5.10.4. CALCULATIONS FOR THE MARSHALL MIX DESIGN OF BITUMINOUS MIXTURES

1. Scope.

This method covers the formulas used to compute the various values used in the Marshall Mix Design of 100% virgin aggregate mixtures or reclaimed material and virgin aggregate mixtures.

2. Procedure.

2.1. Aggregate Specific Gravity.

2.1.1. Virgin Aggregate: Measure the Bulk (Dry) Specific Gravity of the coarse and fine aggregate fractions (KT-6, Procedure I & II).

2.1.2. Reclaimed Material: KT-6, as indicated above can be used on extracted aggregate if a sufficient quantity is available. If sufficient extracted aggregate is not available, conduct KT-39 on the reclaimed material. Obtain the specific gravity of the extracted asphalt and calculate the specific gravity of the combined aggregate in the reclaimed material.

2.2. Determine the specific gravity of the asphalt cement.

2.3. Calculate the Bulk Specific Gravity of the aggregate combination in the paving mixture. (Gsb)

2.4. Measure the Maximum Specific Gravity of the loose paving mixture. (KT-39) (Gmm)

2.5. Measure the Bulk Specific Gravity of the compacted paving mixture. (KT-15) (Gnb)

2.6. Calculate the Effective Specific Gravity of the aggregate. (Ge)

2.7. Calculate asphalt absorption of the aggregate. (Pba)

2.8. Calculate the effective asphalt content of the mixture. (Pbe)

2.9. Calculate the percent voids in the mineral aggregate in the compacted paving mixture. (VMA)

2.10. Calculate the percent air voids in the compacted mixture. (Pa)

2.11. Calculate the percent voids filled with asphalt in the compacted mixture. (VFA)

2.12. Calculate the limiting asphalt content at the tentative design asphalt content. (P''max)

2.13. Calculate the Bearing Capacity for each asphalt content.

3. Equations.

Equations for the above calculations follow in this text and their application may be expedited by use of the appropriate worksheet (Figure 1). Also, there is a computer program available which will complete these calculations. For purposes of illustration, the following data is presumed "known" for a bituminous mixture under evaluation.
3.1. BASIC DATA FOR SAMPLE OF PAVING MIXTURE

3.1.1. Constituents:

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Test Method</th>
<th>Mixture Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Apparent</td>
<td>Bulk Dry</td>
<td>Percent by wt. of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Mix</td>
</tr>
<tr>
<td>Asph. Cement</td>
<td>G_b</td>
<td>T-228</td>
<td>P_b</td>
</tr>
<tr>
<td>Coarse Aggr.</td>
<td>2.759</td>
<td>G_1</td>
<td>KT-6-I</td>
</tr>
<tr>
<td>Fine Aggr.</td>
<td>2.905</td>
<td>G_2</td>
<td>KT-6-II</td>
</tr>
</tbody>
</table>

|                |                  |             | 7.48       | 55.30              |
|                |                  |             | 51.45      | 44.70              |

Table 1

3.1.2. Paving Mixture: Bulk specific gravity of compacted paving mixture sample. \( G_{mb} (KT-15) = 2.344 \)

Maximum specific gravity of paving mixture sample. \( G_{mm} (KT-39) = 2.438 \)

NOTE: The calculations are simplified by converting from percent by dry weight of aggregates to percent by total weight of mixture. This is accomplished by use of the following formulas:

\[
P_b = \frac{(P'_b \times 100)}{(100 + P'_b)}
\]

\[
P_I = \frac{(P'_I \times 100)}{(100 + P'_I)}
\]

Where:

- \( P_b \) = Percent asphalt, total mixture basis.
- \( R'_b \) = Percent asphalt, dry weight basis.
- \( P_I \) = Percent Coarse Aggr., total mixture basis.
- \( R'_I \) = Percent Coarse Aggr., dry weight basis.

Example: \( P_b = \frac{(7.48 \times 100)}{(100 + 7.48)} = 6.96\% \) (asphalt)

\[
P_1 = \frac{(55.30 \times 100)}{(100 + 7.48)} = 51.45\% \) (coarse aggr.)

\( P_2 \) and \( P_3 \) are calculated in the same manner as \( P_1 \).

