Informed by and “borrowing” from . . .

Back 2 Basics: Volumetrics

Understanding How They Control Performance

April 4, 2017

Gerry Huber
Heritage Research Group
“I learn something new every day. The problem is, most of it is stuff that I probably should already know.”

Unknown
History of Mix Design & Volumetrics

1905
- Clifford Richardson - New York Testing Co.
- Calculates VMA and adjusts for correct %AC

1920’s
- Hubbard Field Method - Asphalt Association
- Used lab compacted specimens and volumetric analysis.

1932
- Hveem Design Method - California
- Determined Asphalt content based on aggregate surface area (film thickness)
History of Mix Design & Volumetrics

1930’s
- Marshall Mix Design - Mississippi
- Used Voids and VFA

1962
- Asphalt Institute updates MS-2
- Incorporates VMA into Marshall Design
- VMA requirements based on NMAS
Rutting in the 1980s eventually led to Superpave
History of Mix Design & Volumetrics

1993
- SuperPave Volumetric Mix Design – SHRP
- Gyratory Compactor, VMA used to determine minimum %AC
- Consensus aggregate properties on blend.

2000
- WisDOT adopts Superpave mix design methodology
Terminology

- **Volumetric** – Of or relating to measurement by volume.
- **Gravimetric** – Of or relating to measurement by weight.
- **Empirical** – Based on observation or experience rather than logic or theory (measured).
Superpave Empirical Properties

* Aggregates

* Compacted Mix

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Terminology: Specific Gravity

- Relates Density of an Object to the same Volume of Water

\[ D = G \times 1.000 \]

- Density in g/cm³
- Specific gravity of object
- Density of water

The “Rosetta Stone” for asphalt mix volumetrics
Terminology: Specific Gravity

• Specific Gravity Terms “G”
  • $G_{mb}$ - bulk specific gravity of the compacted mix. (Gyratory Puck or Pavement Core)
  • $G_b$ - specific gravity of the binder (~1.03)
Teminology: Specific Gravity

• Specific Gravity Terms “G”
  • \( G_{mm} \) - theoretical
    maximum specific gravity
    of the mix.
  Uncompacted, no air
  voids. (Rice test)
Terminology: Specific Gravity

• Specific Gravity Terms “G”
  • $G_{mb}$ - bulk specific gravity of the compacted mix.
    (Gyratory Puck or Pavement Core)
Terminology: Specific Gravity

- Specific Gravity Terms “G”
  - $G_b$ - specific gravity of the binder ($\approx 1.03$)
  - $G_{sb}$ - bulk specific gravity of the aggregate
  - $G_{se}$ - effective specific gravity of the aggregate
Volume for Bulk Gravity

Gray + Blue area

Volume of the aggregate plus

Volume of voids penetrated by water
Volume for Effective Gravity

Gray + White area

Volume of the aggregate plus
Volume of voids penetrated by water but not by asphalt
• **Air voids** ($V_a$) – Total *volume* of air in a compacted mix. (3%-4%)

  $$V_a = 100 \times \frac{(G_{mm} - G_{mb})}{G_{mm}}$$

• Low voids – potential for rutting

• High voids – lower compaction and loss of durability

• **Voids are a big deal!**
**Effective Asphalt Content** ($P_{be}$) – % of non-absorbed asphalt

- $P_{be} = P_{b} - P_{ba}$
- $P_{ba}$ calculated using $G_{se}$ and $G_{sb}$

*Gravimetric*
Compacted Specimen with Asphalt Removed

Aggregate

VMA
VMA = Air Voids + Effective AC

TOTAL Specimen Volume

Air Voids

Effective AC

Absorbed AC

Aggregate Volume

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Voids in Mineral Aggregate (VMA)

- **Definition:** *volume* of intergranular void space in a compacted mix % by volume total mix.

- **VMA =** \(100 - \left[G_{mb} \times \left(100-P_b\right)/G_{sb}\right]\)

- **Strongly influenced by gradation.**

- **Increased VMA = Increased Asphalt Content = Increased Film Thickness**
12.5 mm Mix - .45 Power Curve
9.5 mm Porous - .45 Power Curve
Mix VMA Requirements
Voids in the Mineral Aggregate

<table>
<thead>
<tr>
<th>Nom Max Size (Grade) (mm)</th>
<th>Minimum VMA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 9.5</td>
<td>15.0 (15.5)</td>
</tr>
<tr>
<td>4 12.5</td>
<td>14.0 (14.5)</td>
</tr>
<tr>
<td>3 19</td>
<td>13.0</td>
</tr>
<tr>
<td>2 25</td>
<td>12.0</td>
</tr>
<tr>
<td>1 37.5</td>
<td>11.0</td>
</tr>
</tbody>
</table>
VMA vs. Asphalt Content
Terminology

- **Voids Filled with Binder (VFB or VFA)** – The percentage of VMA filled with asphalt binder.
  
