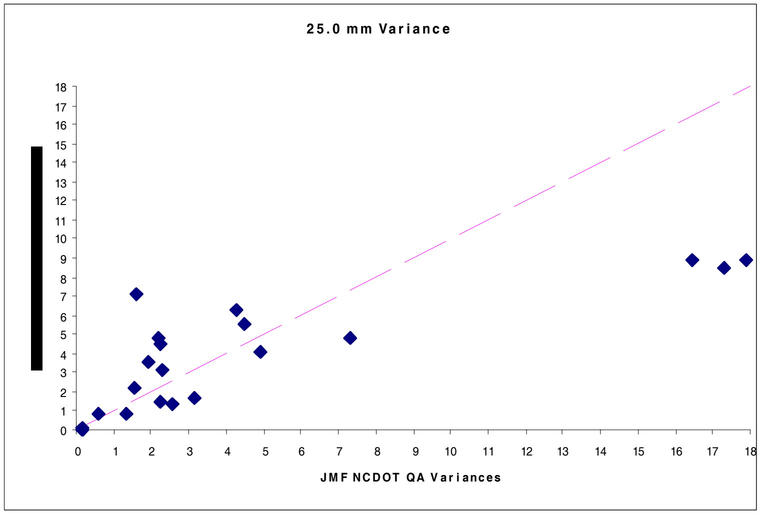

Figure C.22. 25.0 mm JMF Variances –
North Carolina DOT QA and Contractor QC

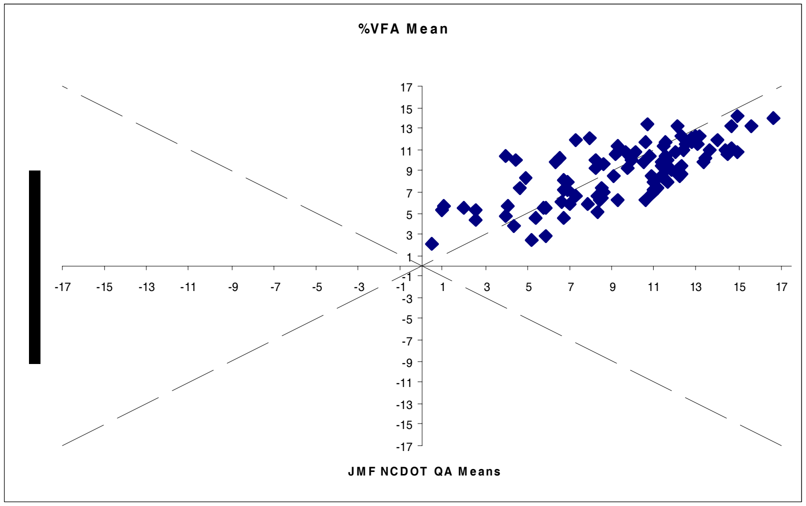

Figure C.23. % VFA JMF Means –
North Carolina DOT QA and Contractor QC

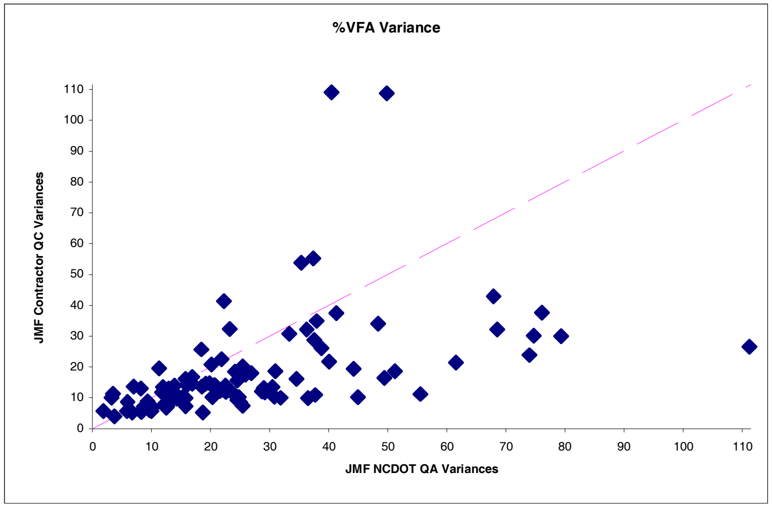

Figure C.24. % VFA JMF Variances –
North Carolina DOT QA and Contractor QC

APPENDIX D

PLOTS OF CALTRAN AND CONTRACTOR HOT MIXED ASPHALT CONCRETE PROJECT MEANS AND VARIANCES

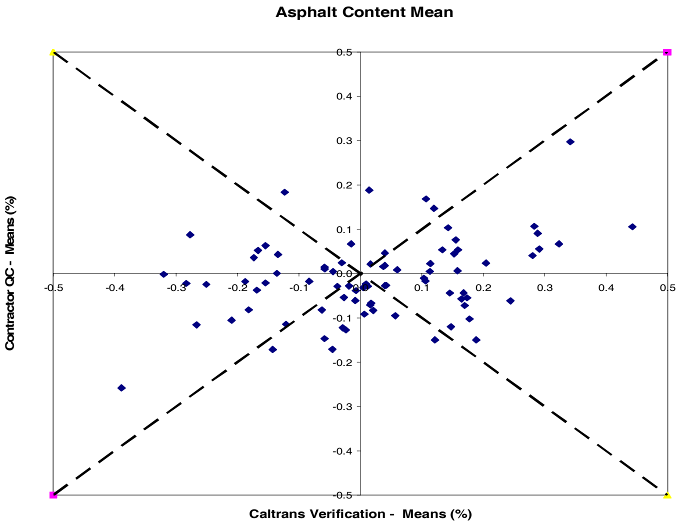

Figure D.1. Asphalt Content Project Means – Caltrans Verification and Contractor QC

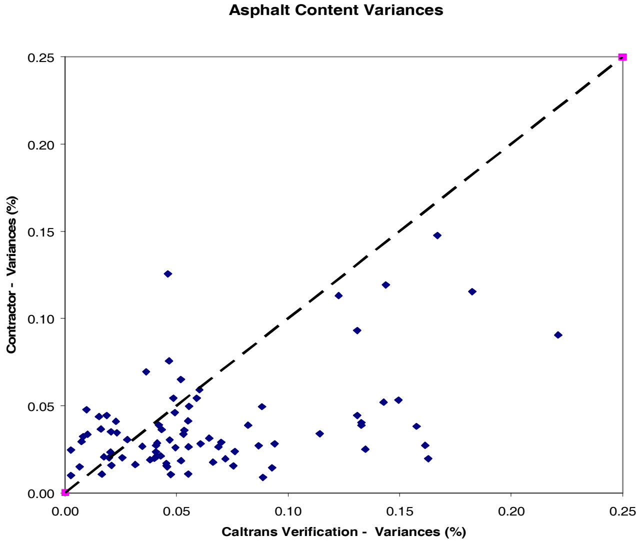

Figure D.2. Asphalt Content Project Variances – Caltrans Verification and Contractor QC