3.2. Bulk Specific Gravity of Aggregate: When the total aggregate consists of separate fractions of coarse aggregate, fine aggregate, and mineral filler, all having different specific gravities, the bulk and apparent specific gravities for the total aggregate are calculated as follows:
3.2.1. Bulk Specific Gravity, $G_{sb}$.

$$G_{sb} = \frac{P_1}{G_1} + \frac{P_2}{G_2} + ... + \frac{P_n}{G_n} \quad (Eq. 1, Figure 1)$$

Where:

- $G_{sb}$ = Bulk dry specific gravity of the total aggregate
- $P_1, P_2, P_n$ = Percentages by weight of aggregates, 1,2,n;
- $G_1, G_2, G_n$ = Bulk specific gravities of aggregates 1,2,n.

The bulk specific gravity of mineral filler is difficult to determine accurately at the present time. However, if the apparent specific gravity of the filler is used instead, the error is usually negligible.

Calculation using the data from Table 1.

$$G_{sb} = 51.450 + 41.590 = \frac{51.450}{2.606} + \frac{41.590}{2.711}$$

$$= \frac{93.040}{19.743 + 15.341} = 2.652$$

3.3. Effective Specific Gravity of Aggregate: When based on the maximum specific gravity of a paving mixture, $G_{mm}$, the effective specific gravity of the aggregate, $G_{se}$, includes all void spaces in the aggregate particles except those that absorb asphalt. It is determined as follows

$$G_{se} = \frac{P_{mm} - P_b}{P_{mm}} \quad (Eq. 2, Figure 1)$$

Where:

- $G_{se}$ = Effective specific gravity of aggregate
- $P_{mm}$ = total loose mixture = 100%
- $P_b$ = asphalt, percent by total weight of mixture
- $G_{mm}$ = maximum specific gravity of paving mixture (no air voids), (KT-39)
- $G_b$ = specific gravity of asphalt

Calculation using the data from Table 1.

$$G_{se} = \frac{100 - 6.960}{2.438} - \frac{6.960}{1.010} = \frac{93.040}{34.126} = 2.726$$

NOTE: The volume of asphalt binder absorbed by an aggregate is almost invariably less than the volume of water absorbed. Consequently, the value for the effective specific gravity of an aggregate ($G_{se}$) should
be between its bulk ($G_{sb}$) and apparent specific gravities ($G_{sa}$). When the effective specific gravity falls outside these limits, its value must be assumed to be incorrect. If this occurs, the calculations, the maximum specific gravity of the total mix (KT-39) and the composition of the mix should then be rechecked for the source of the error.

If the apparent specific gravity of the coarse aggregate is 2.759 and the apparent specific gravity of the fine aggregate is 2.905 (see Table 1.), the apparent specific gravity, $G_{sa}$, of the total aggregate can be calculated by the same formula as the bulk specific gravity by using the apparent specific gravity of each aggregate constituent. For this example, then, the calculated apparent specific gravity, $G_{sa}$, is;

$$G_{sa} = \frac{51.450}{2.759} + \frac{41.590}{2.905} = \frac{93.040}{32.965} = 2.822$$

In the example, the three specific gravities are as follows:

- Bulk Specific Gravity $G_{sb} = 2.652$
- Effective Specific Gravity $G_{se} = 2.726$
- Apparent Specific Gravity $G_{sa} = 2.822$

### 3.4. Maximum Specific Gravities of Mixtures with Different Asphalt Contents:

In designing a paving mixture with a given aggregate, the maximum specific gravities, $G_{mm}$, at different asphalt contents are needed to calculate the percentage of air voids for each asphalt content. While the same maximum specific gravity can be determined for each asphalt content by KT-39, the precision of the test is best when the mixture has close to the optimum asphalt content. Also, it is preferable to measure the maximum specific gravity in duplicate or triplicate.

After averaging the results from these tests and calculating the effective specific gravity of the aggregate, the maximum specific gravity for any other asphalt content can be obtained. For all practical purposes, the effective specific gravity of the aggregate is constant because the asphalt absorption does not vary appreciably with variations in asphalt content.

$$G_{mm} = \frac{P_{mm}}{P_s + P_b} \cdot \frac{P_b}{G_b} \quad \text{(Eq. 3, Figure 1)}$$

Where:

- $G_{mm}$ = maximum specific gravity of paving mixture (no air voids)
- $P_{mm}$ = total loose mixture = 100%
- $P_s$ = aggregate, percent by total weight of mixture ($P_1 + P_2 + P_3 + P_n$)
- $P_b$ = asphalt, percent by total weight of mixture.
- $G_{se}$ = effective specific gravity of aggregate.
- $G_b$ = specific gravity of asphalt.

