The Use of Volume Increase Ratio on Dense-Graded Mixtures

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Introduction

For many years, average film thickness (AFT) has been proposed for use in determining the minimum asphalt content required to produce a durable hot-mixed asphalt concrete (HMAC) [1, 2, 3]. The inherent problem in measuring film thickness is determining accurate surface area factors for aggregates of widely varying shapes and specific gravities [2, 4, 5].

In 2002 this author et al. developed an alternate means of measuring asphalt cement coating for use on open-graded mixtures [6]. The method involved comparing the volume of effective asphalt to the bulk volume of the aggregate. This simple ratio was called the Volume Increase Ratio (VIR). VIR was shown to be a better means than AFT for characterizing open-graded mix properties during mixture production.

Recent escalations in the price of asphalt cement has triggered the need to better characterize film coatings on dense-graded mixtures with the goal of producing least cost mixtures while still maintaining the desired durability characteristics essential to long term performance.

This paper covers the equations that relate VIR to established volumetric computations for dense-graded mixtures. Comparisons are made between VIR and AFT using existing databases from MnROAD and the Iowa DOT. VIR is correlated with performance data from MnROAD.

Background

The volumetric properties of dense-grade mixtures have long been measured both during the development of the job mix formula (JMF) and during quality control (QC) and quality assurance (QA) activities. It has generally been surmised that well performing HMAC mixtures must have the correct volumetric properties in order to provide long lasting performance [2, 7].

In particular, HMAC mixtures must have the right combination of the volume of effective asphalt cement ($V_{be}$), the volume of air voids ($V_a$) and the volume of voids in mineral aggregate (VMA). These three basic volumetric properties of compacted mixtures are related as follows:

$$VMA = V_{be} + V_a$$  \(1\)

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Owner/agencies generally specify values for VMA and \( V_a \) (e.g. - AASHTO M323) thereby indirectly controlling the amount of effective asphalt (\( V_{be} \)) in the mixture. This paper looks at an alternate means of specifying \( V_{be} \) and \( V_a \) and thereby indirectly controlling the VMA.

**Volume Increase Ratio**

A brief review of VIR is presented here based on the original work in Oregon on open-graded mixtures [6]:

A different way to look at film thickness is to recognize that as asphalt coating increases, so should the volume per unit mass of the mixture. If this volume change can be accurately quantified, then a less subjective measure of film thickness may be obtained.

Such a measure can be calculated using currently established test methods; the specific gravity test for bituminous materials (AASHTO T228), the aggregate specific gravity tests (AASHTO T84 & T85), and the “Rice” test (AASHTO T209). The aggregate specific gravity tests give us the aggregate contribution to mixture volume and the Rice test gives us the mixture volume. The difference in the two will be the “non-absorbed” asphalt cement contribution to mixture volume.

The relationship between the specific gravity of the mixture and the specific gravities of the constituents of the mix (effective aggregate and asphalt liquid) is given as follows [8]:

\[
\frac{100}{G_{mm}} = \frac{P_s}{G_{se}} + \frac{P_b}{G_b}
\] (2)

\( P_s \) is the percentage of the mix by mass that is aggregate. The first term on the right hand side of Equation 2 represents the effective aggregate contribution to mixture specific gravity and the second term represents the liquid asphalt contribution. However, the desired quantity is the “bulk” volume of aggregate and the “non-absorbed” volume of asphalt.

The liquid asphalt contribution is a combination of “absorbed” and “non-absorbed” materials. Only the “non-absorbed” asphalt will contribute to and increase in film thickness. The relationship between “absorbed” and “non-absorbed” asphalt is as follows [9]:

\[
\frac{P_{ba}}{100} = \frac{P_b}{P_s} - \frac{P_{be}}{P_s}
\] (3)
P_{ba} is the percent by mass of asphalt binder that is absorbed into the aggregate and is unavailable to bind aggregate together. The relationship between “absorbed” asphalt and aggregate specific gravity is known and is as follows [10]:

\[
\frac{P_{ba}}{100} = \frac{G_b}{G_{sb}} - \frac{G_b}{G_{se}}
\]  

(4)

Equating Equations 3 and 4 results in the following:

\[
\frac{P_b}{G_b} = \frac{P_{be}}{G_b} + \frac{P_s}{G_{sb}} - \frac{P_s}{G_{se}}
\]

(5)

The first term on the right hand side of Equation 5 represents the contribution of the “non-absorbed” asphalt to the liquid asphalt portion of the mixture specific gravity. The second and third terms represent the “absorbed” asphalt contributions.

Substituting Equation 5 into Equation 2 we obtain the following:

\[
\frac{100}{G_{mm}} = \frac{P_s}{G_{sb}} + \frac{P_{be}}{G_b}
\]  

(6)

Equation 6 now establishes the desired relationship between “bulk” volume of aggregate per unit mass and the volume of “non-absorbed” asphalt per unit mass. The Volume Increase Ratio (VIR) of these two terms represents the increase in volume of the mixture due to the “non-absorbed” asphalt coating.

\[
Volume\ Increase\ Ratio = \frac{P_{be}}{P_s} \frac{G_b}{G_{sb}}
\]  

(7)

When multiplied by 100, the VIR becomes a percentage increase (VIR%) with the “bulk” aggregate volume as the basis.