  - $VFB = 100 \times \frac{(VMA - V_a)}{VMA}$
  
  - Generally required to be between about 65 – 75%.

- **Volumetric**
<table>
<thead>
<tr>
<th></th>
<th>9.5-mm</th>
<th>12.5-mm</th>
<th>19.0-mm</th>
<th>25.0-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voids in Mineral Aggregate, %</td>
<td>15.0</td>
<td>14.0</td>
<td>13.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Air Voids, %</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Minimum Effective Volume</td>
<td>11.0</td>
<td>10.0</td>
<td>9.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Volume Asphalt Binder, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Asphalt Outside the Aggregate

**Convert percent volume to percent weight**

\[ p_{be} = \frac{V_{be}}{2.25} \]

<table>
<thead>
<tr>
<th></th>
<th>9.5-mm</th>
<th>12.5-mm</th>
<th>19.0-mm</th>
<th>25.0-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent by Volume</td>
<td>11.0%</td>
<td>10.0%</td>
<td>9.0%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Percent by Weight</td>
<td>4.4%</td>
<td>4.0%</td>
<td>3.6%</td>
<td>3.2%</td>
</tr>
</tbody>
</table>

Values approximate depending upon specific gravity of aggregates

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Why Focus on Effective Binder Content?

Why not just focus on total binder content?
SAME VMA and Different AC Contents?

* **Design 1**
  * VMA = 13.4%
  * Voids = 4.0%
  * Total AC = 4.6%

* **Design 2**
  * VMA = 13.4%
  * Voids = 4.0%
  * Total AC = 4.8%

- The Difference Is **Asphalt Absorption**
How Much Asphalt is Enough?

* Total Asphalt Content
  * Inside Rock
  * Outside Rock

Values approximate depending upon specific gravity of aggregates and actual absorption

<table>
<thead>
<tr>
<th>Water Absorption</th>
<th>9.5-mm</th>
<th>12.5-mm</th>
<th>19.0-mm</th>
<th>25.0-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>4.4%</td>
<td>4.0%</td>
<td>3.6%</td>
<td>3.2%</td>
</tr>
<tr>
<td>1%</td>
<td>4.9%</td>
<td>4.5%</td>
<td>4.1%</td>
<td>3.7%</td>
</tr>
<tr>
<td>2%</td>
<td>5.6%</td>
<td>5.2%</td>
<td>4.8%</td>
<td>4.4%</td>
</tr>
<tr>
<td>3%</td>
<td>6.3%</td>
<td>5.9%</td>
<td>5.5%</td>
<td>5.1%</td>
</tr>
<tr>
<td>4%</td>
<td>7.0%</td>
<td>6.6%</td>
<td>6.2%</td>
<td>5.8%</td>
</tr>
</tbody>
</table>
Superpave fixed the rutting problem but lowered effective asphalt contents which led to loss of durability.
### Minimum VMA requirements increased for LT and MT mixes