Calculation using specific gravity data from Table 1., effective specific gravity, $G_{se}$, determined in section 3.3., and an asphalt content, $P_b$ of 6.96%


\[ G_{mm} = \frac{100}{\frac{93.04}{2.726} + \frac{6960}{1.010}} = \frac{100}{41.022} = 2.438 \]

3.5. Asphalt Absorption: Absorption is expressed as a percentage by weight of aggregate rather than as a percentage by total weight of mixture. Asphalt, \( P_{ba} \), absorption is determined as follows:

\[
P_{ba} = 100 \left( \frac{G_{se} - G_{sb}}{G_{sb} \times G_{se}} \right) G_b \quad (Eq. 4, Figure 1)
\]

Where:

- \( P_{ba} \) = absorbed asphalt, percent by weight of aggregate.
- \( G_{se} \) = effective specific gravity of aggregate.
- \( G_{sb} \) = bulk specific gravity of aggregate.
- \( G_b \) = specific gravity of asphalt.

Calculation using bulk and effective gravities determined in sections 3.2 and 3.3 and asphalt specific gravity from Table 1.

\[
P_{ba} = 100 \times \frac{(2.726 - 2.652)}{(2.652 \times 2.726)} \times 1.010 = 100 \times \frac{0.074}{7.229} \times 1.010 = 1.03
\]

3.6. Effective Asphalt Content of a Paving Mixture: The effective asphalt content, \( P_{be} \), of a paving mixture is the total asphalt content minus the quantity of asphalt lost by absorption into the aggregate particles. It is the portion of the total asphalt content that remains as a coating on the outside of the aggregate particles, and is the asphalt content on which service performance of an asphalt paving mixture depends. The formula is:

\[
P_{be} = P_b - \left( \frac{P_{ba}}{100} \right) P_s \quad (Eq. 5, Figure 1)
\]

Where:

- \( P_{be} \) = effective asphalt content, percent by total weight of mixture.
- \( P_b \) = asphalt, percent by total weight of mixture.
- \( P_{ba} \) = absorbed asphalt, percent by weight of aggregate.
- \( P_s \) = aggregate, percent by total weight of mixture.

Calculation using data from Table 1 and section 3.5.

\[
P_{be} = 6.96 - \left( \frac{1.03}{100} \right) \times 93.04 = 6.96 - 0.96 = 6.00
\]

3.7. Percent VMA in Compacted Paving Mixture: The voids in the mineral aggregate, VMA, are defined as the intergranular void space between the aggregate particles in a compacted paving mixture, that includes the air voids and the effective asphalt content, expressed as a percent of the total volume. The VMA is calculated on the basis of the bulk specific gravity of the aggregate and is expressed as a percentage of the bulk volume of the compacted paving mixture. Therefore, the VMA can be calculated by subtracting the volume of the aggregate determined by its bulk specific gravity from the bulk volume of the compacted paving mixture. The method of calculation is illustrated as follows:
If mix composition is determined as percent by weight of the total mixture:

\[ VMA = 100 - \frac{G_{mb} P_s}{G_{sb}} \]  \quad (Eq. 6, Figure 1)

Where:
- \( VMA \) = voids in mineral aggregate (percent of bulk vol.)
- \( G_{sb} \) = bulk specific gravity of aggregate.
- \( G_{mb} \) = bulk specific gravity of compacted mixture.  \( \text{(KT-15)} \)
- \( P_s \) = aggregate, percent by total dry weight of mixture.