This simple ratio gives a dimensionless measure of how the mixture volume is changing as the asphalt liquid is added to the uncoated aggregate. The measure is determined from known laboratory measurements and not from “assumed” surface area factors. It does not require gradation inputs and therefore is insensitive to minor swings in the passing No. 200.
The Relationship Between VIR and VMA

The relationship between VIR% and VMA is may now be established. VMA is defined as follows [11]:

\[
VMA = 100 - \frac{G_{mb} P_s}{G_{sb}}
\]  

(8)

The bulk specific gravity of compacted mixture \((G_{mb})\) is defined as follows [12]:

\[
G_{mb} = \left(\frac{100 - V_a}{100}\right) G_{mm}
\]  

(9)

The Rice specific gravity of mixture \((G_{mm})\) was defined above in Equation 6 as:

\[
G_{mm} = \frac{100}{\frac{P_{be}}{G_b} + \frac{P_s}{G_{sb}}}
\]  

(10)

Substituting Equation 10 into Equation 9 defines \(G_{mb}\) as the following:

\[
G_{mb} = \left(\frac{100 - V_a}{100}\right) \frac{P_{be}}{G_b} + \frac{P_s}{G_{sb}}
\]  

(11)

As a percentage, Equation 7 for VIR can be written as follows:

\[
\frac{P_{be}}{G_b} = \left(\frac{P_s}{G_{sb}}\right) \frac{VIR\%}{100}
\]  

(12)

Substituting Equation 12 into Equation 11 and Equation 11 into Equation 8 produces the relationship between VIR and VMA as follows:

\[
VMA = 100 - \frac{\left(\frac{100 - V_a}{100} + 1\right)}{\left[\frac{VIR\%}{100} + 1\right]}
\]  

(13)
Equation 13 allows an owner/agency to specify the desired air voids and a minimum volume on effective asphalt and thereby indirectly specifying a minimum VMA. Table 1 provides a range of VMA values for given air voids and VIR%.

### Table 1 Minimum VMA for Given Va and VIR% Criteria

<table>
<thead>
<tr>
<th>Va</th>
<th>8.0</th>
<th>9.0</th>
<th>10.0</th>
<th>11.0</th>
<th>12.0</th>
<th>13.0</th>
<th>14.0</th>
<th>15.0</th>
<th>16.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>10.19</td>
<td>11.01</td>
<td>11.82</td>
<td>12.61</td>
<td>13.39</td>
<td>14.16</td>
<td>14.91</td>
<td>15.65</td>
<td>16.38</td>
</tr>
<tr>
<td>3.5</td>
<td>10.65</td>
<td>11.47</td>
<td>12.27</td>
<td>13.06</td>
<td>13.84</td>
<td>14.60</td>
<td>15.35</td>
<td>16.09</td>
<td>16.81</td>
</tr>
<tr>
<td>4.0</td>
<td>11.11</td>
<td>11.93</td>
<td>12.73</td>
<td>13.51</td>
<td>14.29</td>
<td>15.04</td>
<td>15.79</td>
<td>16.52</td>
<td>17.24</td>
</tr>
<tr>
<td>4.5</td>
<td>11.57</td>
<td>12.39</td>
<td>13.18</td>
<td>13.96</td>
<td>14.73</td>
<td>15.49</td>
<td>16.23</td>
<td>16.96</td>
<td>17.67</td>
</tr>
<tr>
<td>5.0</td>
<td>12.04</td>
<td>12.84</td>
<td>13.64</td>
<td>14.41</td>
<td>15.18</td>
<td>15.93</td>
<td>16.67</td>
<td>17.39</td>
<td>18.10</td>
</tr>
</tbody>
</table>

Similar to VMA the VIR% required for any given mix will be a function of the nominal maximum size of the aggregate in the mixture. A 3/8” mixture will require at a higher minimum VIR% than a 1” mixture.

AASHTO specification M 323 lists minimum VMA requirements at 4.0% air voids and recommends a maximum of + 2.0% above the minimum. Table 2 shows the equivalent range of VIR% for different nominal maximum mixtures.

### Table 2 Equivalent VIR% Range to Meet AASHTO M 323 for $V_a= 4.0$

<table>
<thead>
<tr>
<th>Nominal Maximum Aggregate Size, in.</th>
<th>VIR%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1½”</td>
<td>7.9 – 10.3</td>
</tr>
<tr>
<td>1”</td>
<td>9.1 – 11.6</td>
</tr>
<tr>
<td>3/4”</td>
<td>10.3 – 12.9</td>
</tr>
<tr>
<td>1/2”</td>
<td>11.6 – 14.3</td>
</tr>
<tr>
<td>3/8”</td>
<td>12.9 – 15.7</td>
</tr>
<tr>
<td>No. 4</td>
<td>14.3 – 17.1</td>
</tr>
</tbody>
</table>

**VIR% Versus Voids Filled with Asphalt (VFA) for Field Control**

AASHTO M323 also specifies VFA as a measure of non-absorbed asphalt volume relative to the space between the aggregate, VMA. This concept has some value when the air voids are fixed (e.g. - at 4.0% as in mix design). Generally, in mix design, placing limits on VFA indirectly sets an upper limit on VMA.

