HMA Acceptance Specifications - Assessing Contractor Risk

Who Really Has Risk?

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Outline

- Introduction
- Mechanics of Typical Quality Assurance Specifications
- Payment Drivers in QC/QA Specifications
- Common Challenges and Potential Solutions
- Summary/Conclusions/Recommendations
Introduction

- Many States using Quality Assurance Specifications

- Quality Assurance Spec Objective:
  - To specify and measure quality related to pavement performance and pay for quality provided (Pay For Performance)

- Statistically Based
  - Acceptance Sampling and Testing
  - PWL used to Quantify Quality
  - Pay Factors = f(PWL)
Introduction

- Many Specifications Seem Alike

- Engineering Judgment Used to Select Many Specification Parameters

- Specifications Sensitive to
  - Variability in Measured Quality Characteristics
    - Sampling, Testing, M/C
  - N and n
  - Specifications Limits
Macro View - Typical Quality Assurance Specs

QC Testing → Assurance Testing → F- and t-tests for Validity

- Pass → Calculate PWL from QC or QA Data → Calculate Pay Factor from PWL
- Fail → Resolve, Possibly Use QA Data
Statistically Based Acceptance Plan

- Components
  - Acceptance Sampling and Testing
  - Quality Characteristics
  - Specification Limits
  - Statistical Model
  - Quality Level Goals
  - Risk
  - Pay Factors
Common Challenges

- Understanding Variability & Setting Specification Limits
- Understanding of Risk
- Impact of Small Changes (ie. Sampling location)
- Test Turn Around Time
- Dispute Resolution
  - No Outlier Definition, Detection, or Handling/Disposition
  - Independent Labs
- Serving Multiple Customers
  - Offset Between Labs
Statistically Based Acceptance Plan

- Acceptance Sampling and Testing
  - QC & PC – Acceptance – IA
  - Lot and Sublot Definitions
  - Sampling/Testing Frequencies
  - Sampling Methods/Locations
  - Test Methods
  - Basis: Engineering Judgment

- Quality Characteristics (What is Specified)

Determine the Composite Pay Factor (CPF) for each mixture. The CPF shall be rounded to 3 decimal places.

\[
CPF = \left[ f_{\text{VMA}} (TPF_{\text{VMA}}) + f_{\text{voids}} (TPF_{\text{voids}}) + f_{\text{density}} (TPF_{\text{density}}) \right] / 100
\]

Substituting from Table 1:

\[
CPF = \left[ 0.3 (TPF_{\text{VMA}}) + 0.3 (TPF_{\text{voids}}) + 0.4 (TPF_{\text{density}}) \right] / 100
\]
Statistically Based Acceptance Plan

- Specification Limits
  - Define *Acceptable and Unacceptable* Material Quality
  - Function of \( (S^2_T) = S^2_s + S^2_t + S^2_{m/c} \)
  - Basis: Engineering Judgment?

- Statistical Model
  - Quality Defined as Percent of Quality Characteristic (ie. In-place Density) Within Spec Limits
  - PWL Method Normally used to Define Quality
  - Use QC, QA, QC+QA Data? – Engineering Judgment
Establishing Specification Limits

Quality Characteristic (ie. %AV)

Target Value

Tolerance = \( f(S_T^2) \)

Upper Spec limit

Lower Spec limit
Statistical Model = PWL

Single and Double Spec Limits

Single-Limit Specification

Quality Characteristic Distribution

- Lower Spec Limit
- Mean ($x$)
- Percent Within Limits (PWL)
- Percent Defective (PD)

Double Limit Specification

Quality Characteristic Distribution

- Lower Spec Limit
- Mean ($x$)
- Percent Within Limits (PWL)
- Percent Defective (PD)
- Upper Spec Limit
Statistically Based Acceptance Plan

Quality Level Goals
- AQL = Min Quality (PWL) at Full Acceptance
  - 90 or 95
- RQL = Max Quality (PWL) at Unacceptable
  - 60 to 75
- Basis: Engineering Judgment

