Understanding Testing Variability

Rocky Mountain Asphalt Conference & Equipment Show

February 19-21, 2014
Denver, Colorado

Jon Epps
Understanding Testing Variability

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Jon Epps
Outline

- Introduction
- Variability
- Sampling Variability
- Testing Variability
- Materials/Construction Variability
- Percent within Limit
- Typical Variability
- Summary
Why Understand Testing Variability

- Provide quality product to our customer
- Remain in business
- Establish specification limits
- Predict pay factors
“Quality”

- Customer
- Engineer
Quality – Customer

- Product Meets or Exceeds Customer’s Expectation
  - Short Term
  - Long Term (Durability)
- Appearance
Quality – Pavements

- Looks Good
- Rides Smoothly
- No Splash and Spray
- Quiet
- Provide Friction
Quality – Engineer

- Meets or Exceeds Expectation (Performance)
  - Short Term
  - Long Term
- Meets or Exceeds Specifications
- Uniform Product
Quality-Pavements (Engineer)

- Meets or Exceeds Specification
- Satisfies Customer
- Short & Long Term Performance
  - Rutting
  - Bleeding
  - Patching
  - Raveling
  - Cracking
Quality Pavements

- Mixture/Materials Designs
- Thickness of Pavement
- Specifications
- Construction
Who Is Responsible for Quality?

- Owner (Public Agency)
- Contractor/Material Supplier
- All Levels of the Organization
Role of Specifications

- Contractors/Material Supplier (Control Quality)
- Owner (Public Agencies) (Specify Quality)
Referee

Contractor/Material Supplier
- Process Control
- Quality Control

Owner (Public Agency)
- Quality Assurance

Independent Assurance
Types of Specifications

- Proprietary Method
- QC/QA
- End Result

- Performance Related
- Performance Based
- Statistically Based
- Warranty/Guarantee
Specifications – Quality Control/Quality Assurance

- Lot/Sublot
- Process Control/Quality Control
- Quality Assurance
- Acceptance
- Measurement
- Pay Adjustment
- Certification/Accreditation
Outline

- Introduction
- Variability
  - Sampling Variability
  - Testing Variability
  - Materials/Construction Variability
  - Percent within Limit
  - Typical Variability
Statistical Representation of Variability

- Mean – \( \bar{x} \)
- Standard Deviation – \( s \)
- Coefficient of Variation – \( \frac{s}{\bar{x}} \)
QC/QA and Variability

Variability = variability + variability + variability

(QC/QA) (sampling) (test method) (mat./const.)

\[ S^2_{QC/QA} = S^2_s + S^2_t + S^2_{m/c} \]
Sources of Variability

- Sampling – random variation in sampling methods or procedures
- Testing – random variation in testing performance and equipment

Sampling + testing variability = about 50% of the variation in test results

- Material – random natural variation
- Construction – variation inherent in production and construction methods
### Effect of Number of Samples and Associated Risk

<table>
<thead>
<tr>
<th>Number of Samples (n)</th>
<th>Contractor’s Risk (α)</th>
<th>Owner’s Risk (β)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0%</td>
<td>84%</td>
</tr>
<tr>
<td>1</td>
<td>5%</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>0%</td>
<td>16%</td>
</tr>
<tr>
<td>4</td>
<td>5%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
Reported Test Result

- Single sample/size test result
- Single sample/multiple test result
- Multiple samples/multiple test result

\[ S_n = \frac{s}{\sqrt{n}} \]
Sample Size & Frequency

- Increase Sample Size & Increase Frequency (#)
  - Large Nom Max Agg Size
  - Large Mixture Variability
  - High Reliability
  - Large Effect on Performance
  - New Materials or Production
  - Non-Compliance w/Specifications
Number and Size of Samples

ASTM Standards

- **D3665** – Random Sampling of Construction Materials
- **E105** – Probability Sampling of Materials
- **E122** – Choice of Sample Size to Estimate the Average Quality of a Lot or Process
- **E141** – Acceptance of Evidence
Lot/Sublots/ #Tests