Calculation using data from Table 1 and section 3.2.

\[ VMA = 100 - \left( \frac{2.344 \times 93.04}{2.652} \right) = 100 - 82.23 = 17.77 \]

Calculation using data from Table 1 and section 3.2.

\[ P_s = \left( \frac{100}{100 + P'_b} \right) x 100 \]

Where:
- \( P'_b \) = asphalt, percent by dry weight of aggregate.

\[ VMA = 100 - \left( \frac{2.344}{2.651} \times \frac{100}{100 + 7.48} \right) = 100 - 82.27 = 17.73 \]

3.8. Calculation of Percent Air Voids in Compacted Mixture: The air voids, \( P_a \), in a compacted paving mixture consist of the small air spaces between the coated aggregate particles. The percentage of air voids in a compacted mixture can be determined by the following equation:

\[ P_a = 100 \left( \frac{G_{mn} - G_{mb}}{G_{mn}} \right) \]  \quad (Eq. 7, Figure 1)

Where:
- \( P_a \) = air voids in compacted mixture, percent of total volume.
- \( G_{mn} \) = maximum specific gravity of paving mixture (as determined in section 3.4, or as determined directly for a paving mixture by KT-39).
- \( G_{mb} \) = bulk specific gravity of compacted mixture.

Calculation using data from Table 1.

\[ P_a = 100 \left( \frac{2.438 - 2.344}{2.438} \right) = \frac{9.400}{2.438} = 3.85 \]
3.9. Calculation of Percent Voids Filled with Asphalt: The voids filled with asphalt, VFA, in a compacted paving mixture consists of that portion of the initial voids in the aggregate, VMA, which has been filled with the non-absorbed, or effective asphalt. The percentage of voids filled with asphalt in a compacted specimen can be determined by the following equation:

\[
VFA = \left( \frac{P_{be}}{G_b} \right) \times 100 \\
= \left( \frac{VMA}{G_{mb}} \right) \times 100
\]

or

\[
VFA = \left( \frac{VMA - P_a}{VMA} \right) \times 100
\]

(Eq. 8, Figure 1)

Where:

- VMA = voids in mineral aggregate, percent of bulk vol.
- P_{be} = effective asphalt content.
- G_b = specific gravity of asphalt.
- G_{mb} = bulk specific gravity of compacted mixture.

\[
VFA = 100 \times \left( \frac{5.98}{1.01} \right) \left( \frac{17.73}{2.344} \right) = 100 \times \frac{5.921}{7.564} = 78.3\%
\]

or

\[
VFA = \left( \frac{17.73 - 3.85}{17.73} \right) \times 100 = \left( \frac{13.88}{17.73} \right) \times 100 = 78.3\%
\]
WORKSHEET FOR ANALYSIS OF COMPACTED PAVING MIXTURE

Contract #:  
Project Number:  
Lab No.:  

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P_b</td>
<td>7.48</td>
<td>6.96</td>
<td>93.04</td>
<td>1.010</td>
<td>2.652</td>
<td>2.438</td>
</tr>
</tbody>
</table>

Theo. Max. KG/M³

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G_b</td>
<td>2.726</td>
<td>5.98</td>
<td>17.73</td>
<td>2.344</td>
<td></td>
<td>3.85</td>
<td>78.3</td>
</tr>
</tbody>
</table>

P'b Max

| Eq. | Eff. Film Thickness | Filler/Binder Ratio  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>2.759</td>
<td>2.606</td>
</tr>
<tr>
<td>E</td>
<td>2.905</td>
<td>2.711</td>
</tr>
</tbody>
</table>