**WisDOT Aggregate Specifications**

**TABLE 460-1 AGGREGATE GRADATION MASTER RANGE AND VMA REQUIREMENTS**

<table>
<thead>
<tr>
<th>SIEVE</th>
<th>No. 1 (37.5 mm)</th>
<th>No. 2 (25.0 mm)</th>
<th>No. 3 (19.0 mm)</th>
<th>No. 4 (12.5 mm)</th>
<th>No. 5 (9.5 mm)</th>
<th>SMA No. 4 (12.5 mm)</th>
<th>SMA No. 5 (9.5 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0-mm</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.5-mm</td>
<td>90 – 100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0-mm</td>
<td>90 max</td>
<td>90 – 100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.0-mm</td>
<td>___</td>
<td>90 max</td>
<td>90 – 100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.5-mm</td>
<td>___</td>
<td>___</td>
<td>90 max</td>
<td>90 – 100</td>
<td>100</td>
<td>90 – 97</td>
<td>100</td>
</tr>
<tr>
<td>9.5-mm</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>90 max</td>
<td>90 – 100</td>
<td>58 – 72</td>
<td>90 – 100</td>
</tr>
<tr>
<td>4.75-mm</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>90 max</td>
<td>25 – 35</td>
<td>35 – 45</td>
</tr>
<tr>
<td>75-µm</td>
<td>0 – 6.0</td>
<td>1.0 – 7.0</td>
<td>2.0 – 8.0</td>
<td>2.0 – 10.0</td>
<td>2.0 – 10.0</td>
<td>8.0 – 12.0</td>
<td>10.0 – 14.0</td>
</tr>
<tr>
<td>% MINIMUM VMA</td>
<td>11.0</td>
<td>12.0</td>
<td>13.0</td>
<td>14.0[1]</td>
<td>15.0[2]</td>
<td>16.0</td>
<td>17.0</td>
</tr>
</tbody>
</table>

[2] 15.5 for LT and MT mixes.
Increase Asphalt Content by Lowering Voids

Effective with December 2016 Letting

ADDITIONAL SPECIAL PROVISION 6
ASP 6 - Modifications to the standard specifications

Make the following revisions to the standard specifications:

460.2.1 General
Replace the entire text with the following effective with the December 2016 letting:

(1) Furnish a homogeneous mixture of coarse aggregate, fine aggregate, mineral filler if required, SMA stabilizer if required, recycled material if used, warm mix asphalt additive or process if used, and asphaltic material. Design mixtures conforming to table 460-1 and table 460-2 to 4.0% air voids to establish the aggregate structure.

(2) Determine the target JMF asphalt binder content for production from the mix design data corresponding to 3.0% air voids (97% Gmm) target at the design the number of gyrations (Ndes). Add liquid asphalt to achieve the required air voids at Ndes.
Determine Asphalt Content @ 4.0% Voids

<table>
<thead>
<tr>
<th>Mixture Type</th>
<th>Design Gyrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT</td>
<td>40</td>
</tr>
<tr>
<td>MT</td>
<td>75</td>
</tr>
<tr>
<td>HT</td>
<td>100</td>
</tr>
</tbody>
</table>

Use linear regression to determine asphalt content at 3.0% air voids.
Asphalt Content @ 4.0% & 3.0% Voids

Increase in $P_b$ goes directly to $P_{be} = \text{increased film thickness}$
Bottom Line - VMA is King

- Allows for increased effective asphalt volume (film thickness) while maintaining voids.

- Improves durability while maintaining rut resistance.
Balance the Mix Design

Not to be confused with “Balanced Mix Designs”

Smooth Quiet Ride
Skid Resistance

Strength/Stability
Rut Resistance
Shoving
Flushing Resistant

Durability
Crack Resistance
Raveling
Permeability

DON’T ATTACK ONE HALF AT THE EXPENSE OF THE OTHER HALF!!

Dave Johnson – Asphalt Institute, 2016
Calculating Effective Binder Content

What goes into the calculation?
Calculation of Effective Asphalt Content

\[ P_{be} = P_b - \left( \frac{P_{ba}}{100} \times (100 - P_b) \right) \]

\[ P_{ba} = \left( \frac{G_{se} - G_{sb}}{G_{se}} \right) \times G_b \]

\[ G_{se} = \left( \frac{100 - P_b}{100} \right) \times \left( \frac{P_b}{G_{mb}} \right) \]

\[ VMA = 100 - \left( \frac{G_{mb} \times (100 - P_b)}{G_{sb}} \right) \]

“Measurement of Effective Asphalt Content”
Canadian Technical Asphalt Association 2016
12.5-mm NMPS Mixture Properties

* $P_b$ 5.4%
* $G_{mb}$ 2.419
* $G_{mm}$ 2.520
* $G_{sb}$ 2.672
* $G_b$ 1.030
* VMA 14.4%
* Air Voids 4.0%
* $P_{ba}$ 1.05%

Which measured value has most impact on effective asphalt calculation?
Maximum Specific Gravity

Range 0.7%

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Aggregate Bulk Specific Gravity