Risk
- Use Sample not Population, so Risk
- Wrongful Acceptance or Rejections
- Balance Seller and Buyer Risks with \( n \)
- Basis: Engineering Judgment and Logistics
OC Curves

- Risk
- Sample/Test Frequency
Statistically Based Acceptance Plan

- **Pay Factors**
  - Quality (Defined by PWL) is Related to Payment by Pay Factor
    - Incentives (Bonuses) for
      - PWL > AQL
    - Disincentives (Penalties) for
      - AQL > PWL > RQL

- **Composite Pay Factors**

\[ \text{CompositePayFactor} = \frac{\sum (PF_n \times Wt_n)}{\sum Wt_n} \times 100 \]
Advantages

- PWL is Best Tool to Quantify Quality Relative to TV, Spec Limits Mean, Variability

- QC/QA with PWL: Transfer of Responsibility from SHA to Material Producer/Contractor for Quality

- Opportunity for Producer/Contractor to Control Processes

- Opportunity to Be Compensated for Quality Provided

- Opportunity for Producer/Contractor to Refine Processes and Build Technical Competency
Lack of Knowledge of Risk in Specifications

Risk and Payment Changes with:
- Lot and Sublot Size
- Samples and Tests per Lot and Sublot
- Sampling Location
- Test Methods and Test Method Options
- Acceptance Limit Changes
- Specification Limit Changes
- Pay Factor Equations, Weights and Variables
- …

Are tools are not perfect, so we can’t eliminate risk
Specification Selection & Changes

Borrow Specification and Make “Small Refinements”

- Tests per Sublot
  - 5 vs. 10 for Density
- Sample Location
  - Mat vs. Truck
- Test Method Options
- Specification Limits
  - Changes for Several Reasons
- Pay Factor Equation
  - Continuous to Stepped Function
Outline

- Introduction
- Mechanics of Typical Quality Assurance Specifications
- Payment Drivers in QC/QA Specifications
- Common Challenges and Potential Solutions
- Summary/Conclusions/Recommendations
PWL and Pay Factor Theory
(It Doesn't Have to be a Gamble!)

<table>
<thead>
<tr>
<th>Asphalt Binder Content</th>
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</thead>
<tbody>
<tr>
<td>4.6</td>
</tr>
<tr>
<td>No. of Samples</td>
</tr>
</tbody>
</table>

![Bar chart showing distribution of Asphalt Binder Content with a smooth curve fitting the data points.](Image)
Percent Within Limits Concept

- Percent Within Limits (PWL) methodology and Pay Factors
  - Small number of tests results outside the specification limits is normal and not necessarily detrimental to performance
  - Led to Acceptable Quality Level (AQL) definition
  - Thus Percent Deficient (PD) and Percent Within Limits (PWL) definitions
  - PWL = the percent of a lot falling within set specification limits
  - Payment is based on PWL and allows for both potential penalty or bonus
  - Idea is to tie Quality (& Payment) to Performance
Normal Distribution
A Bell Curve of the Histogram

Asphalt Binder Content

No. of Samples

Can Define Normal Distribution if Mean and Standard Deviation Are Known

X = 5.1

4.6  4.7  4.8  4.9  5.0  5.1  5.2  5.3  5.4  5.5  5.6
Normal Distribution and Standard Deviation

-3s, -2s, -1s, 1s, 2s, 3s

s = standard deviation

- 68% within 1 standard deviation
- 96% within 2 standard deviations
- 99.7% within 3 standard deviations
PWL and PD Concepts

PWL = Area of Distribution within Spec Limits

PWL = 100 - (PD_U + PD_L)
Mechanics of PWL

PWL = 100 - (PD_U + PD_L)

Where:

PD_U = Percent Defective (upper), obtained from PD table for calculated QI_U and given n

PD_L = Percent Defective (lower), obtained from PD table for calculated QI_L and given n

n = number of test results
Mechanics of PWL

\[ QI_U = \frac{(UL - \bar{X})}{S} \]

\[ QI_L = \frac{(\bar{X} - LL)}{S} \]

Where:

