Chapter 3 Marshall Method of HMA Mix Design

C3.1 General

The Marshall method of mix design is for dense graded HMA mixes (DBM/AC). For a single selected aggregate gradation, five different asphalt contents are tested for various volumetric and strength criteria to select the optimum binder content. The test results should always be reported as the average for three compacted, “identical” specimens. The selection of the optimum binder content requires engineering judgment, depending on traffic, climate and experience with the local materials used. In most cases, the optimum binder content should be selected for which the compacted specimens have 4 percent air voids.

Steps for Marshall Method

1. Aggregate and Bitumen Evaluation (Chapter 2); and aggregate proportion by weight
2. Preparation of Marshall Specimens
3. Density and Voids Analysis
5. Tabulating and Plotting Test Results
6. Optimum Asphalt Content Determination

C3.2 Applicable standards

The Marshall test procedures have been standardized by the American Society for Testing and Materials (ASTM) and by the American Association of State Highway and Transportation Officials (AASHTO). Procedures are given by:


The original Marshall method is applicable only to hot mix asphalt paving mixtures containing aggregates with maximum sizes of 25 mm or less. A modified Marshall method has been developed for aggregates with maximum sizes up to 38 mm. Procedures for 6-inch diameter specimen are given by ASTM D5581.

The Marshall method is intended for laboratory design and field control of asphalt hot mix dense-graded paving mixtures. Because the Marshall stability test is empirical in nature, the meaning of the results in terms of estimating relative field behavior is lost when any modification is made to the standard procedures. An example of such modification is preparing specimens from reheated or remolded materials. If reheating cannot be avoided, a correlation should be made to adjust the compactive effort on the reheated mix to match the volumetric properties (such as VMA and % air voids) of the compacted mix which was not reheated.

C3.3 Outline of method

The procedure for the Marshall method starts with the preparation of test specimens. Steps preliminary to specimen preparation are:

- all materials proposed for use meet the physical requirements of the project specifications;
- aggregate blend combinations meet the gradation requirements of the project specifications; and
for the purpose of performing density and voids analyses, the bulk specific gravity of all aggregates used in the blend and the specific gravity of the asphalt concrete are determined.

These requirements are matters of routine testing, specifications and laboratory technique that must be considered for any mix design method.

The Marshall method uses standard test specimens of 63.5 mm height by a 101.6 mm diameter. These are prepared using a specified procedure for heating, mixing, and compacting the asphalt-aggregate mixture. The two principle features of the Marshall method of mix design are a density-voids analysis and a stability-flow test of the compacted test specimens.

The stability of the test specimen is the maximum load resistance in Newtons that the standard test specimen will develop at 60°C when tested as outlined. The flow value is the total deformation, in units of 0.25 mm, occurring in the specimen between no load and the point of maximum load during the stability test.

A modified Marshall method for 152.4 mm diameter specimens has been standardized by ASTM D5581 for mixes composed of aggregates with maximum size up to 38 mm. Specially, for Dense Graded Bituminous Macadam, the modified Marshall method should be adopted.

C3.4 Preparation of test specimens

C.3.4.1 General

In determining the design asphalt content for a particular gradation of aggregates by the Marshall method, a series of test specimens is prepared for a range of different asphalt contents so that the test data curves show well-defined relationships. Tests should be planned on the basis of 0.5 percent increments of asphalt content, with at least two asphalt contents above the expected design value and at least two below this value.

The “expected design” asphalt content can be based on any or all of these sources: experience or computational formula. The expected design asphalt content, in percent by total weight of mix, could then be estimated to be approximately equivalent to the percentage of aggregate in the final gradation passing the 75-μm (No. 200) sieve.