P = M = 100 * E - K

P'ba = H = 100 * E - K

VMA = J = 100 - K

Figure 1. SI Example
WORKSHEET FOR ANALYSIS OF COMPACTED PAVING MIXTURE

<table>
<thead>
<tr>
<th>Contract #</th>
<th>Date</th>
<th>Project Number</th>
<th>Lab No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>% AC by Wt. Aggr.</td>
<td>7.48</td>
<td>AC by Wt. Mix</td>
<td>6.96</td>
</tr>
<tr>
<td>% Aggr. by Wt. Mix</td>
<td>93.04</td>
<td>S. G. of Asphalt</td>
<td>1.010</td>
</tr>
<tr>
<td>S. G. of Aggr. (bulk)</td>
<td>2.652</td>
<td>Max. S. G. Mix (KT-39)</td>
<td>2.438</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_b'</td>
<td>% AC by Wt. Aggr.</td>
<td>7.48</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_b</td>
<td>% Aggr. by Wt. Mix</td>
<td>93.04</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>S. G. of Asphalt</td>
<td>1.010</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>P_b'</td>
<td>A</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>S. G. of Aggr. (bulk)</td>
<td>2.652</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Max. S. G. Mix (KT-39)</td>
<td>2.438</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>(computed)</td>
<td></td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Theo. Max. KG/M³</td>
<td></td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Eff. S. G. of Aggr.</td>
<td>2.726</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>% Abs. Asphalt</td>
<td>1.05</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Eff. Asph. Content</td>
<td>5.98</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>% V. M. A.</td>
<td>17.73</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>S. G. of plugs (KT-15)</td>
<td>2.344</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Lab Plugs KG/M³</td>
<td></td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>% Air Voids</td>
<td>3.85</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>% Voids Filled</td>
<td>78.3</td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>P_b' Max</td>
<td></td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Eff. Film Thickness</td>
<td></td>
</tr>
<tr>
<td>Eq.</td>
<td>P_s</td>
<td>Filler/Binder Ratio</td>
<td></td>
</tr>
</tbody>
</table>

| Eq. | P_b | % |  |
| Eq. | P_b | P_b' | 100 + P_b | 100 + P_b' |
| Eq. | P_b | 2.759 | 2.606 | 55.30 |
| Eq. | P_b | 2.905 | 2.711 | 44.70 |
| Eq. | P_b | P_b = B = 100 - A |  |
| Eq. | P_b | Theo. Comb. | 2.822 |

\[ F = E \times 62.4 \]
\[ G_a = G = \frac{B}{100 + A} \times \frac{E}{C} \]
\[ P_b = H = 100 \times \frac{G - D}{D \times G} \times C \]
\[ P_b = I = \frac{H}{100 + B} \times K \times B \]
\[ VMA = J = 100 - \frac{K \times B}{D} \]

Figure 1. English Example
4. Preliminary Calculations for Recycled Mixtures:

When designing recycled mixtures, certain calculations must be made to obtain the correct values for $P_{b}$', $G_{b}$ and $G_{sb}$ prior to entering the "Worksheet for Analysis of Compacted Paving Mixtures" (Figure 1). The following sequence of equations may be followed to obtain the needed values.

4.1. Reclaimed Roadway (RAP).

Given:

- $P_{BRAP}$ = Percent asphalt in RAP from extractions = 6.2
- $P_{BN}$ = Percent added asphalt or recycling agent.
- $G_{AC,RAP}$ = Specific gravity of reclaimed asphalt = 1.025
- $G_{BN}$ = Specific gravity of added asphalt or recycling agent = 1.008
- $G_{RAG}$ = Specific gravity of reclaimed agg. = 2.522
- $G_{SBN}$ = Specific gravity of new aggregates = 2.651
- $P_{RAP}$ = Percent reclaimed in aggregate blend = 40%
- $P_{VA}$ = Percent new aggregate in blend = 60%

4.1.1. % asphalt in RAP (Wet Weight Basis)

$$\frac{P_{BRAP}}{(1 + \frac{P_{BRAP}}{100})} = \frac{6.2}{1 + (\frac{6.2}{100})} = 5.84$$

4.1.2. % aggregate in RAP (Wet Weight Basis)