However, as a field management tool, VFA becomes more difficult to interpret as both air voids and VMA vary from the design target. Mixture having the same volume of asphalt as the mix design may fall outside the criteria for VFA because of the shifts in air voids and VMA.
If adjustments are made to asphalt cement content in reaction to a VFA issue when the proper response is a gradation change to fix air voids or VMA, then mix quality will most likely be negatively affected. Agencies that hold field produced mixtures to the AASHTO M323 VFA criteria may inadvertently be compromising mixture quality.

VIR% is independent of air voids and VMA and therefore, it provides a more rational field tool for managing mix. VIR% should be the basis for managing the asphalt cement content in the field. For a plant that is operating consistently, bringing the VIR% to the JMF target is a relatively easy plant operator adjustment. This places field volumetric management focus on the expensive constituent which is the asphalt cement.

If the VIR% is being controlled at the JMF target and air void or VMA issues arise, then the primary fix is limited to making appropriate gradation changes.

**Dust-to-Binder Ratio Criteria**

In addition to V_a, VMA, and VFA the AASHTO specification for Superpave Volumetric Mix Design (AASHTO M 323) places limits on the amount of material (by mass) passing the No. 200 sieve relative to the amount of effective asphalt, P_{be}. The shortcoming of this concept is that P_{be} is calculated on a total mass of mix basis and does not account for aggregates of varying specific gravity.

A more fundamental parameter would be to compare the volume of passing No. 200 to the volume of effective asphalt. It can be shown (Appendix A) that VIR% can be written as follow:

\[
VIR\% = \frac{V_{be}}{V_{sb}} \times 100
\]  

(14)

And,

\[
%\text{Pass No.200} = \frac{\text{Mass } P_{200}}{\text{Mass Total Agg.}} \times 100
\]  

(15)

Define the parameter Volume of Dust to Volume of Effective Binder:

\[
\frac{V_{200}}{V_{be}} = \frac{\text{Pass No.200}}{VIR\%}
\]  

(16)
Substitute Eqs. 14 and 15 into Eq. 16:

\[
V_{200 \text{ to } V_{be}} = \frac{\frac{\text{Mass } P200}{\text{MassTotal Agg.}} \times 100}{\frac{V_{be}}{V_{sb}} \times 100}
\]

(17)

Rearranging and canceling common terms Eq. 17 can be written as:

\[
V_{200 \text{ to } V_{be}} = \frac{\frac{\text{Mass } P200}{\text{MassTotal Agg.}} \times V_{sb}}{V_{be}}
\]

(18)

The numerator in Eq. 18 is nothing more than the volume of P200.

\[
\frac{\text{Mass } P200}{\text{MassTotal Agg.}} \times V_{sb} = V_{P200}
\]

(19)

Substituting Eq. 19 into Eq. 18:

\[
V_{200 \text{ to } V_{be}} = \frac{V_{P200}}{V_{be}}
\]

(20)

Eq 20 demonstrates that Eq 16 is simply a ratio of volumes.

Table 3 below is actual mix design data from Oregon DOT contracts for 2008. It can be seen that aggregates of significantly different aggregate specific gravities will give similar P_{be} results but have different non-absorbed asphalt volumes.
The minimum and maximum specification P200 represent the theoretical high and low values for passing No. 200 that would meet the AASHTO M 323 specifications for Dust to Binder Ratio for coarse graded mixes (0.8 – 1.6). The last two columns represent the Dust to Binder Ratios for a fixed passing No. 200 of 6.0%.

Table 3 Comparison of Dust to Binder Using $P_{be}$ and VIR% (ODOT 2008)

<table>
<thead>
<tr>
<th>JMF</th>
<th>JMF $G_{sb}$</th>
<th>JMF $P_{be}$</th>
<th>JMF VIR%</th>
<th>Minimum Spec. $P_{200}$</th>
<th>Maximum Spec. $P_{200}$</th>
<th>Dust to Binder $P_{200} = 6.0%$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$P_{be}$</td>
</tr>
<tr>
<td>1</td>
<td>2.538</td>
<td>5.20</td>
<td>13.70</td>
<td>4.16</td>
<td>8.32</td>
<td>1.15</td>
</tr>
<tr>
<td>2</td>
<td>2.910</td>
<td>4.56</td>
<td>13.55</td>
<td>3.65</td>
<td>7.30</td>
<td>1.32</td>
</tr>
<tr>
<td>3</td>
<td>2.604</td>
<td>5.06</td>
<td>13.54</td>
<td>4.05</td>
<td>8.10</td>
<td>1.19</td>
</tr>
<tr>
<td>4</td>
<td>2.543</td>
<td>4.54</td>
<td>11.85</td>
<td>3.63</td>
<td>7.26</td>
<td>1.32</td>
</tr>
</tbody>
</table>

JMF samples 1 and 2 have significantly different JMF $P_{be}$’s and result in different conventional dust to binder ratios at a given 6.0% P200. However, the JMF $P_{be}$’s are misleading because of the large difference in aggregate specific gravity. When compared on a volume basis (VIR%) the dust-to-binder ratios are reasonably close.

Conversely JMF samples 2 and 4 have very close JMF $P_{be}$ values and result in identical conventional dust-to-binder ratios of 1.32 at a given 6.0% P200. In reality, the two samples have significantly different volumes of asphalt (JMF VIR%) and when compared on a volume basis the dust-to-binder ratios show a significant difference.

Finally, JMF samples 2 and 3 have virtually the same volume of asphalt (JMF VIR%) though the JMF $P_{be}$’s are 0.5% different. The dust-to-binder ratios computed on a volume basis are identical for these two samples. The current AASHTO specifications however, would allow a different range of P200 values for JMF 2 versus JMF 3.