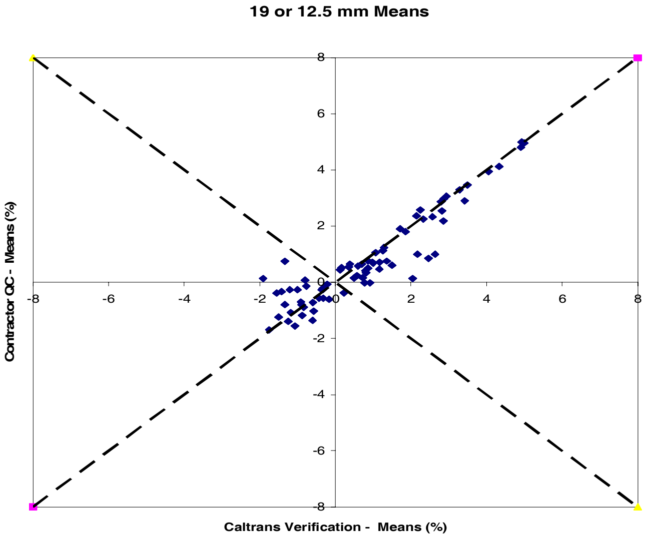

Figure D.3. ¾" or ½" Sieve Project Means – Caltrans Verification and Contractor QC

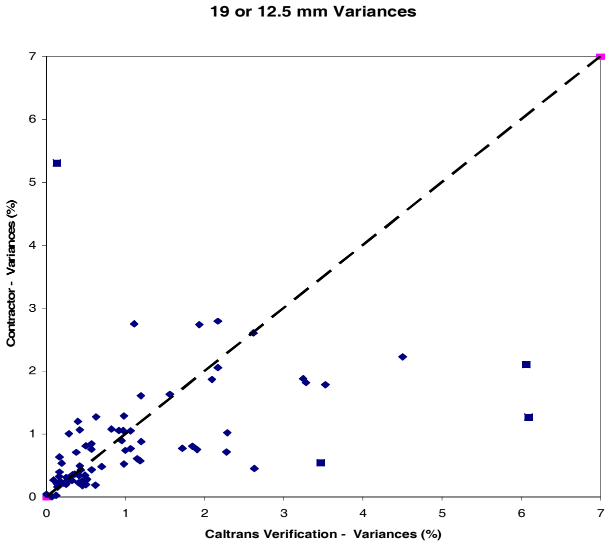

Figure D.4. ¾" or ½" Sieve Project Variances – Caltrans Verification and Contractor QC