One example of a computational formula is this equation:

\[ P = 0.035a + 0.045b + Kc + F \]

Where:

\[ P = \text{approximate asphalt content of mix, percent by weight of mix} \]
\[ a = \text{percent of mineral aggregate retained on 2.36-mm (No. 8) sieve} \]
\[ b = \text{percent of mineral aggregate passing the 2.36-mm (No. 8) sieve and retained on the 75-μm (No. 200) sieve} \]
\[ c = \text{percent of mineral aggregate passing 75-μm (No. 200) sieve} \]
\[ K = 0.15 \text{ for 11–15 percent passing 75-μm (No. 200) sieve} \]
\[ 0.18 \text{ for 6–10 percent passing 75-μm (No. 200) sieve} \]
\[ 0.20 \text{ for 5 percent or less passing 75-μm (No. 200) sieve} \]
\[ F = 0 – 2.0 \text{ percent. Based on the absorption of light or heavy aggregate, in the absence of other data, a value of 0.7 is suggested.} \]

To provide adequate data, at least three test specimens are prepared for each asphalt content selected. Therefore, a Marshall mix design using five different asphalt contents will normally require at least 15 test specimens. Each test specimen will usually require approximately 1.2 kg of aggregate. Assuming
some minor waste, the minimum aggregate requirements for one series of test specimens of a given blend and gradation will be approximately 23 kg. About 4 liters of asphalt will be adequate.

Table 3.1: Approximate asphalt content of mix, percent by weight of mix for specimen preparation, based on above equation

<table>
<thead>
<tr>
<th>Nominal Maximum Aggregate Size, mm</th>
<th>Approximate asphalt content of mix, percent by weight of mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.2</td>
<td>5.344</td>
</tr>
<tr>
<td>19.0</td>
<td>4.855</td>
</tr>
<tr>
<td>26.5</td>
<td>4.610</td>
</tr>
<tr>
<td>35.5</td>
<td>4.610</td>
</tr>
</tbody>
</table>

Equipment

The equipment (calibrated as needed) required for the preparation of test specimens is:

- flat-bottom metal pans for heating aggregates;
- round metal pans or a mixing bowl, approximately 4-liter capacity, for mixing asphalt and aggregate;
- oven and hot plate, preferably thermostatically controlled, for heating aggregates, asphalt and equipment;
- scoop for batching aggregates;
- containers: gill-type tins, beakers, pouring pots and sauce pans for heating asphalt;
- thermometers or other thermometric devices: armored, glass or dial-type with metal stem, 10°C to 235°C, for determining temperature of aggregates, asphalt and asphalt mixtures;
- balances: 5-kg capacity, sensitive to 1 g, for weighing aggregates and asphalt, and 2-kg capacity, sensitive to 0.1 g, for weighing compacted specimens;
- large mixing spoon or small trowel;
- large spatula;
- mechanical mixer (optional): commercial bread dough mixer 4-liter capacity or larger, equipped with two metal mixing bowls and two wire stirrers, or an equivalent type mixer;
- compaction pedestal (see Figure 3.1), consists of a 200×200×460 mm wooden post capped with a 305×305×25 mm steel plate. The wooden post should be oak, pine or other wood having a dry weight of 670 to 770 kg/m³. The wooden post should be secured by four angle brackets to a solid concrete slab. The steel cap should be firmly fastened to the post. The pedestal should be installed so that the post is plumb, the cap level, and the entire assembly free from movement during compaction. Compaction hammers can be either manually or mechanically operated, as shown in Figure 3.1. Mechanically operated hammers drop the hammer at a rate of 64 ± 4 blows per minute.
Mechanical hammers can also have single or multiple hammer and mold sets for compacting single or multiple specimens at a time. Some mechanically operated hammers are designed with a rotating base mechanism which rotates at 18 to 30 revolutions per minute;

- compaction mold, consisting of a base plate, forming mold and collar extension. The forming mold has an inside diameter of 101.6 mm and a height of approximately 75 mm; the base plate and collar extension are designed to be interchangeable with either end of the forming mold. ASTM D5581 references a 154.2-mm mold with a 114.3-mm height for use with aggregate up to 38mm NMAS (for modified Marshall Test) and should conform to requirements of ASTM D6926;

- compaction hammer, consisting of a flat, circular tamping face, 98.4 mm in diameter and equipped with a 4.5-kg weight constructed to obtain a specified 457 mm height of drop, should conform to requirements of ASTM D6926;

- mold holder, consisting of spring-tension device designed to hold compaction mold centered in place on the compaction pedestal, should conform to requirements of ASTM D6926;

- paper disks, 100 mm;

- steel specimen extractor, in the form of a jack and a disk with a diameter not less than 100 mm and 13 mm thick for extruding compacted specimen form mold. The steel specimen extractor for the 6-inch mold is 151.5 to 152.5 mm (5.950 to 5.990 in.) in diameter and 13 mm (0.5 in.) thick;

- welders’ gloves, for handling hot equipment. Rubber gloves for removing specimens from water bath; and

- marking crayons, for identifying test specimens.