- **Lot**
  - Amount of material being evaluated for payment purposes
  - Commonly defined by length of roadway or material mass

- **Sublots/Lot**
  - Sampling divisions within given lot
  - Commonly 4 or 5 with 1 test/sublot

- **Tests/Sublot**
  - Number of material tests or measurements per lot or sublot
    - Typically 1 to 5 depending on lot and sublot
Random Sampling

With simple random Sampling, all samples could end up in one section of a Roadway lot.
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Random Sampling

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Random Sampling

With simple random Sampling, All samples could end Up in one section of a Roadway lot
Stratified Random Sampling
Point of Sampling

- **Asphalt**
  - Plant Tank or Middle 1/3 of Truck Load
  - Bleed off & Discard Prior to Sampling
  - Sample & Seal
Point of Sampling

- **Asphalt Content**
  - Loose Plant, Truck, Mat (entire lift), Windrow, or Paver (auger) Samples, Cores

- **Aggregate Gradation**
  - Coldfeeds or hot bins
  - Extracted from HMA (loose samples or cores)

- **Lab Compacted Volumetrics**
  - Loose Plant, Truck, Mat (entire lift),
Cold Feed “Belt Cuts” are taken from the collector belt enroute to the dryer drum.
Truck
Point of Sampling

- In-Place Density
  - Compacted Mat
- Thickness
  - Compacted Mat
- Smoothness
  - Longitudinal Profile or Index
Sample Splitting

Coarse @ 3.79%ac Fine @ 5.21%ac
Outline

- Introduction
- Variability
- Sampling Variability
- **Testing Variability**
- Materials/Construction Variability
- Percent within Limit
- Typical Variability
Test or Measurement Method

- Must be suitable for Field Applications
  - Inexpensive, easy set-up (mobile), relative insensitive to environment, easy to analyze data
- Understand Associated Variability!
- Specification Tolerances = \( f(\text{Variability}) \)
Mix Design Volumetric

- Superpave
  - $G_{mi, d, m}$, AV, VMA, VFA, DP

- Marshall
  - AV, VMA, VFA
Mixture Volumetrics

- All Specified Volumetric Properties Calculated from Measured Material Properties (AASHTO or ASTM Test Methods):
  - Asphalt Content (AC)
  - Asphalt Cement Specific Gravity ($G_b$)
  - Combined Aggregate Specific Gravity ($G_{sb}$)
  - Bulk Specific Gravity of Compacted Mixture ($G_{mb}$)
  - Theoretical Maximum Specific Gravity
### Properties Calculated Mixture Properties are Function of

<table>
<thead>
<tr>
<th>Calculated Property</th>
<th>Variables the Property is a Function of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gsb</td>
<td>P, Gsb</td>
</tr>
<tr>
<td>Gse</td>
<td>Pmm, Pb, Gmm, Gb</td>
</tr>
<tr>
<td>Gmm</td>
<td>Pmm, Ps, Gse, Pb</td>
</tr>
<tr>
<td>Pba</td>
<td>Gb, Gse, Gsb</td>
</tr>
<tr>
<td>Pbe</td>
<td>Pb, Pba, Ps</td>
</tr>
<tr>
<td>AV</td>
<td>Gmb, Gmm</td>
</tr>
<tr>
<td>VMA</td>
<td>Gmb, Gsb, Ps</td>
</tr>
<tr>
<td>VFA</td>
<td>VMA, AV</td>
</tr>
<tr>
<td>%Gmm_i</td>
<td>Gmb, Gmm</td>
</tr>
<tr>
<td>%Gmm_m</td>
<td>Gmb, Gmm</td>
</tr>
<tr>
<td>DP</td>
<td>p0.075, Pbe</td>
</tr>
</tbody>
</table>
Question?

What are the combined effects of variability in material and mixture property measurements on calculated volumetric properties and optimum asphalt content selection?