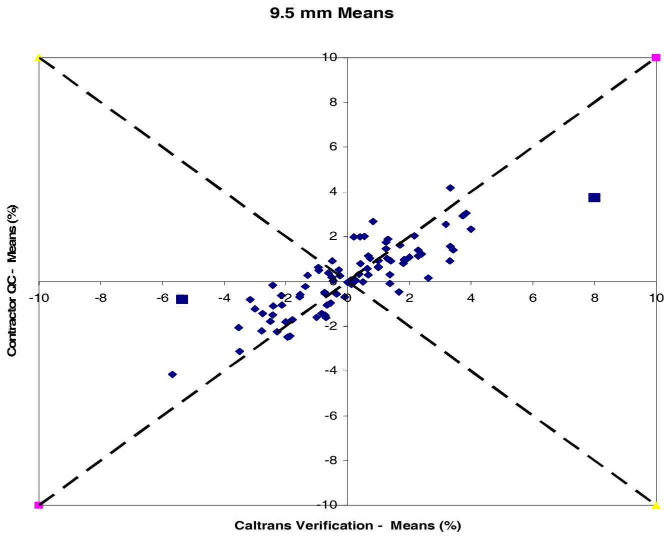

Figure D.5. 3/8” Sieve Project Means – Caltrans Verification and Contractor QC

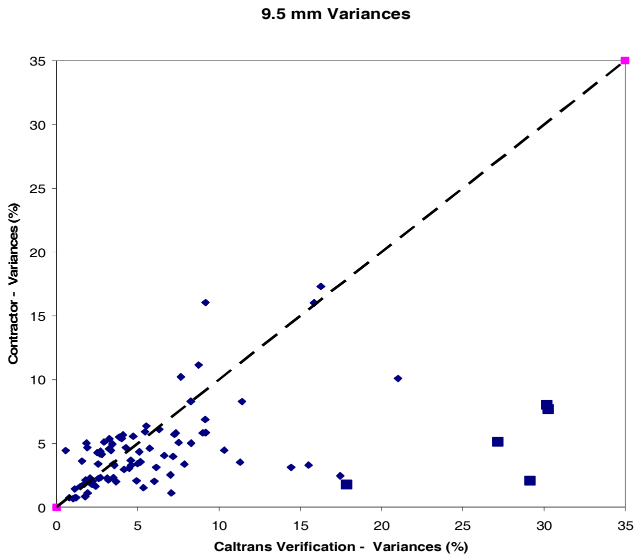

Figure D.6. 3/8” Sieve Project Variances – Verification and Contractor QC

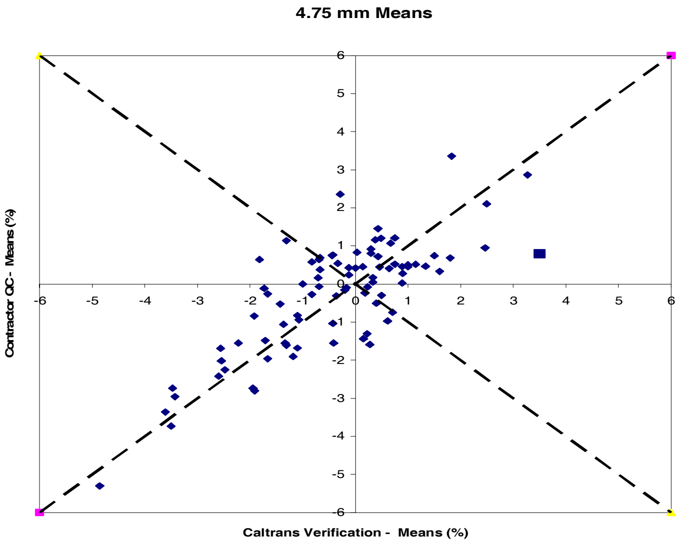

Figure D.7. #4 Sieve Project Means – Verification and Contractor QC

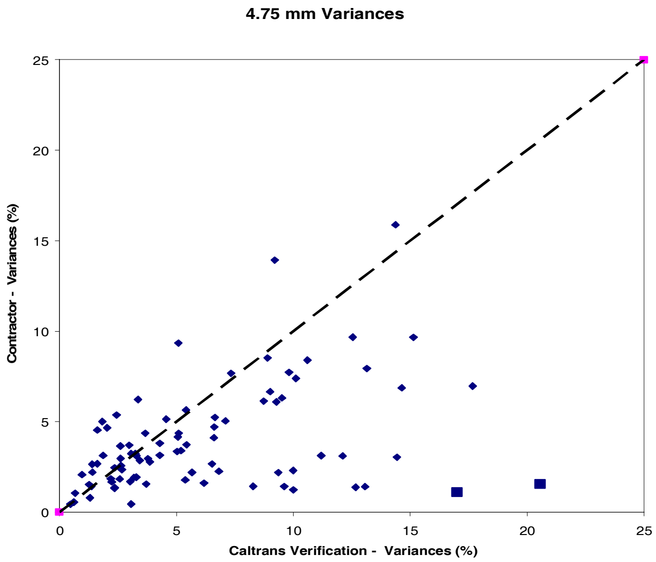

Figure D.8. #4 Sieve Project Variances – Caltrans Verification and Contractor QC

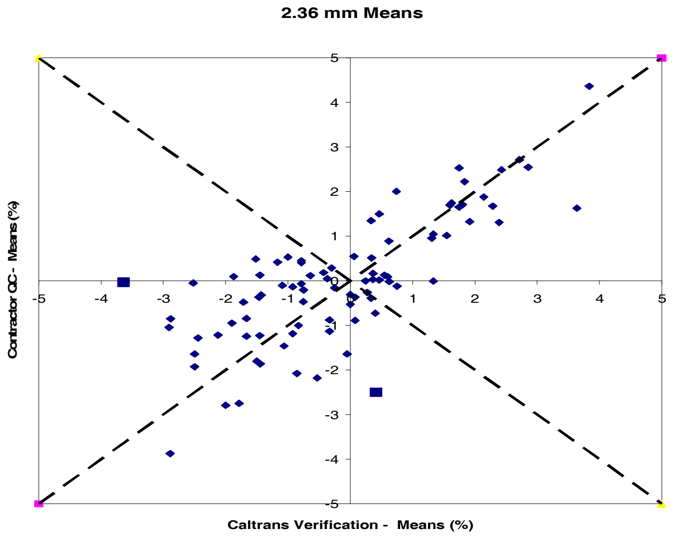

Figure D.9. #8 Sieve Project Means – Caltrans Verification and Contractor QC

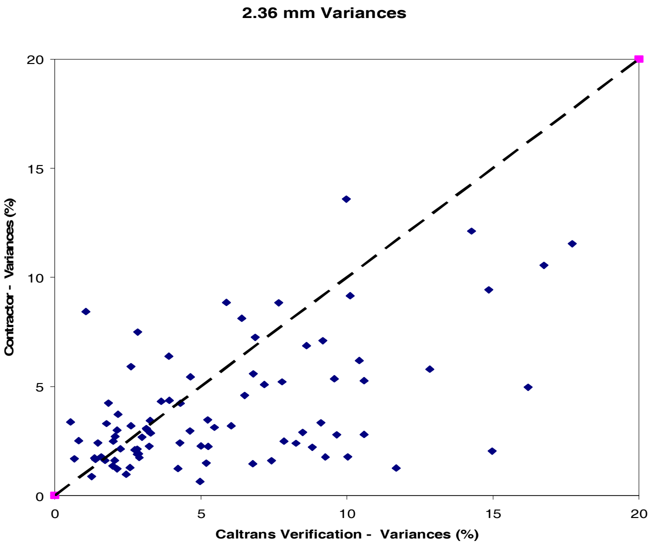

Figure D.10. #8 Sieve Variances – Caltrans Verification and Contractor QC

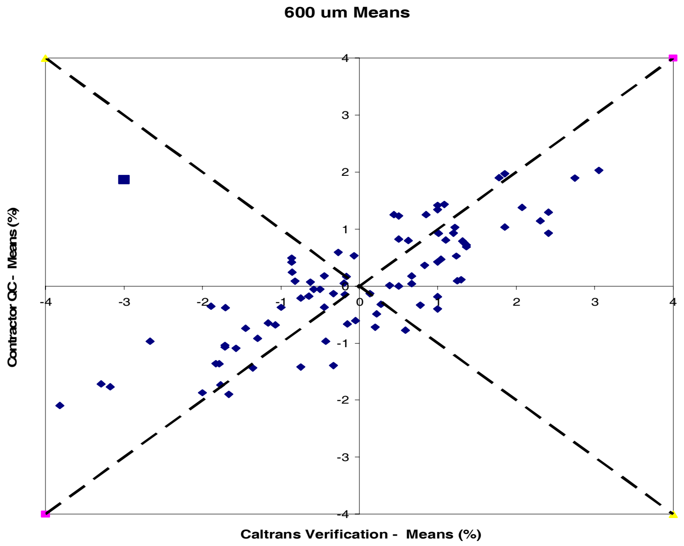

Figure D.11. #30 Sieve Project Means – Caltrans Verification and Contractor QC

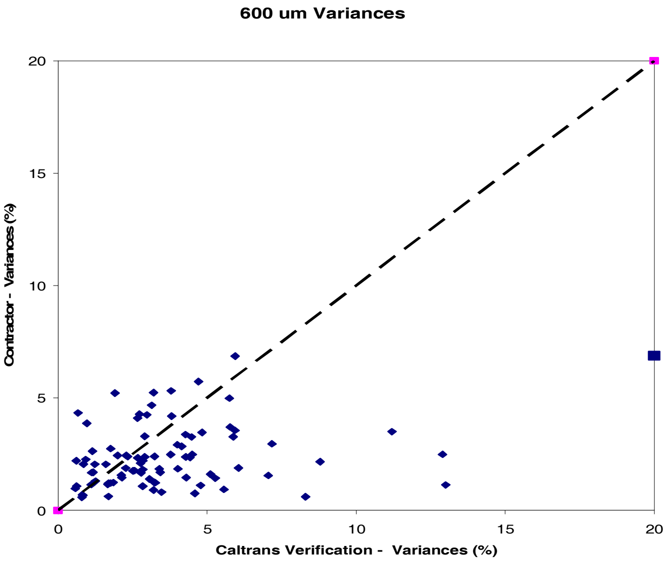

Figure D.12. #30 Sieve Project Means – Caltrans Verification and Contractor QC

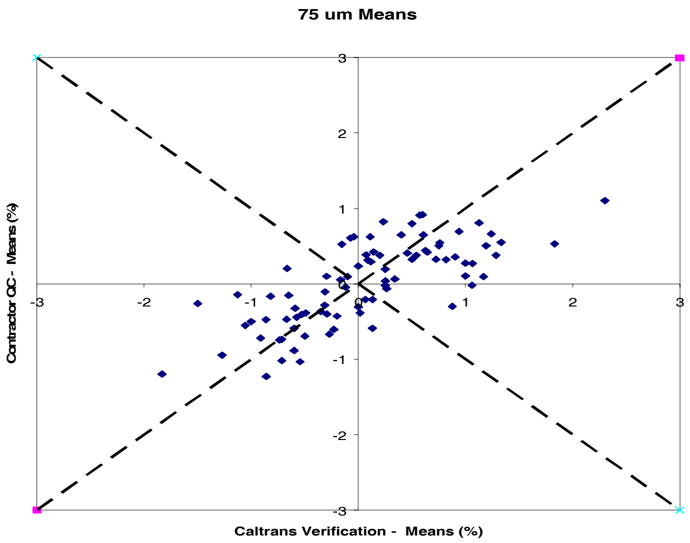

Figure D.13. #200 Sieve Project Means – Caltrans Verification and Contractor QC

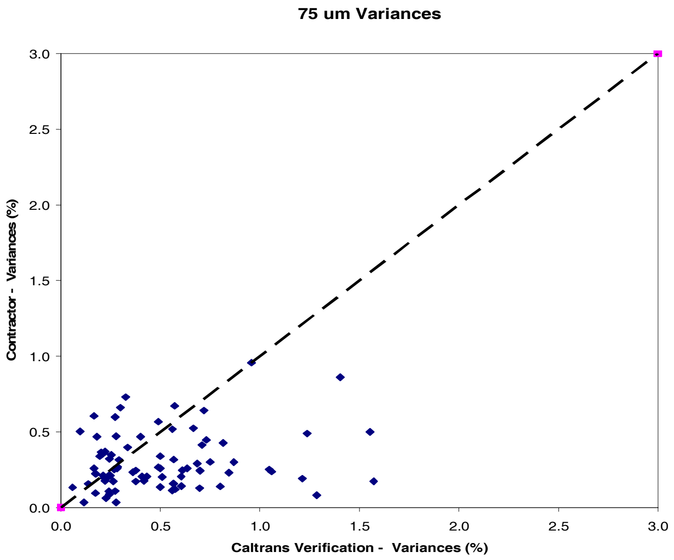

Figure D.14. #200 Sieve Project Variances – Caltrans Verification and Contractor QC