C3.5 Preparation of test specimens

These steps are recommended for preparing Marshall test specimens.

(a) **Number of specimens**—prepare at least three specimens for each combination of aggregates and binder content.

(b) **Preparation of aggregates**—dry aggregates to constant weight at 105°C to 110°C and separate the aggregates by dry sieving into the desired size fractions. **These size fractions are recommended:**

- 38.0-25.0 mm
- 25.0 to 19.0 mm
- 19.0 to 13.2 mm
- 13.2 to 4.75 mm
- 4.75 to 2.36 mm (No. 4 to No. 8)
- Passing 2.36 mm (No. 8)

**Aggregate batching and mix sample preparation**

There are no AASHTO, ASTM or other widely accepted standards for the batching of aggregates for asphalt mix design. Many variations exist and are specified by some agencies. An important part of any batching procedure is to completely dry the aggregates before beginning. Aggregate samples from the plant or quarry may come to the lab saturated with moisture. Fine aggregate stockpiles tend to absorb a higher percentage of moisture than coarser aggregate. Without completely drying the aggregate first, the absorbed moisture will increase the aggregate weight, resulting in inaccurate material proportions in the batch.

Prior to batching samples for the mix design, gradations should be performed on each material submitted. Aggregate material submitted for mix design should be accompanied with production test
results. Submitted materials should then be compared with production test results to assure the materials submitted for mix design are representative of the materials that will be used in the project. Softer aggregates tend to degrade more during the production process than harder aggregates, often resulting in a finer gradation than the aggregate sample used for mix design. It can be taken account by determining the extent of the additional fines created during production and making a corresponding adjustment to the aggregate batch for mix design. Performing this adjustment may help avoid the drop in air voids and VMA often seen in plant mixes versus laboratory mixes.

Therefore, a careful comparison of gradations and all other specified characteristics should be made prior to conducting a mix design. Conducting a mixture design using aggregate that does not meet a project specification or is not representative of field-produced material is of little use. There are many different methods that can be utilized to prepare aggregate samples for mixture testing. They can range from very accurate and time-consuming to relatively quick but with less accuracy. Accurately prepared specimens that are representative of the final aggregate blend produced by the mixing plant will give the most reliable mixture design data. The mix designer should use the most accurate method practical that obtains representative and reproducible results and specimen with minimal variability. Many agencies specify certain methodologies for specimen preparation.

The Asphalt Institute recommends that in order to achieve the highest level of accuracy and repeatability of laboratory-prepared specimens, individual samples should be batched rather than multiple specimens being batched, mixed and then divided into individual samples.

**Method 1—Partial fractionation of individual stockpiles**

The smallest practical sieve for a large capacity tray-type shaker is usually 0.15 or 0.075 mm. Fractionate each stockpile sample on each specified sieve, leaving the entire amount passing the smallest sieve as one fraction to be added during batching. The pan material using this method becomes all of the material that passes the 0.075 mm sieve (or whatever sieve is on the bottom of the stack). Large capacity, tray-type mechanical shakers have the capacity to fractionate samples up to 23 or more kg. Care should be taken to prevent overloading of sieve screens. The amount allowed on each sieve is dependent on the nominal maximum aggregate size (NMAS), as outlined in Table 2.5.

A typical batching sheet for one stockpile would appear as shown in Table 3.2 using the following equations, and must be repeated for each stockpile of aggregate to be used:

Determine the grams needed from each aggregate stockpile:

\[
\text{Stockpile grams needed} = \text{Total specimen size} \times \bin \text{split % / 100}
\]

Determine the percent retained on each sieve:

\[
\% \text{ Retained on a sieve} = \% \text{ Passing the next larger sieve} - \% \text{ Passing the sieve}
\]

Determine the amount to be contributed from each individual sieve fraction:

\[
\text{Grams of each fraction required} = \% \text{ Retained} \times \text{Grams Needed / 100}
\]

Care must be taken to assure that the large amounts of pan material shown are uniformly blended and added to the batch sample.
## Table 3.2 Sample of Method 1