Absorbed Asphalt Binder, %

Aggregate Bulk Specific Gravity

Range 1.3%
Aggregate Bulk Specific Gravity

* AASHTO D2S
  * Coarse Aggregate 0.038
  * Fine Aggregate 0.066

* 50:50 Blend
  * Say 0.052
## Effect of Incorrect $G_{sb} (\pm 0.052)$

<table>
<thead>
<tr>
<th>Property</th>
<th>2.620</th>
<th>2.672</th>
<th>2.724</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voids in Mineral Aggregate (VMA)</td>
<td>14.4%</td>
<td>14.4%</td>
<td>14.4%</td>
</tr>
<tr>
<td>Volume of Effective Binder ($V_{be}$)</td>
<td>10.4%</td>
<td>10.4%</td>
<td>10.4%</td>
</tr>
<tr>
<td>Calculated Absorbed Asphalt Content ($P_{ba}$)</td>
<td>1.80%</td>
<td>1.05%</td>
<td>0.48%</td>
</tr>
<tr>
<td>Effective Asphalt Content ($P_{be}$)</td>
<td>4.46%</td>
<td>4.41%</td>
<td>4.41%</td>
</tr>
<tr>
<td>Asphalt Binder Content ($P_{b}$)</td>
<td>6.15%</td>
<td>5.40%</td>
<td>4.87%</td>
</tr>
</tbody>
</table>

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## With Correct $G_{sb}$

<table>
<thead>
<tr>
<th>Property</th>
<th>2.672</th>
<th>2.672</th>
<th>2.672</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Binder Content ($P_b$)</td>
<td>6.15%</td>
<td>5.40%</td>
<td>4.87%</td>
</tr>
<tr>
<td>Voids in Mineral Aggregate (VMA)</td>
<td>16.0%</td>
<td>14.4%</td>
<td>13.2%</td>
</tr>
<tr>
<td>Volume of Effective Binder ($V_{be}$)</td>
<td>12.0</td>
<td>10.4</td>
<td>9.2</td>
</tr>
<tr>
<td>Calculated Absorbed Asphalt Content ($P_{ba}$)</td>
<td>1.07%</td>
<td>1.05%</td>
<td>1.05%</td>
</tr>
<tr>
<td>Effective Asphalt Content ($P_{be}$)</td>
<td>5.15%</td>
<td>4.41%</td>
<td>3.87%</td>
</tr>
</tbody>
</table>

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How do performance tests tie into empirical properties??
Rutting Test Failure

* Materials
  * Aggregate
    * Crushed faces
    * Fine Aggregate Angularity
    * Surface chemistry
  * Asphalt binder
    * High temperature PG
    * Low temperature PG
* Proportions
  * Air voids
    * Volume effective asphalt
  * Voids filled with Asphalt
Fatigue Cracking Test Failure

* Materials
  * Aggregate
    * Crushed faces
    * Fine Aggregate Angularity
  * Surface chemistry
  * Asphalt binder
    * High temperature PG
    * Low temperature PG
  * Proportions
    * Air voids
    * Volume effective asphalt
    * Voids filled with Asphalt
Low Temperature Cracking Test Failure

- **Materials**
  - Aggregate
    - Crushed faces
    - Fine Aggregate Angularity
    - Surface chemistry
  - Asphalt binder
    - High temperature PG
    - Low temperature PG
- **Proportions**
  - Air voids
  - Volume effective asphalt
  - Voids filled with Asphalt

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Moisture Damage Test Failure

- **Materials**
  - Aggregate
    - Crushed faces
    - Fine Aggregate Angularity
  - Surface chemistry
  - Asphalt binder
    - High temperature PG
    - Low temperature PG

- **Proportions**
  - Air voids
  - Volume effective asphalt
  - Voids filled with Asphalt

Gerry Huber – Heritage Research Group, 2017
Aging Relationship to Empirical Properties

* **Materials**
  * Aggregate
    * Crushed faces
    * Fine Aggregate Angularity
    * Surface chemistry
  * Asphalt binder
    * High temperature PG
    * Low temperature PG

* **Proportions**
  * Air voids
  * Volume effective asphalt
  * Voids filled with Asphalt
Bottom Line - VMA is King

- Allows for increased effective asphalt volume (film thickness) while maintaining voids.
- Improves durability while maintaining rut resistance.
Volumetrics

- Relatively inexpensive testing and can be quickly determined.
- Has been used to predict performance in past.
- Will likely still play a role in the age of performance testing (surrogate properties).
Thank you!!

Questions?