- \( QI_U \) = Upper Quality Index
- \( QI_L \) = Lower Quality Index
- \( \bar{X} \) = mean of test results
- \( S \) = standard deviation
- \( UL \) = Upper specification Limit (target value + tolerance)
- \( LL \) = Lower specification Limit (target value - tolerance)
Quality Level Analysis (PWL=f(n, spec limits))

### Illinois Department of Transportation

**PFP Quality Level Analysis**  
**Appendix E.1**  
(continued)

Effective: December 12, 2003  
Revised: January 1, 2017

#### TABLE 2: QUALITY LEVELS

QUALITY LEVEL ANALYSIS BY STANDARD DEVIATION METHOD

<table>
<thead>
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<th>P_U OR P_L PERCENT WITHIN LIMITS FOR POSITIVE VALUES OF Q_U OR Q_L</th>
<th>n=3</th>
<th>n=4</th>
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<th>n=10 to n=11</th>
<th>n=12 to n=14</th>
<th>n=15 to n=18</th>
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</tbody>
</table>
From Quality (PWL) to Payment (CPF)

Composite Pay Factor = CPF

Payment = PF x HMA (tonnage) x HMA Unit Price ($/ton)

(9) Once the project is complete determine the Total Pay Factor (TPF) for each parameter by using a weighted lot average by tons (mix) or distance (density) of all lots for a given parameter.

\[ TPF = W1PF_{Lot1} + W2PF_{Lot(n+1)} + \text{etc.} \]

Where:

- \( W1, W2 \ldots = \text{weighted percentage of material evaluated} \)
- \( PF = \text{Pay factor for the various lots} \)
- \( TPF = \text{Total pay factor for the given parameter} \)

(10) Determine the Composite Pay Factor (CPF) for each mixture. The CPF shall be rounded to 3 decimal places.

\[ CPF = \left[ f_{VMA}(TPF_{VMA}) + f_{voids}(TPF_{voids}) + f_{density}(TPF_{density}) \right] / 100 \]

Substituting from Table 1:

\[ CPF = \left[ 0.3(TPF_{VMA}) + 0.3(TPF_{voids}) + 0.4(TPF_{density}) \right] / 100 \]

Where:

- \( f_{VMA}, f_{voids}, \text{and } f_{density} = \text{Price Adjustment Factor listed in Table 1} \)
- \( TPF_{VMA}, TPF_{voids}, \text{and } TPF_{density} = \text{Total Pay Factor for the designated measured attribute from (9)} \)

(11) Determine the final pay for a given mixture.

\[ \text{Final Pay} = \text{Mixture Unit Price} \times \text{Quantity} \times CPF \]
Can We have a PF less than 1.0 even if all test results are in Spec?
Effect on PWL's
(Equal Means but Different Standard Deviations)

<table>
<thead>
<tr>
<th>Target Value</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limits</td>
<td>± 0.4</td>
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</table>

<table>
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<tr>
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<th>X</th>
<th>s</th>
<th>PWL</th>
<th>PF</th>
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<td>5.0</td>
<td>0.40</td>
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<td>89</td>
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</tbody>
</table>

Asphalt Binder Content

Lot 1

Lot 2

Lower Spec limit

Upper Spec limit

(Equal Means but Different Standard Deviations)
Effect on PWL's
(Off Target Means and Same Standard Deviations)

<table>
<thead>
<tr>
<th>Target Value</th>
<th>5.0</th>
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<th>PF</th>
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<td>0.20</td>
<td>100</td>
<td>105</td>
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<td>2</td>
<td>4.8</td>
<td>0.20</td>
<td>84</td>
<td>96</td>
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</table>

Asphalt Binder Content

Lot 1

Lot 2

Lower Spec limit

Upper Spec limit
Single Spec Limit PWL (Density)

Minimum Specification Limit

X = 93.5
S = 0.75

X = 96.0
S = 2.0
Outline

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Acceptance & Payment Drivers in Assurance Specifications