Answer

Perform an analysis to find out
Analysis

- Show the effect of what is considered acceptable variability in $G_b$, $G_{sb}$, $G_{mb}$, $G_{mm}$ measurements on mixture volumetrics for both within and between laboratory conditions

- 19mm Superpave mix design data
- ASTM single-operator and multilaboratory precision
- Monte Carlo Simulations
- Generate range of volumetric properties due to test method variability
Test Method Precision and

- Precision Statements Account for Inherent Test Method Variability (uncontrollable random error)
- Single-operator, within lab, repeatability
- Multilaboratory, between lab, reproducibility
- One-Sigma Limits (standard deviation, $\sigma$, 1S)
Precision and Bias

- Precise
- Not Bias

- Not Precise
- Not Bias

- Precise, Biased

Texas A&M Transportation Institute

Wednesday, March 5, 14
Precision and Bias

Precise Not Bias

Low Variability

Not Precise Not Bias

High Variability

Precision Statements are Based on Interlaboratory Studies
**Within Laboratory Precision**
*(Single Operator Precision)*

<table>
<thead>
<tr>
<th>Designations</th>
<th>Description</th>
<th>Single Operator Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AASHTO</td>
</tr>
<tr>
<td><strong>Standard Deviation (1S)</strong></td>
<td></td>
<td><strong>Acceptable Range of Two Results (D2S)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AASHTO</td>
</tr>
<tr>
<td>T228</td>
<td>Asphalt Cement Specific Gravity</td>
<td>0.0008</td>
</tr>
<tr>
<td>T85</td>
<td>Coarse Aggregate Specific Gravity</td>
<td>0.009</td>
</tr>
<tr>
<td>T84</td>
<td>Fine Aggregate Specific Gravity</td>
<td>0.011</td>
</tr>
<tr>
<td>T166</td>
<td>Bulk Specific Gravity of Compacted Bituminous Specimens</td>
<td>*</td>
</tr>
<tr>
<td>T209</td>
<td>Theoretical Maximum Specific Gravity of Bituminous Mixture</td>
<td>0.0040 (0.0064)</td>
</tr>
</tbody>
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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").
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<tr>
<th>Designations</th>
<th>Description</th>
<th>Multilaboratory Precision</th>
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<td></td>
<td>AASHTO</td>
</tr>
<tr>
<td>T228</td>
<td>Asphalt Cement Specific Gravity</td>
<td>0.0024</td>
</tr>
<tr>
<td>T85</td>
<td>Coarse Aggregate Specific Gravity</td>
<td>0.013</td>
</tr>
<tr>
<td>T84</td>
<td>Fine Aggregate Specific Gravity</td>
<td>0.023</td>
</tr>
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<td>0.0064 (0.0193)</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”).
Monte Carlo Simulation Process

- Develop Probability Distributions from Mix Design Property Means and ASTM One-Sigma Limits for Each Input Variable
  - eg.: $G_{mb}$ and $G_{mm}$

- Repeatedly Sample the Input Distributions ($G_{mb}$ and $G_{mm}$) and Calculate the Output Variable to Generate an Output Distribution
  - eg.: %AV
Monte Carlo Simulation

\[ \%AV = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}} \]

\( G_{mm} \) and \( G_{mb} \) = inputs

\( \%AV \) = output
Summary Plots

%AV Output Distribution at 5.25% AC

%AV Output Distribution at 5.75% AC

%AV Output Distribution at 6.25% AC

%AV Output Distribution at 6.75% AC

-5%

-1SD

Mean

+1SD

+95%

%AV Output Distribution at 5.25% AC

%AV Output Distribution at 5.75% AC

%AV Output Distribution at 6.25% AC

%AV Output Distribution at 6.75% AC

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Within Laboratory Air Voids

- AV (%)
- Asphalt Content (%)

-5%, +1SD, Mean, +95%

0.7% AC

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Between Laboratory Air Voids

1.4% AC

Asphalt Content (%)
Summary and Conclusions

- “Acceptable” Variability Associated with the Measurement of the Properties Required to Determine HMA Volumetrics can Have a Significant Impact on Calculated Volumetric Properties
Summary and Conclusions