$$100 - a. = 100 - 5.84 = 94.16$$

4.1.3. Weight of asphalt in RAP portion/100 g of aggregate blend

$$\frac{(a.)(P_{RAP})}{100} = \frac{(5.84)(40)}{100} = 2.34$$

4.1.4. Weight of aggregate in RAP portion/100 g of aggregate blend

$$\frac{(b.)(P_{RAP})}{100} = \frac{(94.16)(40)}{100} = 37.66$$

4.1.5. Weight of reclaimed material/100 g of aggregate blend

$$c. + d. = 2.34 + 37.66 = 40.00$$

4.1.6. Weight of new aggregate/100 g of aggregate blend

$$100 - e. = 100 - 40.00 = 60.00$$
## COMBINED MATERIALS

<table>
<thead>
<tr>
<th></th>
<th>%</th>
<th>%</th>
<th>%</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>g. % additive - Dry wt. basis</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>h. Additive wt./100 g sample = (P(_{BN}))</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>c. Asphalt wt. in RAP/100 g sample</td>
<td>2.34</td>
<td>2.34</td>
<td>2.34</td>
<td>2.34</td>
</tr>
<tr>
<td>i. Revised wt of bitumen (c. + h.)</td>
<td>4.34</td>
<td>4.84</td>
<td>5.34</td>
<td>5.84</td>
</tr>
<tr>
<td>d. Aggr. wt. in RAP/100 g sample</td>
<td>37.66</td>
<td>37.66</td>
<td>37.66</td>
<td>37.66</td>
</tr>
<tr>
<td>f. New aggr. wt./100 g sample</td>
<td>60.00</td>
<td>60.00</td>
<td>60.00</td>
<td>60.00</td>
</tr>
<tr>
<td>j. Revised wt. of aggr. = (d + f)</td>
<td>97.66</td>
<td>97.66</td>
<td>97.66</td>
<td>97.66</td>
</tr>
<tr>
<td>k. Total weight = (i + j)</td>
<td>102.0</td>
<td>102.5</td>
<td>103.0</td>
<td>103.5</td>
</tr>
<tr>
<td>l. % asphlt dry wt of aggr (ij)(100) Enter as P(_b) on Fig. 1 worksheet</td>
<td>4.44</td>
<td>4.96</td>
<td>5.47</td>
<td>5.98</td>
</tr>
<tr>
<td>m. Specific gravity - combined bituminous material</td>
<td>1.017</td>
<td>1.016</td>
<td>1.015</td>
<td>1.015</td>
</tr>
<tr>
<td>n. Specific gravity - Combined aggregates (Bulk Dry)</td>
<td>2.600</td>
<td>2.600</td>
<td>2.600</td>
<td>2.600</td>
</tr>
</tbody>
</table>

\[
\frac{i}{h + \frac{c}{G_{BN} / G_{AC-RAP}}} \quad \text{Enter as } G_b \text{ on Fig. 1 worksheet}
\]

\[
\frac{j}{d + \frac{f}{G_{RAG} / G_{SBN}}} \quad \text{Enter as } G_{Sb} \text{ on Fig. 1 worksheet}
\]

### Supplemental Calculations (Dry Aggregate Basis):

#### 5.1. Calculation of Film Thickness:

The film thickness is a calculated or theoretical value and does not denote a measurable property of the mix. It is, however, useful in the analysis of bituminous mixtures when evaluating the effect of gradation changes. Higher film thickness is generally desirable (within practical considerations) since thicker films are better able to withstand asphalt hardening. Film thickness is calculated for other purposes such as slurry seal design.

Convert the gradation (percent retained) to percent passing and enter into a worksheet (similar to the table below). Then complete the calculations for Surface Area (S.A.).
**DETERMINATION OF SURFACE AREA**

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent x S.A. Factor</th>
<th>Surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing</td>
<td>m²/kg (ft²/lb)</td>
<td>m²/kg (ft²/lb)</td>
</tr>
<tr>
<td>19.0 mm (3/4 in.)</td>
<td>100</td>
<td>0.410(2.0)</td>
</tr>
<tr>
<td>12.5 mm (1/2 in.)</td>
<td>93</td>
<td>*</td>
</tr>
<tr>
<td>9.5 mm (3/8 in.)</td>
<td>81</td>
<td>*</td>
</tr>
<tr>
<td>4.75 mm (No. 4)</td>
<td>65</td>
<td>0.266(1.30)</td>
</tr>
<tr>
<td>2.36 mm (No. 8)</td>
<td>48</td>
<td>0.393(1.92)</td>
</tr>
<tr>
<td>1.18 mm (No. 16)</td>
<td>38</td>
<td>0.623(3.04)</td>
</tr>
<tr>
<td>600 µm (No. 30)</td>
<td>27</td>
<td>0.774(3.78)</td>
</tr>
<tr>
<td>300 µm (No. 50)</td>
<td>13</td>
<td>0.799(3.90)</td>
</tr>
<tr>
<td>150 µm (No. 100)</td>
<td>8</td>
<td>0.983(4.80)</td>
</tr>
<tr>
<td>75 µm (No. 200)</td>
<td>6.8</td>
<td>2.228(10.88)</td>
</tr>
</tbody>
</table>

Total Surface Area = 6.476 m²/kg (31.62 ft²/lb)

#Surface area factors shown are applicable only when all the above-listed sieves are used in the sieve analysis.