APPENDIX E

PLOTS OF FHWA-WFLHD AND CONTRACTOR GRANULAR BASE PROJECT MEANS AND VARIANCES

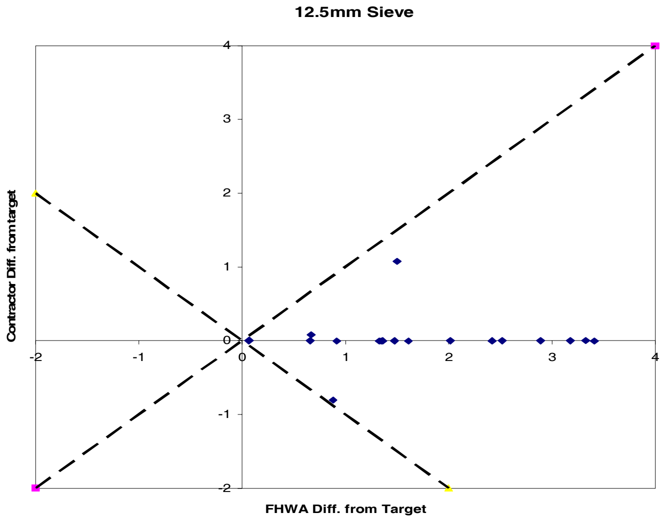

Figure E.1. Percent Passing ½" Sieve Project Means – FHWA-WFLHD Verification and Contractor QC

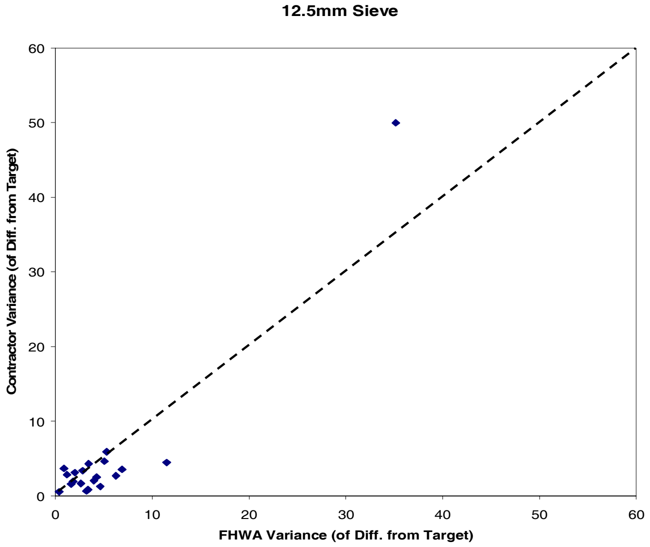

Figure E.2. Percent Passing ½" Sieve Project Variances – FHWA-WFLHD Verification and Contractor QC

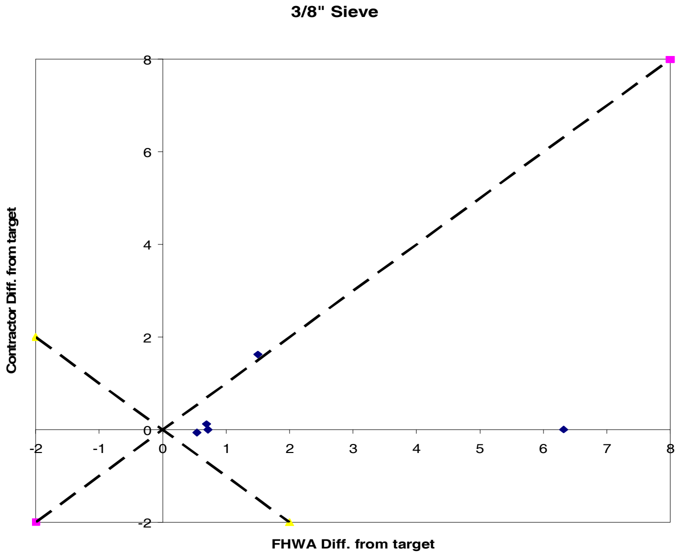

Figure E.3. Percent Passing 3/8" Sieve Project Means – FHWA-WFLHD Verification and Contractor QC

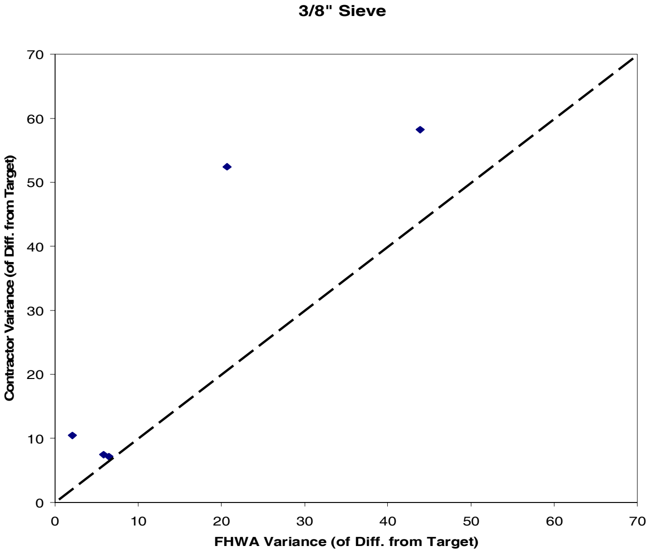

Figure E.4. Percent Passing 3/8" Sieve Project Variances – FHWA-WFLHD Verification and Contractor QC

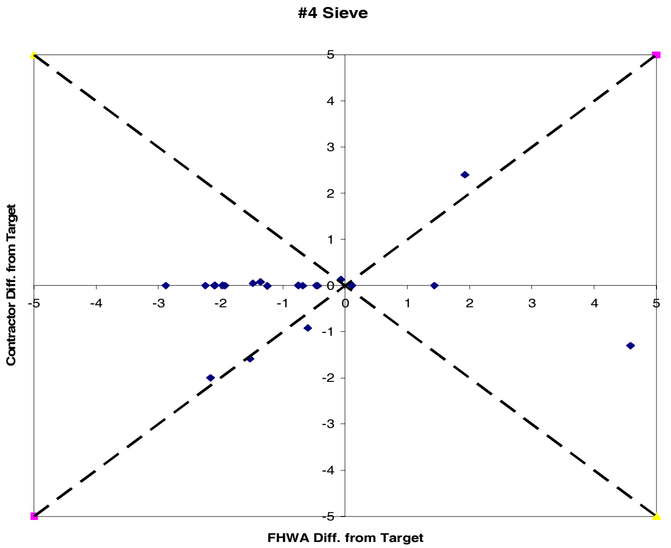

Figure E.5. Percent Passing #4 Sieve Project Means – FHWA-WFLHD Verification and Contractor QC