JMF sample 3 represents a more typical aggregate specific gravity of 2.604. Applying the minimum and maximum specification P200 values from Table 3 for JMF Sample 3, a recommended range for dust-to-binder on a volume basis (VIR%) for coarse gradations would be 0.30 to 0.60.
Empirical Relationship between VIR% and AFT Using MnROAD Data

Li et.al. [13] examined whether film thickness had a rational relationship with pavement performance by using field performance data from MnROAD. MnROAD is an instrumented pavement test track that includes a section of I-94 carrying interstate traffic.

Li et.al. concluded there was a relationship between film thickness and rutting, but further work would be needed on the other distress types. This paper uses the same data set from MnROAD to determine if such a relationship with pavement performance also exists for VIR%. This paper also examines the relationship between VIR% and average film thickness (AFT).

Figure 1 shows the comparison between measured VIR% and calculated AFT for 173 QC samples for cells 14 to 23 from the MnROAD 10-year HMA mainline sections. The mixture was a 1/2" nominal maximum dense-graded using two grades of asphalt and four different design compaction levels (See Table 3). The data was compared with a simple linear least squares regression with the following results:

\[
y = 1.0934x + 4.452
\]

\[R^2 = 0.529\]

Figure 1  AFT vs. VIR% (Based on MnROAD Cells 14 – 23)
From the linear regression analysis in figure 1 an equation relating VIR% and AFT can be written for the MnROAD dataset.

\[ \text{VIR}\% = 1.0934\text{AFT} + 4.452 \]  \hspace{1cm} (14)

\[ r^2 = 0.529 \]

The $r^2$ was not particularly good between VIR% and AFT, however, two caveats must be noted on the data set. First asphalt cement contents were only reported to 0.1% which reduces the precision of the VIR calculations. Second the Nos. 8, 16, 30, 50, and 100 sieves are not reported as part of the original QC testing and were added to the data set by interpolation. These sieves have the largest surface area factors and minor errors in estimating their value will impact the precision of the AFT calculation. It should also be noted that very few data points fell below a VIR% of 12% for these 1/2" mixtures.

Table 2 shows the results of applying Equation 14 to a range of average film thicknesses:

**Table 2** VIR% for a Given AFT (Based on MnROAD Cells 14 – 23)

<table>
<thead>
<tr>
<th>AFT (microns)</th>
<th>6.00</th>
<th>6.50</th>
<th>7.00</th>
<th>7.50</th>
<th>8.00</th>
<th>8.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIR (%)</td>
<td>11.01</td>
<td>11.56</td>
<td>12.11</td>
<td>12.65</td>
<td>13.20</td>
<td>13.75</td>
</tr>
</tbody>
</table>

**Volume Increase Ratio and In-Place Performance of Mixtures**

Table 3 shows the MnROAD 5-year mainline performance data (cells 1-4) and 10-year HMA mainline section performance data (cells 14 – 23). VIR% was calculated based on the QC measurements made for each cell and compared with the field performance data. A similar comparison between AFT and the performance data was made and reported elsewhere [13].

The primary performance measurements were International Roughness Index (IRI), rutting, transverse cracking, transverse cupping, and top down cracking. Two binders were used; 120/150 (PG 58-28) and AC-20 (PG 64-22) and the number of lifts constructed varied from 3 to 5 lifts. In addition, four design methods were used for developing the JMF’s; 100 gyration Superpave™, 35, 50, and 75 blow Marshall. It is important to note that within any given cell the same mix and grade of asphalt was used for all lifts.

Because the majority of the distress either occurs on the top lift or is initiated from the top down, the data was evaluated under the following separate scenarios:

- Top Lift only
- Average of Top Two Lifts
- Average of Top Three Lifts
- Average of All Lifts
This allowed inclusion of all cells in the analysis regardless of numbers of lifts constructed.