- Variability (from Mechanics)
  - On Target and Standard Deviation

- Variability and Spec Limits

- Reducing Variability and Specification Limits

- Examples
  - Sample Location
  - Test Methods
  - Pooling QC & QA Data for Payment
  - Spec Limit Changes
# Effect on PWL's

*(Equal Means but Different Standard Deviations)*

<table>
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<th>Lot</th>
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<td>5.0</td>
<td>0.40</td>
<td>67</td>
<td>89</td>
</tr>
</tbody>
</table>

![Graph showing the effect on PWL's with asphalt binder content](image)
Establishing Specification Limits

Quality Characteristic (%AC)

Lower Spec limit

Target Value

Upper Spec limit

Tolerance = \( f(S_T^2) \)

Tolerance = \( f(S_T^2) \)
Variability and Spec Limits

Several Components of Total Variability
- Little Work to Define Percent Distribution of Components for Most Quality Characteristics
- Materials Supplier/Contractor only Controls One Component

Establishing Specification Limits
- R9: $3 \times S_T$
- Stroup-Gardner/Newcomb/Savage: $3 \times S_t$
Variability in (total) can be broken down into:

- Variability from (sampling) components
- Variability from (test method) components
- Variability from (mat./const.) components

Mathematically, this can be expressed as:

\[ S^2_{\text{total}} = S^2_s + S^2_t + S^2_{m/c} \]
Sampling Variability ($s^2$)

- 10-30% of Total Variability
  - Sample Location
  - Sample Method
  - Sample Size
  - Sample Split

Materials/Construction: 34%
Testing: 43%
Sampling: 23%
**Test Method Variability ($s^2_t$)**

- 30 to 50% of Total Variability
- Precision and Bias Statements
- Within vs. Between Lab Variability
  - Use of QC vs. QC+QA vs. QA data to calc PWL

### Designations Multilaboratory Precision

<table>
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<th>Designations</th>
<th>Description</th>
<th>Multilaboratory Precision</th>
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<tr>
<td></td>
<td></td>
<td>Standard Deviation (1S)</td>
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<tr>
<td></td>
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<td>AASHTO</td>
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<tr>
<td>AASHTO Method</td>
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<td>Coarse Aggregate Specific Gravity</td>
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<td>Fine Aggregate Specific Gravity</td>
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<td>Bulk Specific Gravity of Compacted Bituminous Specimens</td>
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<td>T209</td>
<td>D2041</td>
<td>Theoretical Maximum Specific Gravity of Bituminous Mixture</td>
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*(0.0193) (0.0193) (0.055) (0.055)
Precision, Bias and Accuracy

Accurate and Precise

Precise, but Biased

Accurate, but not Precise

Low and High Variability
**Precision, Bias and Accuracy**

- **Accurate and Precise**
  - Low Variability

- **Accurate, but not Precise**
  - High Variability

Precision Statements are Based on Interlaboratory Studies (Round Robin)
# ASTM Interlaboratory Studies

<table>
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<tr>
<th>Material ID</th>
<th>Laboratory Number</th>
<th>Replicate Number</th>
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ASTM Interlaboratory Studies

Precision Statements are Based on Pooled Variance ($\sigma_p$)

- **Accurate and Precise**
  - Low Variability
  - Lab 1

- **Accurate, but not Precise**
  - High Variability
  - Lab 2

- **Pooled Variability - All Labs**

Precision Statements are Based on Pooled (all labs) Variance ($\sigma_p$)
**Within Laboratory Precision**  
*(Single Operator Precision)*

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<tr>
<th>Designations</th>
<th>Single Operator Precision</th>
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<td>T85 C127</td>
<td>Coarse Aggregate Specific Gravity</td>
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<td>T84 C128</td>
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<td>T166 D2726</td>
<td>Bulk Specific Gravity of Compacted Bituminous Specimens</td>
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<td>T209 D2041</td>
<td>Theoretical Maximum Specific Gravity of Bituminous Mixture</td>
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* - “Duplicate specific gravity results by the same operator should not be considered suspect unless they differ more than 0.02.”