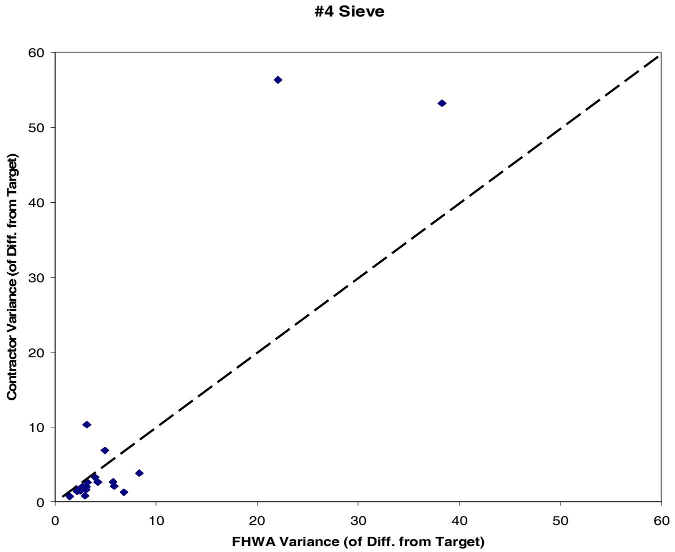

Figure E.6. Percent Passing #4 Sieve Project Variances – FHWA-WFLHD Verification and Contractor QC

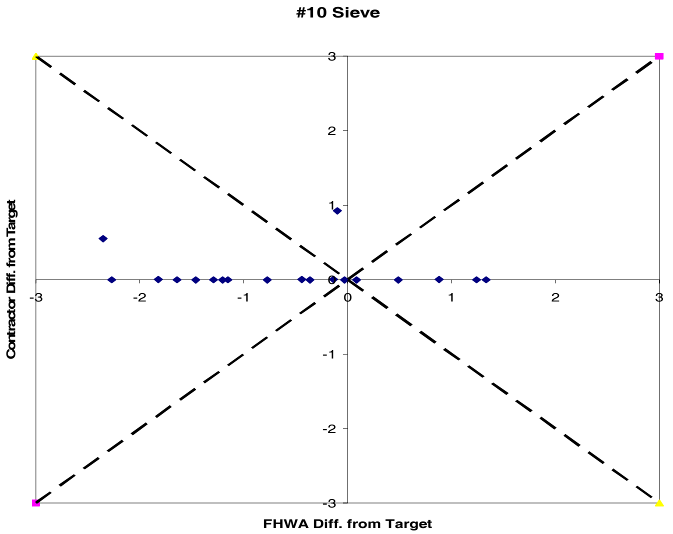

Figure E.7. Percent Passing #10 Sieve Project Means – FHWA-WFLHD Verification and Contractor QC

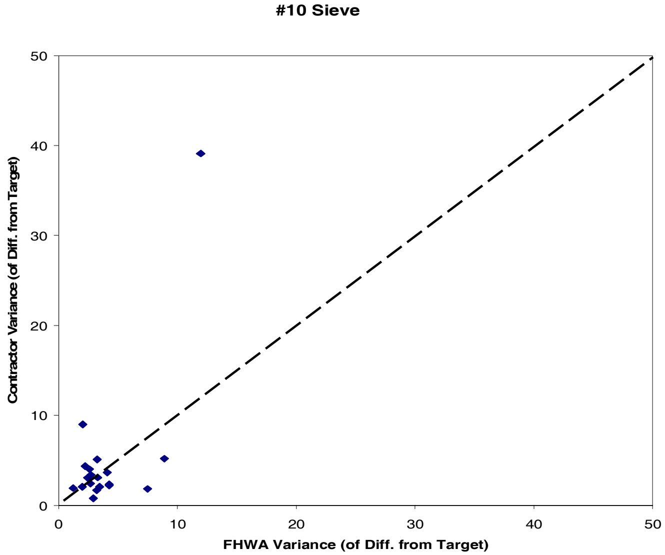

Figure E.8. Percent Passing #10 Sieve Project Variances – FHWA-WFLHD Verification and Contractor QC

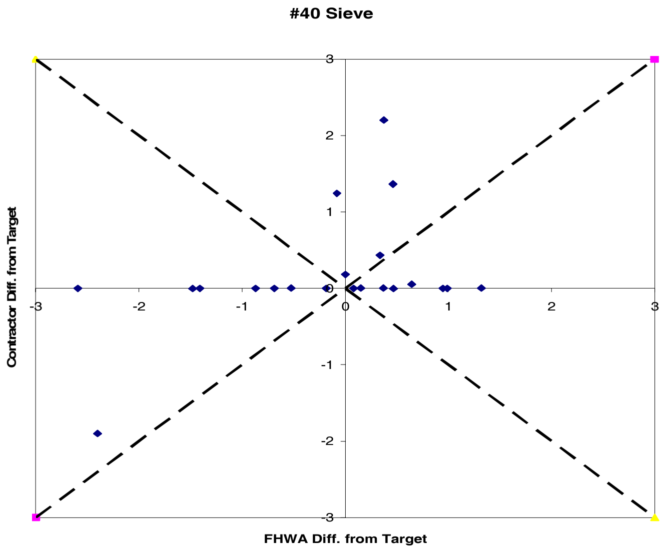

Figure E.9. Percent Passing #40 Sieve Project Means – FHWA-WFLHD Verification and Contractor QC

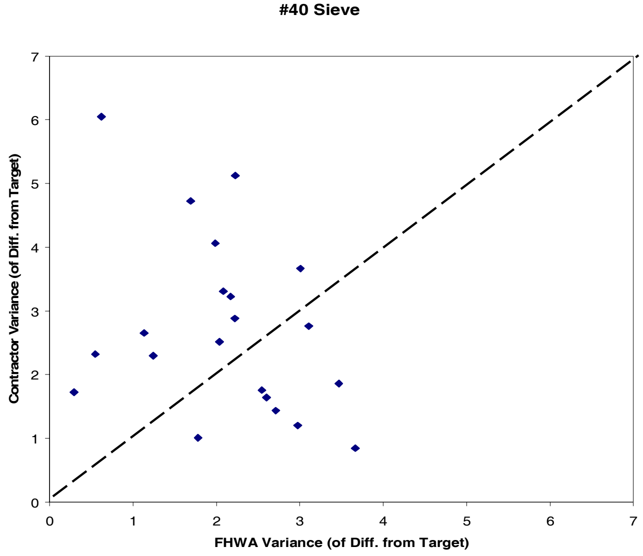

Figure E.10. Percent Passing #40 Sieve Project Variances – FHWA-WFLHD Verification and Contractor QC