<table>
<thead>
<tr>
<th>Size</th>
<th>19-13.2mm</th>
<th>13.2-4.75mm</th>
<th>Fine(passing 2.36mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin Split %</td>
<td>25</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>Grams needed</td>
<td>1250</td>
<td>2250</td>
<td>1500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>% Pass</th>
<th>% Retained</th>
<th>Individual Wt.,gm</th>
<th>Cumulative</th>
<th>% Pass</th>
<th>% Retained</th>
<th>Individual Wt.,gm</th>
<th>Cumulative</th>
<th>% Pass</th>
<th>% Retained</th>
<th>Individual Wt.,gm</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>90</td>
<td>10</td>
<td>125.0</td>
<td>125.0</td>
<td>100</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>100</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>13.2</td>
<td>40</td>
<td>50</td>
<td>625.0</td>
<td>750.0</td>
<td>90</td>
<td>10</td>
<td>225.0</td>
<td>225.0</td>
<td>100</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>9.5</td>
<td>25</td>
<td>15</td>
<td>187.5</td>
<td>937.5</td>
<td>40</td>
<td>50</td>
<td>1125.0</td>
<td>1350.0</td>
<td>100</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4.75</td>
<td>0</td>
<td>25</td>
<td>312.5</td>
<td>1250.0</td>
<td>0</td>
<td>40</td>
<td>900.0</td>
<td>2250.0</td>
<td>90</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2.36</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>1250.0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>2250.0</td>
<td>0</td>
<td>0</td>
<td>375.0</td>
<td>375.0</td>
</tr>
<tr>
<td>1.18</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>1250.0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>2250.0</td>
<td>0</td>
<td>0</td>
<td>300.0</td>
<td>675.0</td>
</tr>
<tr>
<td>Pan</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>1250.0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>2250.0</td>
<td>0</td>
<td>0</td>
<td>825.0</td>
<td>1500.0</td>
</tr>
</tbody>
</table>

# Bin Split should be such that the blended mix of aggregate should satisfy the gradation requirement as per Table 2.5.
Chapter 3 Marshall Method of HMA Mix Design

Method Two—Pre-blending of samples prior to fractionation

This method utilizes a process where a sample of aggregate is prepared by combining a predetermined amount of every stockpile sample into one combined blend and then fractionates the combined aggregate sample into a chosen number of size fractions. This method mimics a batch plant, is relatively quick and easy, but has less flexibility and accuracy than Method 1. Method 2 is dependent on the mix design aggregates submitted being representative of field production and the accuracy of splitting out batching portions that are representative.

Because the aggregate is combined, then fractionated, the specific gravities of each aggregate must be reasonably similar. This method should not be used if lightweight or heavyweight aggregate is blended with regular aggregate. This method also loses some batching versatility because the bin splits are locked in once the combined aggregate is fractionated. Changing the percentages of aggregates used will require the process to be started over.

Stir each bucket or pan as well as possible and scoop the required amount from each bucket into a batching pan. Fractionate the resulting pan using a sieve shaker, making sure to limit the quantity of material on a given sieve so that all particles have an opportunity to reach the sieve openings a number of times during the sieving operation.

After shaking, remove the material from each tray and place in a labeled pan designated for that particular size fraction. Make sure that each pan is as homogeneously mixed as possible. This method can be adjusted to use whichever sieves are desired. For example, if the chosen sieves were 13.2 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm and the pan, it would produce six pans that contain fractionated, combined aggregates. If the chosen sieves were 13.2 mm, 4.75 mm, 0.600 mm and the pan, it would produce four pans that contain fractionated, combined aggregates.

For this example, the following trays were used: 13.2 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm and the pan. When fractionating with fewer than the five tray slots typically present, fill the extra slots at the top with sieve trays larger than the largest particle size of the blend or relief sieves if necessary. Fractionate each pan, placing each resulting size fraction into a separate pan. Calculate the number of grams required of each size fraction to make each 5,000-gram batch as previously described in Method 2 and summarized in Table 3.3.