( ) - supplemental procedure for mixtures containing porous aggregate conditions (“dryback procedure”).
## Between Laboratory Precision (Multilaboratory Precision)

### Designations

<table>
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</tbody>
</table>

* - “Duplicate specific gravity results by the same operator should not be considered suspect unless they differ more than 0.02.”

( ) - supplemental procedure for mixtures containing porous aggregate conditions (“dryback procedure”).
Material/Construction Variability ($s^2_{m/c}$)

- 30 to 40% of Total Variability
- Asphalt Binder, Aggregate
- Production
- Placement

\[
S^2_T = S^2_s + S^2_t + S^2_{m/c}
\]

Fixed?

What Payment Should Reflect!
Variability and Spec Limit Changes

$$S^2_{\text{total}} = S^2_{s} + S^2_{t} + S^2_{m/c}$$

Total Variability in Quality Characteristic
**Spec Limits and Variability**

\[ S_{QC/QA}^2 = S_s^2 + S_t^2 + S_{m/c}^2 \]
Example - Sampling Location

What is Influence of Sampling Location on Gradation PWLs

- Use Data as an Example
  - 45 sublots
  - Loose = truck samples
  - Cores = 6” cores from mat
  - Note MTV used
Effect of Sampling Location on Gradation Variability (Fine Mixture)
## Influence of Sampling Location on PWL

<table>
<thead>
<tr>
<th>Sieve</th>
<th>Sample Location &amp; Standard Deviations</th>
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<tr>
<td></td>
<td></td>
<td>Truck</td>
<td>Cores</td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td>4.9</td>
<td>2.2</td>
</tr>
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<td>#8</td>
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<td>PWL(^1)</td>
<td></td>
<td>98.4</td>
<td>99.9</td>
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</table>

\(^1\) Assumes that PWL for Asphalt Content and Voids in Total Mixture are 100
Example - Pooling QC&QA Data for Payment Determination

- Specification Developed Around Within Lab Testing Variability
- Pooling QC and QA Data Results in Between Lab Variability in PWL Determination
- Decreased PWL, Decreased Payment

- Two Examples
  - SHA Spec When t-test Significant, Pool QC and QA
  - Contract Administrator Dictates Post-Contract Award, Pre-Construction to Eliminate Potential for Dispute
Influence of Within and Between Lab Variability on PWL

Asphalt Binder Content

Upper limit

Within Lab

Between Lab

Lower limit
Pooling QC and QA Data for Payment

- Used State DOT QC/QA Spec
- Assumed Means = Target Values
- Determined Standard Deviations to Get PF = 1.0
- Increased Standard Deviations by Difference in Within and Between Lab 1S
  - Holding Sampling and Materials Variability Constant
- Compared Composite Pay Factors
# Increase in 1S from Within to Between Lab Case

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Standard Deviations (1S)</th>
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<tr>
<td>Density</td>
<td>AASHTO T166/T209/T269</td>
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<tr>
<td>Air Voids</td>
<td>AASHTO T166/T209/T269</td>
<td>0.51</td>
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<tr>
<td>19.0 mm</td>
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<td>AASHTO T27</td>
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<tr>
<td>0.075mm</td>
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## Reduction in PWL and PF from Within to Between Lab Case

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<th>Weighting Factor</th>
<th>Standard Deviation</th>
<th>Percent Within Limits (PWL)</th>
<th>Individual Pay Factor</th>
<th>Composite Pay Factor</th>
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<tr>
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<td></td>
<td>Within Lab</td>
<td>Between Lab</td>
<td>Within Lab</td>
<td>Between Lab</td>
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<td>0.21</td>
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<td>1.43</td>
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<td>84.0</td>
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</table>

- The composite pay factor for the within lab is 1.00, and for the between lab is 0.94.
Laboratory Accreditation

- Quality of Test Results in non-AASHTO Accredited labs
  - STD Labs and STD Qualified Labs (Via STD IA Program)
    - Mix Design Verification Problems
    - STD and Industry Round Robin
      - "Blind" Study of Compacted Mix Gmb Variability
STD/Industry Round Robin