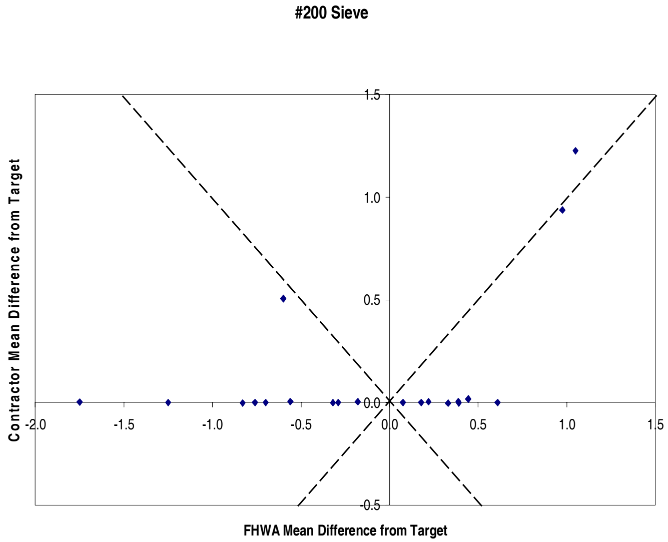

Figure E.11. Percent Passing #200 Sieve Project Means – FHWA-WFLHD Verification and Contractor QC

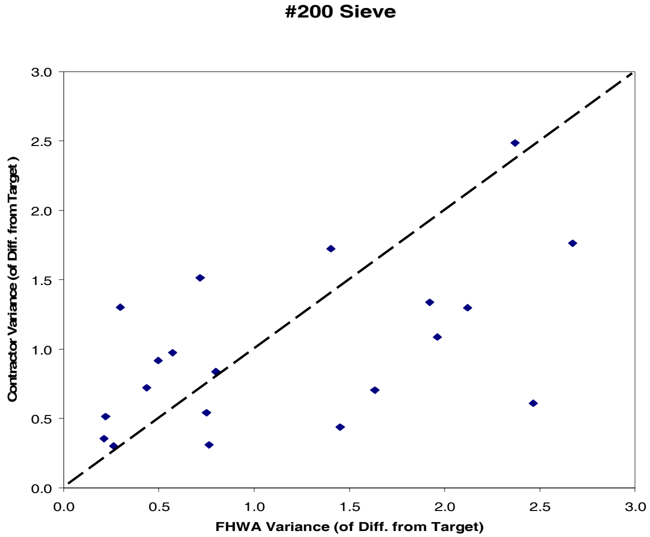

Figure E.12. Percent Passing #200 Sieve Project Variances – FHWA-WFLHD Verification and Contractor QC

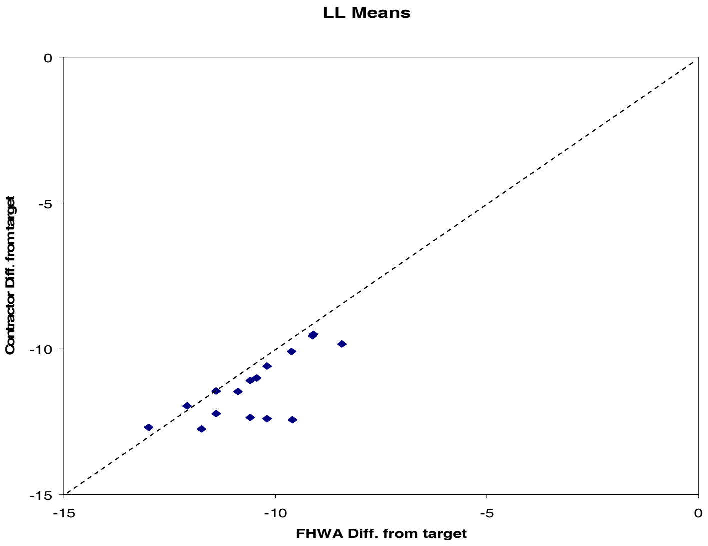

Figure E.13. Percent Passing LL Project Means – FHWA-WFLHD Verification and Contractor QC

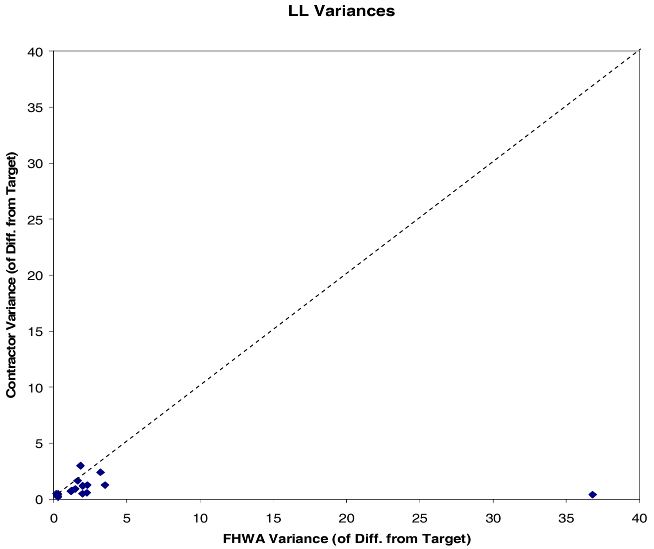

Figure E.14. Percent Passing LL Project Variances – FHWA-WFLHD Verification and Contractor QC

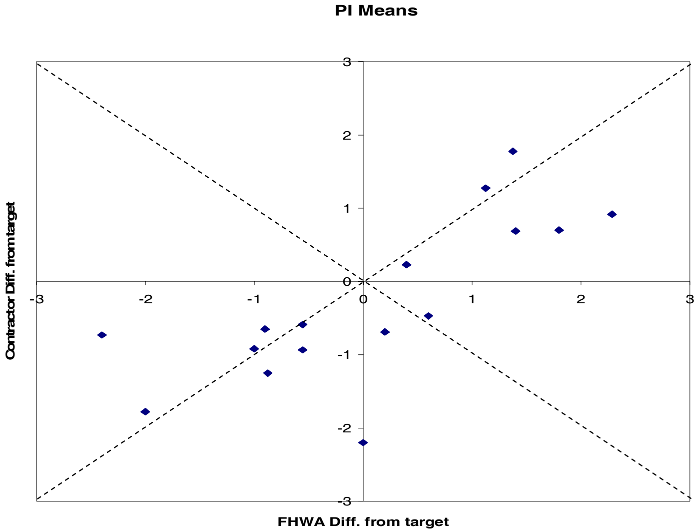

Figure E.15. Percent Passing PI Project Means – FHWA-WFLHD Verification and Contractor QC

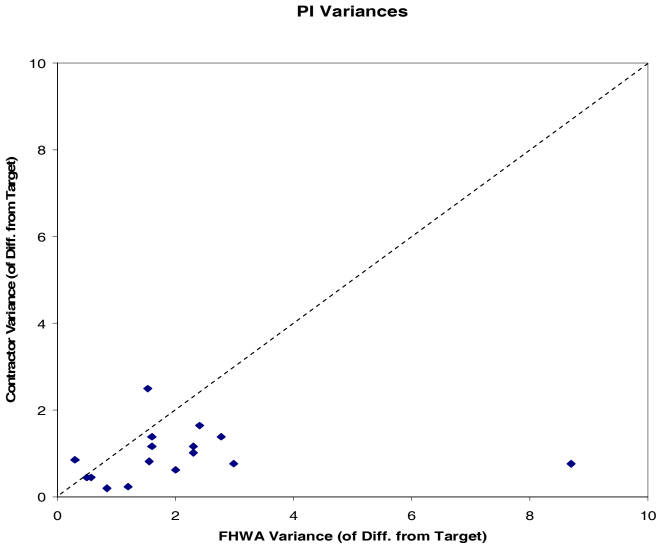

Figure E.16. Percent Passing PI Project Variances – FHWA-WFLHD Verification and Contractor QC