Table 3 MnROAD 10-year HMA Mainline Section Performance Data

<table>
<thead>
<tr>
<th>Cell</th>
<th>Section</th>
<th>IRI (m/km)</th>
<th>Rutting (in)</th>
<th>Transv. Crack (ln. ft)</th>
<th>Transv. Cupping (in)</th>
<th>Top-Down Crack (ln. ft)</th>
<th>No. of Lifts</th>
<th>Binder Type</th>
<th>Design Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5-Year Mainline</td>
<td>1.40</td>
<td>0.23</td>
<td>367</td>
<td>0.33</td>
<td>805</td>
<td>3</td>
<td>120/150</td>
<td>M-75</td>
</tr>
<tr>
<td>2</td>
<td>2.02</td>
<td>0.32</td>
<td>500</td>
<td>0.31</td>
<td>856</td>
<td>3</td>
<td>120/150</td>
<td>M-35</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.64</td>
<td>0.22</td>
<td>386</td>
<td>0.34</td>
<td>901</td>
<td>3</td>
<td>120/150</td>
<td>M-50</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.79</td>
<td>0.34</td>
<td>800</td>
<td>0.56</td>
<td>880</td>
<td>4</td>
<td>120/150</td>
<td>G-100</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>5-Year Mainline</td>
<td>2.16</td>
<td>0.28</td>
<td>926</td>
<td>0.46</td>
<td>126</td>
<td>5</td>
<td>120/150</td>
<td>M-75</td>
</tr>
<tr>
<td>20</td>
<td>1.13</td>
<td>0.57</td>
<td>292</td>
<td>0.21</td>
<td>17</td>
<td>4</td>
<td>120/150</td>
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</tr>
<tr>
<td>21</td>
<td>1.02</td>
<td>0.40</td>
<td>462</td>
<td>0.11</td>
<td>6</td>
<td>4</td>
<td>120/150</td>
<td>M-50</td>
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<tr>
<td>22</td>
<td>1.60</td>
<td>0.22</td>
<td>419</td>
<td>0.34</td>
<td>43</td>
<td>4</td>
<td>120/150</td>
<td>M-75</td>
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<tr>
<td>23</td>
<td>1.61</td>
<td>0.53</td>
<td>369</td>
<td>0.23</td>
<td>35</td>
<td>5</td>
<td>120/150</td>
<td>M-50</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>10-Year Mainline</td>
<td>2.26</td>
<td>0.24</td>
<td>1442</td>
<td>0.70</td>
<td>341</td>
<td>5</td>
<td>AC-20</td>
<td>M-75</td>
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<td>16</td>
<td>2.75</td>
<td>0.18</td>
<td>1335</td>
<td>0.57</td>
<td>21</td>
<td>4</td>
<td>AC-20</td>
<td>G-100</td>
<td></td>
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<tr>
<td>17</td>
<td>2.48</td>
<td>0.20</td>
<td>1024</td>
<td>0.32</td>
<td>530</td>
<td>4</td>
<td>AC-20</td>
<td>M-75</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>2.76</td>
<td>0.22</td>
<td>660</td>
<td>0.37</td>
<td>968</td>
<td>4</td>
<td>AC-20</td>
<td>M-50</td>
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<tr>
<td>19</td>
<td>3.02</td>
<td>0.32</td>
<td>1169</td>
<td>0.50</td>
<td>893</td>
<td>4</td>
<td>AC-20</td>
<td>M-35</td>
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</tr>
</tbody>
</table>
International Roughness Index (IRI) vs. AFT and VIR%

Figure 2 shows the comparison between IRI and AFT or VIR% based on the average of all cells. While VIR showed a slightly better $r^2$, there does not appear to be a strong relationship between either parameter and IRI.

\[
y = -0.0779x + 2.6842 \\
R^2 = 0.0062
\]

\[
y = -0.0919x + 3.2864 \\
R^2 = 0.0216
\]

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Design Method</th>
<th>Top Lift Only</th>
<th>Avg Top 2 Lifts</th>
<th>Avg Top 3 Lifts</th>
<th>Avg All Lifts</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>AFT</td>
<td>VIR%</td>
<td>AFT</td>
<td>VIR%</td>
</tr>
<tr>
<td>All</td>
<td>All</td>
<td>0.0913</td>
<td>0.0264</td>
<td>0.084</td>
<td>0.0332</td>
</tr>
<tr>
<td>120/150</td>
<td>All</td>
<td>0.3944</td>
<td>0.2563</td>
<td>0.4642</td>
<td>0.2908</td>
</tr>
<tr>
<td>AC-20</td>
<td>All</td>
<td>0.4650</td>
<td>0.4201</td>
<td>0.5178</td>
<td>0.4029</td>
</tr>
<tr>
<td>All</td>
<td>G-100</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>All</td>
<td>M-35</td>
<td>0.0206</td>
<td>0.0213</td>
<td>0.0025</td>
<td>0.0010</td>
</tr>
<tr>
<td>All</td>
<td>M-50</td>
<td>0.1257</td>
<td>0.0218</td>
<td>0.0968</td>
<td>0.0028</td>
</tr>
<tr>
<td>All</td>
<td>M-75</td>
<td>0.7387</td>
<td>0.4594</td>
<td>0.4747</td>
<td>0.7066</td>
</tr>
</tbody>
</table>

Table 4 shows the $r^2$ values of the linear least squares fit for comparisons between IRI and AFT or VIR% for the various other scenarios of binder type and design method.

The 75-blow Marshall designs showed the strongest $r^2$ values, however, it may reflect coincidental data in a relatively small data set. Aside from that, the best fit occurred when the data was analyzed by binder type.
Rutting vs. AFT and VIR%

Figure 2 shows the comparison between rutting and AFT or VIR% based on the average of all cells. Again VIR shows a slightly higher r^2 compared to AFT.

![Figure 2 Rutting vs. AFT and VIR% (All Cells)](image)

Table 5 shows the r^2 values of the linear least squares fit for comparisons between rutting and AFT or VIR% for the various combinations of binder type and design method.