- 15 Participating Laboratories
  - STD, Consultants, and Contractors
  - All Labs STD IA Program Qualified
- 1 Material/Mixture
  - Rigorous QC in Sample Preparation
- 10 Specimens per Laboratory
  - Compact all 10
    - 5 - Gmb in Lab
    - 5 – Gmb by DOT Central Lab
- Compactor Calibration Performed/Verified Prior to Study
## Participating Labs

(15 Total)

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ANNOVA - STD Qualified vs. AASHTO Accredited
- Lab Accreditation Significant? **YES**
  - Variability in STD Qualified $\approx$ **Double** AASHTO Accredited
  - All Extreme Data in STD Qualified Labs

**Paired t-Tests of Means (SPLIT SAMPLES)**
- 105 paired t-tests
- 53 of 105 Significant (Over 50%)

**Air Void Differences (Same Gmm)**
- 57% of Between Lab Comparisons $\geq$ 1.0%
- 27% of Between Lab Comparisons $\geq$ 2.0%
- Mix Design Verification

**ALL Labs Should Be AASHTO Accredited!**
## Between Lab %AV Differences

- **Bold = >1.0%**
- **Red = > 2.0%**

**Difference in Air Voids**

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<td>0.7</td>
<td>2.4</td>
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<td><strong>103</strong></td>
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</table>
Laboratory Accreditation

- It is a Priceless Investment
- State DOT vs. AMRL
- AMRL is Best
- Contractor or SHA Central Labs Only NOT Enough
- Internal Controls
- Proficiency Sample Programs
- Correct Between Lab Bias BEFORE Doing a Job!
Technician Qualification

- Qualification Important
- Perceived Cost Significant
- Lack of Appreciation for Importance
  - Who Bears Risk With High Testing Variability?
    - Owner?
    - Consultant?
    - Material Producer/Contractor?
- Rigor of Processes
  - Good Examples
    - Texas, Colorado, and Arizona
- Another Priceless Investment
Producing for Multiple Customers

Handling Offsets

Lab Voids (%)

Sample #

1 2 3 4 5 6 7 8 9 10

Producer  Acceptance Lab A  Acceptance Lab B

2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Dispute Resolution

- Need for Outlier Definition – “Wacky or Flyer”
- Need for Outlier Detection Tool
  - ASTM E178 or some other criteria
- Need for Re-test Provision – Test whole sample or individual test? Split or independent sample…
Fraud

- NCHRP Project
- ARI Postings
- Request Outlier/Re-Test Provisions
  - ASTM
  - Arizona

- WE are the Keepers of Industries Integrity Perception!
- Dispute Resolution Provisions Help US
Summary

- Many Agencies Using Stat Based Quality Assurance Specs with *Pay for Quality Objective*

- Increased Contractor Responsibility with Reduced Agency Demands

- Specs More Complicated than Meet the Eye due to
  - Lack of Relationships between Quality and Pavement Performance
  - Subjective Engineering Judgment in Selection of *Many* Specification Parameters

- Influence of Variability and Spec Limits Critically Important
Reducing Sampling & Testing Variability

- Increase Sampling/Testing Frequency
- Change Sampling Location
- Change Sampling and/or Splitting Methods
- Technician Training
- Technician Certification (Qualified Workforce)
- Laboratory Accreditation (AMRL)
- Regionalize/Standardize Test Methods
- Regionalize/Standardize Test Method Options
- Proficiency Sample Programs (Round Robins)
- Use Single (QC or QA or IA) Data Source

Note Many Engineering Judgment Calls
Suggestions

- Cooperative Spec Development & Refinement
- Knowledgeable Spec Developers - Use Shadow Approach
- Refine Specs Over Time
  - Knowledge/Experience/Equipment Improvements
  - Use Rational Analysis (Avoid Arbitrary Changes)
- Support Efforts to Minimize $\sigma_s$ and $\sigma_t$
- Support Efforts to Develop Relationships between Quality and Pavement Performance
- Develop Databases as Basis for Future Changes
- Support Lab Accreditation
- Support Technician Certification
Thank You and Discussion

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