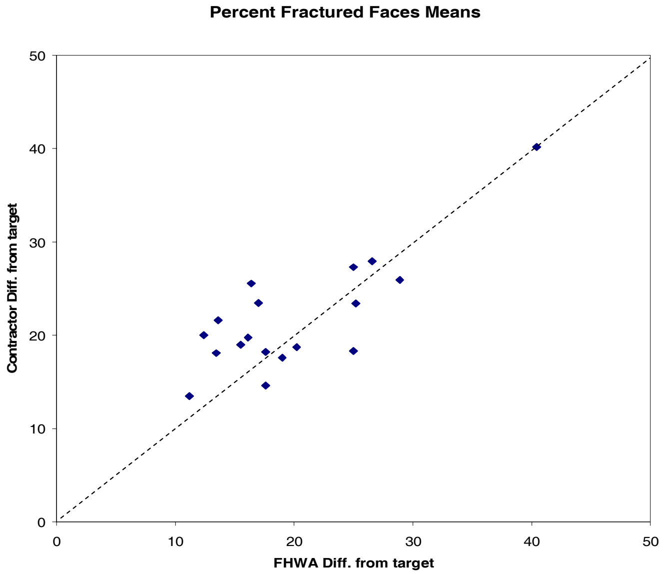

Figure E.17. Percent Passing Fractured Faces Project Means - FHWA-WFLHD Verification and Contractor QC

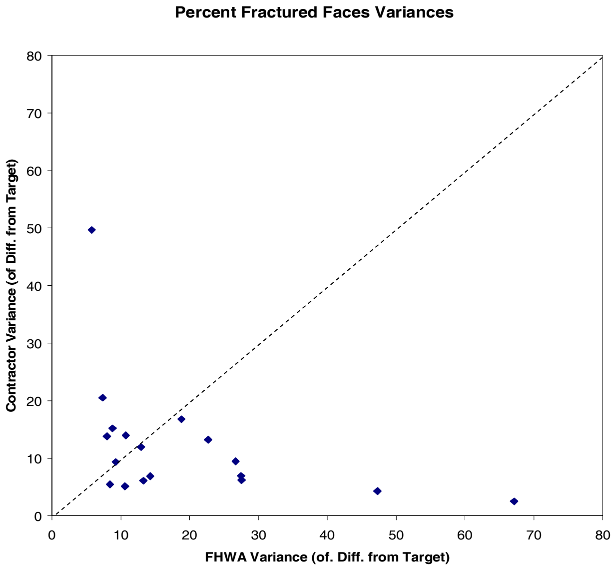

Figure E.18. Percent Passing Fractured Faces Project Variances - FHWA-WFLHD Verification and Contractor QC

APPENDIX F

ACCEPTANCE OUTCOMES USING HOT MIX ASPHALT CONCRETE STATISTICS FOR CALIFORNIA, FLORIDA, GEORGIA, KANSAS, AND NORTH CAROLINA

CALTRANS

Asphalt Content

Statistics

$s^2_{CAL} = 0.087$ $s^2_{CONT.} = 0.042$ s^2 are SD

$\overline{\Delta}_{CAL} = 0.036\%$ $\overline{\Delta}_{CONT.} = -0.003\%$ $\overline{\Delta}$ are SD

Probability of exceeding upper or lower specification limits

Limits = ± 0.50% from targets
Probability = 9.2% with Caltrans statistics
Probability = 1.5% with contractor statistics

7.8% greater chance of exceeding specification limits with Caltrans statistics

Percent Passing ¾ or ½ inch Sieve

Statistics

$s^2_{CAL} = 4.863$ $s^2_{CONT.} = 3.319$ s^2 are SD

$\overline{\Delta}_{CAL} = 0.951\%$ $\overline{\Delta}_{CONT.} = 0.719\%$ $\overline{\Delta}$ are SD

Probability of exceeding upper or lower specification limits

Limits = ± 5.0% from targets
Probability = 3.7% with Caltrans statistics
Probability = 1.0% with contractor statistics

2.7% greater chance of exceeding specification limits with Caltrans statistics

Percent Passing 3/8 inch Sieve

Statistics

$s^2_{CAL} = 11.082$ $s^2_{CONT.} = 6.478$ s^2 are SD

$\overline{\Delta}_{CAL} = -0.093\%$ $\overline{\Delta}_{CONT.} = -0.049\%$ $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 6.0% from targets
Probability = 7.2% with Caltrans statistics
Probability = 1.8% with contractor statistics

5.4% greater chance of exceeding specification limits with Caltrans statistics

Percent Passing #4 Sieve

Statistics

$s^2_{CAL} = 9.258$ $s^2_{CONT.} = 6.770$ s^2 are SD

$\overline{\Delta}_{CAL} = -0.517\%$ $\overline{\Delta}_{CONT.} = -0.381\%$ $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 7.0% from targets
Probability = 2.3% with Caltrans statistics
Probability = 0.8% with contractor statistics

1.5% greater chance of exceeding specification limits with Caltrans statistics

Percent Passing #8 Sieve

Statistics

$s^2_{CAL} = 8.303$ $s^2_{CONT.} = 5.423$ s^2 are SD

$\overline{\Delta}_{CAL} = -0.356\%$ $\overline{\Delta}_{CONT.} = 0.012\%$ $\overline{\Delta}$ are SD

Probability of exceeding upper or lower specification limits

Limits = ± 5.0% from targets
Probability = 8.8% with Caltrans statistics
Probability = 3.2% with contractor statistics

5.6% greater chance of exceeding specification limits with Caltrans statistics

Percent Passing #30 Sieve

Statistics

$s^2_{CAL} = 5.363$ $s^2_{CONT.} = 6.386$ s^2 are SD

$\overline{\Delta}_{CAL} = -0.058\%$ $\overline{\Delta}_{CONT.} = 0.234\%$ $\overline{\Delta}$ are SD

Probability of exceeding upper or lower specification limits

Limits = ± 4.0% from targets
Probability = 8.5% with Caltrans statistics
Probability = 11.5% with contractor statistics

-3.0% greater chance of exceeding specification limits with Caltrans statistics

Percent Passing #200 Sieve

Statistics

s^2_{CAL} = 1.095 $s^2_{CONT.}$ = 0.602 s^2 are SD

$\bar{\Delta}_{CAL}$ = 0.062% $\bar{\Delta}_{CONT.}$ = 0.011% $\bar{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 2.0% from targets
Probability = 5.7% with Caltrans statistics
Probability = 1.0% with contractor statistics

4.7% greater chance of exceeding specification limits with Caltrans statistics

FLORIDA DEPARTMENT OF TRANSPORTATION

Asphalt Content

Statistics

s^2_{DOT} = 0.084 $s^2_{CONT.}$ = 0.062 s^2 are SD

$\overline{\Delta}_{DOT}$ = 0.016% $\overline{\Delta}_{CONT.}$ = -0.012% $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 0.40% from targets
Probability = 16.9% with DOT statistics
Probability = 10.9% with contractor statistics

6.0% greater chance of exceeding specification limits with DOT statistics

Voids Content

Statistics

s^2_{DOT} = 1.308 $s^2_{CONT.}$ = 0.707 s^2 are SD

$\overline{\Delta}_{DOT}$ = -0.289% $\overline{\Delta}_{CONT.}$ = -0.248% $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 1.4% from 4% target
Probability = 23.5% with DOT statistics
Probability = 11.0% with contractor statistics