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Design Method</th>
<th>Top Lift Only</th>
<th>Avg Top 2 Lifts</th>
<th>Avg Top 3 Lifts</th>
<th>Avg All Lifts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AFT</td>
<td>VIR%</td>
<td>AFT</td>
<td>VIR%</td>
</tr>
<tr>
<td>All</td>
<td>All</td>
<td>0.1591</td>
<td>0.4131</td>
<td>0.2346</td>
<td>0.3880</td>
</tr>
<tr>
<td>120/150</td>
<td>All</td>
<td>0.4221</td>
<td>0.5989</td>
<td>0.4890</td>
<td>0.5435</td>
</tr>
<tr>
<td>AC-20</td>
<td>All</td>
<td>0.5411</td>
<td>0.6814</td>
<td>0.6470</td>
<td>0.7241</td>
</tr>
<tr>
<td>All</td>
<td>G-100</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>All</td>
<td>M-35</td>
<td>0.4161</td>
<td>0.4186</td>
<td>0.2358</td>
<td>0.2512</td>
</tr>
<tr>
<td>All</td>
<td>M-50</td>
<td>0.0010</td>
<td>0.0843</td>
<td>0.0008</td>
<td>0.0856</td>
</tr>
<tr>
<td>All</td>
<td>M-75</td>
<td>0.00145</td>
<td>0.0032</td>
<td>0.0222</td>
<td>0.0469</td>
</tr>
</tbody>
</table>

For the most part, VIR showed higher r^2 values than AFT for the majority of scenarios tested under rutting. As might be expected, the best fit occurred when the data was analyzed by binder type.
Transverse Cracking vs. AFT and VIR%

Figure 3 shows the comparison between transverse cracking and AFT or VIR% based on the average of all cells and all lifts. Again, while VIR showed a slightly better $r^2$, there does not appear to be a strong relationship between either parameter and transverse cracking.

\[
y = -34.149x + 1004.9\quad R^2 = 0.0034
\]

\[
y = -75.339x + 1741.7\quad R^2 = 0.0408
\]

Figure 3  Transverse Cracking vs. AFT and VIR% (All Cells)

Table 6 shows the $r^2$ values of the linear least squares fit for comparisons between transverse cracking and AFT or VIR% for the various other scenarios of binder type and design method.

Table 6  Summary of $r^2$ values for Transverse Cracking vs. AFT and VIR%

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Design Method</th>
<th>Top Lift Only</th>
<th>Avg Top 2 Lifts</th>
<th>Avg Top 3 Lifts</th>
<th>Avg All Lifts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AFT</td>
<td>VIR%</td>
<td>AFT</td>
<td>VIR%</td>
</tr>
<tr>
<td>All</td>
<td>All</td>
<td>0.0001</td>
<td>0.0854</td>
<td>0.0168</td>
<td>0.0890</td>
</tr>
<tr>
<td>120/150</td>
<td>All</td>
<td>0.1181</td>
<td>0.2027</td>
<td>0.2125</td>
<td>0.2123</td>
</tr>
<tr>
<td>AC-20</td>
<td>All</td>
<td>0.3700</td>
<td>0.2367</td>
<td>0.2615</td>
<td>0.2080</td>
</tr>
<tr>
<td>All</td>
<td>G-100</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>All</td>
<td>M-35</td>
<td>0.0137</td>
<td>0.0131</td>
<td>0.0937</td>
<td>0.0836</td>
</tr>
<tr>
<td>All</td>
<td>M-50</td>
<td>0.7095</td>
<td>0.3695</td>
<td>0.6166</td>
<td>0.3226</td>
</tr>
<tr>
<td>All</td>
<td>M-75</td>
<td>0.3197</td>
<td>0.4286</td>
<td>0.1632</td>
<td>0.7476</td>
</tr>
</tbody>
</table>
For the most part, VIR showed higher $r^2$ values than AFT for the majority of scenarios tested under transverse cracking. The 75-blow Marshall designs showed the strongest $r^2$ values, however, it again may reflect coincidental data in a relatively small data set.

Transverse Cupping vs. AFT and VIR%

Figure 4 shows the comparison between transverse cupping and AFT or VIR% based on the average of all cells and all lifts. Again, while VIR showed a slightly better $r^2$, there does not appear to be a strong relationship with either parameter.

Table 7 shows the $r^2$ values of the linear least squares fit for comparisons between transverse cupping and AFT or VIR% for the various other scenarios of binder type and design method.
For the most part, VIR showed higher $r^2$ values than AFT for the majority of scenarios tested under transverse cupping.

**Top Down Cracking vs. AFT and VIR%**

Figure 5 shows the comparison between top down cracking and AFT or VIR% based on the average of all cells. This time AFT showed a slightly better $r^2$ than VIR, however, there does not appear to be a strong relationship with either parameter.

![Figure 5](image-url)

**Figure 5** Top Down Cracking vs. AFT and VIR% (All Cells)

Table 8 shows the $r^2$ values of the linear least squares fit for comparisons between top down cracking and AFT or VIR% for the various combinations of binder type and design method.

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Design Method</th>
<th>Top Lift Only</th>
<th>Avg Top 2 Lifts</th>
<th>Avg Top 3 Lifts</th>
<th>Avg All Lifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>All</td>
<td>0.0219</td>
<td>0.0069</td>
<td>0.0047</td>
<td>0.0323</td>
</tr>
<tr>
<td>120/150</td>
<td>All</td>
<td>0.4426</td>
<td>0.4182</td>
<td>0.4194</td>
<td>0.5700</td>
</tr>
<tr>
<td>AC-20</td>
<td>All</td>
<td>0.8887</td>
<td>0.8193</td>
<td>0.8234</td>
<td>0.8926</td>
</tr>
<tr>
<td>All</td>
<td>G-100</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>All</td>
<td>M-35</td>
<td>0.3795</td>
<td>0.2049</td>
<td>0.2195</td>
<td>0.2519</td>
</tr>
<tr>
<td>All</td>
<td>M-50</td>
<td>0.0008</td>
<td>0.1802</td>
<td>0.1802</td>
<td>0.2235</td>
</tr>
<tr>
<td>All</td>
<td>M-75</td>
<td>0.2364</td>
<td>0.4465</td>
<td>0.3534</td>
<td>0.4650</td>
</tr>
</tbody>
</table>
For the most part, AFT showed higher $r^2$ values than VIR for the majority of scenarios tested under top down cracking. Again, the best fit occurred when the data was analyzed by binder type.