*Surface area factor is 0.41 m²/kg (2 ft²/lb) for any material retained above the 4.75 mm (No. 4) sieve. Thus, the surface area equals 0.410 (2.0) for all material above the 4.75 mm (No. 4) sieve.

5.2. Calculation of Bitumen Index: The bitumen index is the ratio of effective asphalt content to the aggregate surface area.

**SI:** Bitumen Index = \( \frac{P_{be}(2.048)}{S.A} \)

**English:** Bitumen Index = \( \frac{P_{be}(10)}{S.A} \)

SI Example: Bitumen Index = \( \frac{5.98(2.048)}{6.476} = 1.891 \)

English Example: Bitumen Index = \( \frac{5.98(10)}{31.62} = 1.891 \)

Where: \( P_{be} = \) effective asphalt content, see section 3.6.

5.3. Conversion of Bitumen Index to Film Thickness (Microns):

Film Thickness (FT) = Bitumen Index x 4.87 = 1.891 x 4.87 = 9.2 Microns

6. Maximum Percent of Asphalt: Determine the maximum percentage of asphalt (\( P_b', \) max) which can be placed in a mix and still maintain a safe level of air voids under conditions of post-construction traffic and elevated mat temperature.

6.1. The maximum volume of asphalt which a mix can contain is the volume of the voids in mineral aggregate (VMA) plus the volume of asphalt absorbed into the aggregate. The volume of the absorbed asphalt (\( V_{pa} \)) may be determined by the following formula:
\[ VP_{ba} = \frac{P_{ba} \times G_{sb}}{G_b} \]

\[ = \frac{1.05 \times 2.651}{1.01} = 2.76 \]

Where: \( P_{ba} = \) absorbed asphalt, section 3.5.
\( G_{sb} = \) bulk dry specific gravity of the total aggregate, section 3.2.1.
\( G_b = \) apparent specific gravity of asphalt, section 3.1.1.

6.2. Total Safe Volume at 74°F (165°F) represents the available volume minus 2% to allow for plant fluctuation. The Total Safe Volume (TSV) is determined by the following equation:

\[ TSV = VMA + VP_{ba} - 2.0 \]

\[ = 17.73 + 2.76 - 2.0 = 18.49 \]

Where: VMA = voids in mineral aggregates, section 3.7.

6.3. Conversion of TSV to percentage of asphalt, \( (P_b') \), is accomplished in the following steps:

\[ P_{b, max} = \frac{TSV(G_b)(0.9638)}{G_{sb}} \]

\[ = \frac{18.49 \times 1.01 \times 0.9638}{2.651} = 6.79\% \]

\[ P_{b, max} = \frac{P_{b, max}(100 + P_{b, max})}{100} \]

\[ = \frac{6.79(106.79)}{100} = 7.25\% \]

Where: \( P_{b, max} = \) maximum percent asphalt by weight of total mix
\( P_{b, max}' = \) maximum percent asphalt by weight of dry aggregate
7. Compute Bearing Capacity, kPa(ksi), as follows:

\[
\text{SI:}
\]

\[
\text{Bearing Capacity, kPa} = \frac{1.55\, \text{Stability}}{\text{Flow}} \left( \frac{120 - \text{Flow}}{100} \right)
\]

Where: Stability in Newtons (N)
Flow in 0.25mm

\[
\text{SI Example:}
\]

\[
\text{Bearing Capacity, kPa} = \frac{1.55(7784)}{12} \left[ \frac{120 - 12}{100} \right] = 1086\text{kPa}
\]

\[
\text{English Example:}
\]

\[
\text{Bearing Capacity, psi} = \frac{\text{Stability}}{\text{Flow}} \times \frac{120 - \text{Flow}}{100}
\]

\[
= \frac{1750}{12} \times \frac{120 - 12}{100} = 157\text{psi}
\]

8. Compute Filler - Binder Ratio as follows:

\[
\frac{F}{B} = \frac{\text{Percent of -75 \text{\mu}m \ (-No.200) fraction (see subsection (f)(1))}}{\text{Percent of asphalt (dry weight basis) (see subsection (c)(1))}}
\]

\[
= \frac{6.8}{7.48} = 0.91
\]