- Within Laboratory Test Method Variability May Lead to Differences in AV and VMA of $1.0^{\pm}\%$ for Any Given Mix Design

- These Differences Translate into Potential Differences of 0.7% in Optimum Asphalt Content Selection
Summary and Conclusions

- Between Laboratory Test Method Variability May Lead to Differences in AV and VMA of over 2.0% for Any Given Mix Design

- These Differences Translate into Potential Differences of Over 1.0% in Optimum Asphalt Content Selection
Outline

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- Percent within Limit
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- Materials/Construction Variability
- Percent within Limit
- Typical Variability
**PWL and PD Concept**

\[ \text{PWL} = 100 - (\text{PD}_U + \text{PD}_L) \]

*In Terms of Area of the Distribution*

**PWL** and **PD**

\[ \text{PWL} = 100 - (\text{PD}_U + \text{PD}_L) \]

*In Terms of Area of the Distribution*
Percent Within Limits

<table>
<thead>
<tr>
<th>Spec</th>
<th>Target Value</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.0</td>
<td>± 0.4</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

Asphalt Binder Content

Lower limit: 4.2
Target: 5.0
Upper limit: 5.8

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Percent Within Limits

Target Value | 5.0
Limits       | ± 0.4

<table>
<thead>
<tr>
<th>Lot</th>
<th>X</th>
<th>s</th>
<th>PWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.0</td>
<td>0.20</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>0.40</td>
<td>68</td>
</tr>
</tbody>
</table>

Asphalt Binder Content

Lot 1

Lower limit

Upper limit

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Percent Within Limits

<table>
<thead>
<tr>
<th>Spec</th>
<th>Target Value</th>
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<td>------</td>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
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Asphalt Binder Content

Lower limit

Upper limit

Lot 1

Lot 2

Target

Wednesday, March 5, 14
Percent within Limits

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<td>1</td>
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<td>96</td>
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<tr>
<td>2</td>
<td>4.8</td>
<td>0.20</td>
<td>84</td>
</tr>
</tbody>
</table>

Target Value: 5.0
Limits: ± 0.4

Asphalt Binder Content

Lot 1
Upper limits

Lot 2
Lower limit

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- Variability
- Sampling Variability
- Testing Variability
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- Typical Variability
## Typical Variability

<table>
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<tr>
<th>Property</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Content, %</td>
<td>0.25</td>
</tr>
<tr>
<td>% pass 4.75 mm, %</td>
<td>3.0</td>
</tr>
<tr>
<td>% pass 2.36 mm to 0.15</td>
<td>2.0</td>
</tr>
<tr>
<td>% pass 0.075 mm, %</td>
<td>0.7</td>
</tr>
<tr>
<td>Air Voids, %</td>
<td>1.0</td>
</tr>
<tr>
<td>VMA, %</td>
<td>1.5</td>
</tr>
<tr>
<td>VFA, %</td>
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Summary
Why Understand Testing Variability

- Provide quality product to our customer
- Remain in business
- Establish specification limits
- Predict pay factors
60 Asphalt Binder Contents

Frequency

- 16
- 14
- 12
- 10
- 8
- 6
- 4
- 2
- 0

4.3 %
4.5 %
4.7 %
4.9 %
5.1 %
Asphalt Content

f(x)
QC/QA and Variability

Variability = variability + variability + variability

(QC/QA)       (sampling)       (test method)       (mat./const.)

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

- Number of Samples and Size
- Sampling Location
  - Random
  - *Stratified Random
  - Systematic – uniform intervals
  - Quota – @ change in process
  - Judgment
- Sampling Method
- Acceptance OR Source Approval OR QC OR Independent Assurance/Verification of Test Procedures
Monte Carlo Simulation

\[ \%AV = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}} \]

\( G_{mm} \) and \( G_{mb} \) = inputs

\( \%AV \) = output
PWL and PD Concept

PWL = 100 - (PD_U + PD_L)

In Terms of Area of the Distribution

Wednesday, March 5, 14
## Typical Variability

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Questions?