**Comparison of VIR% and AFT Using Iowa DOT Data**

The Iowa DOT has monitored average film thickness in their designs for a number of years[14]. This large body of data includes all the required sieves for calculation of AFT and does not rely on interpolation of %Passing as was the case with MnROAD.

Figure 6 shows the comparison between AFT and VIR% for mix designs produced for years 2004 to 2006. The data includes 3 - 1” mixtures, 69 - 3/4” mixtures, 190 - 1/2” Mixtures and 4 - 3/8” mixtures for a total of 266 mixtures.

![Figure 6 AFT vs. VIR% Iowa DOT Mix Designs (2004 to 2006)](image)

The MnROAD data in Figure 1 showed a much stronger correlation between AFT and VIR%, however, it must be noted that the MnROAD data reflects QC results from a single material source and reflecting only 14 cells (JMF’s). The Iowa DOT data reflects 266 individual JMF’s from a broad cross-section of statewide aggregate sources.

The low $r^2$ value in Figure 6 reflects the sensitivity of the average film thickness calculation to finer sieves (No. 50 and smaller). This sensitivity becomes more obvious when the data is subdivided by nominal maximum aggregates size. In figures 7 to 9 it will be shown that as the nominal maximum aggregate size increases a stronger correlation emerges between AFT and VIR%.
The AFT calculation is dependent on two inputs; aggregate surface area and volume of non-absorbed asphalt. If the amount of material passing the finer sieves becomes large enough, then it will be shown that the AFT calculation becomes dominated by surface area and somewhat independent of asphalt volume.

Figure 7 shows the relationship between average film thickness and VIR for 3/8” mixtures. Unfortunately, the data set is quite small.

![AFT vs. VIR% 3/8" Mixtures](image)

The limited data however, does show the inadequacy of average film thickness for very fine mixtures. Keep in mind VIR% is an actual measurement of non-absorbed asphalt volume. If the data is to be believed, the negative slope to the regression curve would say that film thickness actually increases as asphalt volume decreases. This is not realistic and in fact the AFT calculation is so dominated by surface area it has become essentially independent of asphalt volume.
Figure 8 shows the average film thickness and VIR% for 1/2" mixtures.

Figure 8  AFT vs. VIR% Iowa DOT Mix Designs (1/2” mixtures)

Again, there does not appear to be a distinctive linear relationship between AFT and VIR% for 1/2" mixtures. The scatter in the data for 1/2" mixes is still being driven by the large surface area factors for the finer sieves in the AFT calculation. The material passing the No. 50, No. 100 and No. 200 sieves dominate the surface area in these mixes.

Any horizontal line in Figure 8 represents mixtures with the same volume of effective asphalt as a percent of aggregate volume. As an example looking horizontally along the VIR% = 12.00 line, it shows that mixtures with the same volume of effective asphalt had widely varying average film thickness values of approximately 8.00 to 14.00 microns.

Conversely, any vertical line in Figure 8 represents the same average film thickness. As an example looking vertically at mixes in the 12.00 micron average film thickness range the data spans mixtures with volumes of effective asphalt ranging from 12 to 16%. This means that one 1/2" mixture can have approximately one third more asphalt by volume of effective asphalt as another 1/2" mixture and yet they both have the same average film thickness.

The data in Figure 8 does show a positive slope to the linear regression curve which does begin to match reality in that an increase in non-absorbed asphalt volume would see a corresponding increase in average film thickness. The $r^2$ value is too low to say there is a strong relationship between asphalt volume and film thickness. This again demonstrates that for 1/2" mixtures the AFT calculation is still being overwhelmed by the surface area contribution to the calculation.
Figure 9 shows the comparison of AFT and VIR% for 3/4” mixtures.

AFT vs. VIR% 3/4” Mixes

![Graph showing the comparison of AFT and VIR% for 3/4” mixtures. The equation y = 0.6597x + 5.8326 with R² = 0.4895 is displayed.](image)

**Figure 9  AFT vs. VIR% Iowa DOT Mix Designs (3/4” mixtures)**

A clearer linear relationship between AFT and VIR% emerges in figure 9 for the 3/4” mixtures versus the previous data for 1/2” mixtures. In addition, the slope of the linear regression curve is steeper for the 3/4” mixtures versus the 1/2” mixtures indicating a stronger contribution of asphalt volume to the average film thickness calculation.

The r² value for the data in figure 9 does show a significant improvement over the previous data set for the 1/2” mixtures, however, it is not a particularly strong fit. There is still significant scatter in the data. Again looking at a typical horizontal line (e.g. VIR% = 12.00) through the data, the AFT can vary from approximately 8 to 11.5 microns for the same volume of non-absorbed asphalt. This again represents a 30 to 40% swings in AFT values for the same volume of asphalt.

That magnitude of swing in AFT makes it a much less reliable tool for managing HMAC mixtures than VIR%.
Figure 10 shows the comparison of AFT and VIR% for 1"mixtures.