12.5% greater chance of exceeding specification limits with DOT statistics

Percent Passing Number 8 Sieve

Statistics

s^2_{DOT} = 7.533 $s^2_{CONT.}$ = 5.619 s^2 are SD

$\overline{\Delta}_{DOT}$ = 0.679% $\overline{\Delta}_{CONT.}$ = 0.400% $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 3.1% from targets
Probability = 27.3% with DOT statistics
Probability = 19.7% with contractor statistics

7.6% greater chance of exceeding specification limits with DOT statistics

Percent Passing Number 200 Sieve

Statistics

s^2_{DOT} = 0.491 $s^2_{CONT.}$ = 0.376 s^2 are SD

$\overline{\Delta}_{DOT}$ = 0.136% $\overline{\Delta}_{CONT.}$ = 0.072% $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 1.0% from targets
Probability = 16.2% with DOT statistics
Probability = 10.5% with contractor statistics

5.7% greater chance of exceeding specification limits with DOT statistics

Mat Density – Coarse Mixes

Statistics*

s^2_{DOT} = 2.958 $s^2_{CONT.}$ = 2.570 s^2 are SD

$\overline{\Delta}_{DOT}$ = -0.222% $\overline{\Delta}_{CONT.}$ = -0.103% $\overline{\Delta}$ are NSD (p=0.014)

Probability of exceeding upper or lower specification limits

Limits = ± 1.3% from 94.5% of G_{mm} target
Probability = 45.4% with DOT statistics
Probability = 41.8% with contractor statistics

3.6% greater chance of exceeding specification limits with DOT statistics

Mat Density – Fine Mixes

Statistics*

s^2_{DOT} = 2.958 $s^2_{CONT.}$ = 2.570 s^2 are SD

$\overline{\Delta}_{DOT}$ = -0.222% $\overline{\Delta}_{CONT.}$ = -0.103% $\overline{\Delta}$ are NSD (p=0.014)

Probability of exceeding upper or lower specification limits

Limits are -1.0% and +2.0% from 93% of G_{mm} target
Probability = 42.4% with DOT statistics
Probability = 38.2% with contractor statistics

4.2% greater chance of exceeding specification limits with DOT statistics

* Statistics computed with test results from coarse and fine mixes combined.

GEORGIA DEPARTMENT OF TRANSPORTATION

Asphalt Content

Statistics

$s^2_{DOT} = 0.064$ $s^2_{CONT.} = 0.040$ s^2 are SD

$\overline{\Delta}_{DOT} = 0.004\%$ $\overline{\Delta}_{CONT.} = 0.005\%$ $\overline{\Delta}$ are NSD

Probability of pay < 100%

Limit = 0.46% from targets for n=3*

Probability = 0.9% with DOT statistics
Probability = 0.1% with contractor statistics
0.8% greater chance for pay<100% with DOT statistics

Percent Passing 1/2 inch Sieve**

Statistics

$s^2_{DOT} = 6.793$ $s^2_{CONT.} = 5.565$ s^2 are SD

$\overline{\Delta}_{DOT} = 0.196\%$ $\overline{\Delta}_{CONT.} = 0.160\%$ $\overline{\Delta}$ are NSD

Probability of pay<100%

Limit = 6.05% from targets for n=3*

Probability = 0.1% with DOT statistics
Probability $\approx$ 0% with contractor statistics
0.1% greater chance for pay<100% with DOT statistics

Percent Passing 3/8 inch Sieve**

Statistics

$s^2_{DOT} = 6.605$ $s^2_{CONT.} = 6.044$ s^2 are SD

$\overline{\Delta}_{DOT} = 0.246\%$ $\overline{\Delta}_{CONT.} = 0.231\%$ $\overline{\Delta}$ are NSD

Probability of pay<100%

Limit = 4.90% from targets for n=3*

Probability = 0.8% with DOT statistics
Probability = 0.5% with contractor statistics
0.3% greater chance for pay<100% with DOT statistics

Percent Passing Number 4 Sieve**

Statistics

$s^2_{DOT} = 9.959$ $s^2_{CONT.} = 7.707$ s^2 are SD

$\overline{\Delta}_{DOT} = 0.320\%$ $\overline{\Delta}_{CONT.} = 0.293\%$ $\overline{\Delta}$ are NSD

Probability of pay<100%

Limit = 5.0% from targets for n=3*

Probability = 4.3% with DOT statistics
Probability = 1.6% with contractor statistics
2.7% greater chance for pay<100% with DOT statistics

Percent Passing Number 8 Sieve**

Statistics

$s^2_{DOT} = 9.488$ $s^2_{CONT.} = 5.534$ s^2 are SD

$\overline{\Delta}_{DOT} = 0.253\%$ $\overline{\Delta}_{CONT.} = 0.196\%$ $\overline{\Delta}$ are NSD

Probability of pay<100%

Limit = 4.2% from targets for n=3*

Probability = 13.9% with DOT statistics
Probability = 1.6% with contractor statistics
12.3% greater chance for pay<100% with DOT statistics

* Typical LOT pay adjustments based on about 3 samples.

** Limits used for gradation are averages of those specified for Superpave and SMA mixes.

KANSAS DEPARTMENT OF TRANSPORTATION

Voids Content

Statistics

s^2_{DOT} = 0.643 $s^2_{CONT.}$ = 0.318 s^2 are SD

$\overline{\Delta}_{DOT}$ = 0.322% $\overline{\Delta}_{CONT.}$ = 0.262% $\overline{\Delta}$ are NSD

Probability of exceeding upper or lower specification limits

Limits = ± 1% from 4% target

Probability = 24.9% with DOT statistics
Probability = 11.0% with contractor statistics

13.9% greater chance of exceeding specification limits with DOT statistics

Mat Density

Statistics*

s^2_{DOT} = 3.016 $s^2_{CONT.}$ = 1.674 s^2 are SD

$\overline{\Delta}_{DOT}$ = 1.429% $\overline{\Delta}_{CONT.}$ = 1.642% $\overline{\Delta}$ are SD

Probability of exceeding lower* specification limits (LSL)

LSL = 92% of G_{mm} for mainline paving > 2 inches thick
LSL = 91% of G_{mm} for mainline paving $\leq$ 2 inches thick
LSL = 90% of G_{mm} for shoulder paving

Probability = 20.5% with DOT statistics
Probability = 10.2% with contractor statistics

10.3% greater chance of exceeding LSL with DOT statistics

* Mat density is controlled with one sided limits, ie, only a minimum or lower limit is specified. Data from three types of paving were combined by using the variable Δ = X-LSL.

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

Mat Density

Statistics – Contractor and NCDOT Retest

s^2_{DOT} = 2.200 $s^2_{CONT.}$ = 1.657 s^2 are SD

$\overline{\Delta}_{DOT}$ = 0.695% $\overline{\Delta}_{CONT.}$ = 1.114% $\overline{\Delta}$ are SD

Probability of exceeding 92% of G_{mm} minimum compaction requirement*

Probability = 32.0% with DOT statistics
Probability = 19.4% with contractor statistics

12.6% greater chance of exceeding minimum compaction requirements.

* Pay reduction computed with equation, $PF = 100-10(D)^{1.465}$, where D is the deficiency in compaction, i.e., less than 92%