**Figure 10  AFT vs. VIR% Iowa DOT Mix Designs (1” mixtures)**

The data in Figure 10 is highly correlated ($r^2=0.984$), but too small of a data set (3 JMFs) to draw many conclusions.

One general observation that can be made is that overall average film thickness and VIR% dropped as mix size got larger (i.e. – the 3/8” mixes clustered around 15% VIR, the 1/2” mixes clustered around 13% VIR, the 3/4” mixes clustered around the 12.0% VIR, and the 1” mixtures cluster around 10% VIR).

The other observation is that the slope of the regression curve for 1” mixtures approaches 1.0 which suggests that the average film thickness calculation is no longer dominated by surface area. The volume of non-absorbed asphalt impacts the AFT calculation to more or less the same degree as the surface area factor.
CONCLUSIONS

A volumetric model has been developed that allows a specifying owner/agency to place criteria on the minimum volume of non-absorbed asphalt (VIR%) in lieu of voids in mineral aggregate (VMA). The advantage of the model over current practice is it places the focus on the expensive constituent in the mixture which is the asphalt cement.

VIR% is calculated based on actual laboratory measurements and is as precise as the test methods used in its determination.

Average film thickness (AFT) is less precise than VIR% because it is based on assumed universal surface area factors which are based solely on the masses of material passing two-dimensional sieve openings.

The VIR% model allows existing volumetric criteria for VMA to be transposed to generate an equivalent required range for VIR% as a conservative first approach to specifying VIR%.

VIR% is readily calculated from historic volumetric databases to allow researchers and agencies to mine existing databases to better refine VIR% requirements for their own applications.

VIR% is a more rational field volumetric management tool than VFA. Again, this places the focus on managing the expensive constituent in the mixture which is the asphalt cement.

The existing dust-to-binder ratio based on effective asphalt content is skewed for different specific gravity aggregates.

Computing dust-to-binder using VIR% correctly accounts for aggregates of varying specific gravities.

The VIR% model allows existing criteria to be transposed to generate an equivalent required range for dust-to-VIR% as a conservative approach to specifying dust-to-binder.

VIR% was generally equal to or better than AFT in correlating to distress measurements made on the 5-year and 10-year mainline test sections at MnROAD. The one exception was top-down cracking which appeared to better correlate with AFT.

Average film thickness (AFT) relies on two inputs; volume of non-absorbed asphalt and surface area. The Iowa data indicates that AFT for typical mixes 3/4” and smaller are dominated by the surface area input into the calculation.

AFT for typical mixes 1/2” and smaller approach being independent of volume of asphalt input in the equation. This precludes the use of AFT in reliably back-calculating minimum asphalt requirements for these size mixes.
References


13. X. Li, C. Williams, M. Marasteanu, T.R. Clyne, and E. Johnson, “Investigation of In-Place Asphalt Film Thickness and Performance of Hot Mix Asphalt Mixtures”, Minnesota Department of Transportation, 2008

APPENDIX A: Relationship between Mass and Volume for VIR%

The four components of VIR are defined as follows:

\[ P_{be} = \frac{\text{Mass Effective Asphalt}}{\text{Mass Total Mix}} \times 100 \]  
\[ (A1) \]

\[ P_s = \frac{\text{Mass Stone}}{\text{Mass Total Mix}} \times 100 \]  
\[ (A2) \]

\[ G_b = \frac{\text{Mass Total Asphalt} / \text{Volume Total Asphalt}}{\frac{\text{Mass } H_2O}{\text{Volume } H_2O}} \]  
\[ (A3) \]

\[ G_{sb} = \frac{\text{Mass Stone} / \text{Bulk Volume Stone}}{\frac{\text{Mass } H_2O}{\text{Volume } H_2O}} \]  
\[ (A4) \]

Therefore,

\[ \text{VIR}\% = \frac{\left( \frac{\text{Mass Effective Asphalt}}{\text{Mass Total Mix}} \right) \times 100}{\left( \frac{\text{Mass Total Asphalt} / \text{Volume Total Asphalt}}{\frac{\text{Mass } H_2O}{\text{Volume } H_2O}} \right) \times 100} \]  
\[ \left( \frac{\text{Mass Stone} / \text{Mass Total Mix}}{\frac{\text{Mass } H_2O}{\text{Volume } H_2O}} \right) \]  
\[ (A5) \]
Canceling common terms in the numerator and denominator of Eq A5 leaves the following:

\[
VIR\% = \left( \frac{\text{Mass Effective Asphalt}}{\text{Mass Total Asphalt}} \right) \frac{\text{Volume Total Asphalt}}{\text{Bulk Volume Stone}} \times 100
\]  

(A6)

The numerator is nothing more than the volume of effective asphalt, \( V_{be} \).

\[
\left( \frac{\text{Mass Effective Asphalt}}{\text{Mass Total Asphalt}} \right) \text{Volume Total Asphalt} = V_{be}
\]  

(A7)

The denominator is the Bulk Volume of Stone.

\[
\text{Bulk Volume Stone} = V_{sb}
\]  

(A8)

Substituting Eqs. 7 and 8 into Eq. A6, VIR\% can be rewritten as follows:

\[
VIR\% = \frac{V_{be}}{V_{sb}} \times 100
\]  

(A9)

VIR\% is just a ratio of volumes and hence the name Volume Increase Ratio.