Table 3.3 Sample of Method 2

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>JMF Combined Aggregate(%) Passing</th>
<th>% Retained on each Fraction</th>
<th>Total Batch Size</th>
<th>Grams of each Fraction required</th>
<th>Cumulative Wt. for Batch, gm</th>
</tr>
</thead>
<tbody>
<tr>
<td>+13.2</td>
<td>96.2</td>
<td>3.8</td>
<td>5000 gm</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>+9.5</td>
<td>83.2</td>
<td>13</td>
<td></td>
<td>650</td>
<td>840</td>
</tr>
<tr>
<td>+4.75</td>
<td>58.4</td>
<td>24.8</td>
<td></td>
<td>1240</td>
<td>2080</td>
</tr>
<tr>
<td>+2.36</td>
<td>43.1</td>
<td>15.3</td>
<td></td>
<td>765</td>
<td>2845</td>
</tr>
<tr>
<td>+1.18</td>
<td>32.8</td>
<td>10.3</td>
<td></td>
<td>515</td>
<td>3360</td>
</tr>
<tr>
<td>Pan</td>
<td>0</td>
<td>32.8</td>
<td></td>
<td>1640</td>
<td>5000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Method 3—Total fractionation of all aggregate materials

Fractionate each aggregate source with a sieve shaker on every specified sieve, with each aggregate fraction individually batched for each specimen. After shaking, remove the material from each tray and place in a separate, labeled pan. Using the gradation data for all aggregate sources and the standard nest of sieves will result in separate pans from which to batch. Fractionate each aggregate individually and keep each fraction in a separate, labeled pan or bucket. Batching will be done using the entire range of sieves in a standard nest, plus the material passing the last sieve in the stack (#200) referred to as “pan material.”

**Table 3.4 Sample of Method 3**

<table>
<thead>
<tr>
<th>Size</th>
<th>Total Specimen Size = 5000 gms</th>
<th>Fine(passing 2.36mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19-13.2mm</td>
<td>13.2-4.75mm</td>
</tr>
<tr>
<td>Bin Split %</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Grams needed</td>
<td>1250</td>
<td>2250</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>% Pass</td>
<td>% Retained</td>
<td>% Pass</td>
</tr>
<tr>
<td>% Pass</td>
<td>% Retained</td>
<td>% Retained</td>
</tr>
<tr>
<td>Individual Wt.,gm</td>
<td>Cumulative</td>
<td>Individual Wt.,gm</td>
</tr>
<tr>
<td>Cumulative</td>
<td>% Pass</td>
<td>% Retained</td>
</tr>
<tr>
<td>Pan</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

It should be noted that Method 3 is susceptible to significant error when batching materials with high levels of dust. It is not uncommon for elevated amounts of static dust (−0.075mm) to “cling” onto and remain in the larger fractionated sizes of material. In order to compensate for this potential error, a prepared trial batch should be analyzed using a washed sieve analysis. The amount of dust (−0.075mm) in excess of that desired will need to be removed from the −0.075mm pan material added during batching. This reduction in pan material will require an adjustment (increase) on the sieve fractions that are determined to retain this fugitive dust (typically the +0.300mm through +0.075mm) in order to obtain an exact batch weight. A thorough understanding of the material being utilized by the designer is necessary when using Method 3. Mix designers are encouraged to use Methods 1 or 2 for ordinary production mix design.
Table 3.5: Approximate Batching Proportion#

<table>
<thead>
<tr>
<th>Nominal Maximum Aggregate Size, mm</th>
<th>Approximate Batching Proportion, %</th>
<th>Aggregate passing the size</th>
</tr>
</thead>
<tbody>
<tr>
<td>38-25mm</td>
<td>25-19mm</td>
<td>19-13.2mm</td>
</tr>
<tr>
<td>13.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26.5</td>
<td>-</td>
<td>16-27</td>
</tr>
<tr>
<td>35.5</td>
<td>11-22</td>
<td>27-43</td>
</tr>
</tbody>
</table>

# All individual case should be batched to meet the table 2.5

The typical allowable range for dust to binder ratio \( P_{0.075}/P_{bc} \) is 0.6–1.2, with the following exceptions: for coarse-graded mixes whose gradation plots below the Primary Control Sieve (PCS) on a 0.45 power chart, the allowable range may be increased to 0.8–1.6.

In general, this property addresses the workability of asphalt mixtures. A low \( P_{0.075}/P_{bc} \) often results in a tender mix, which lacks cohesion and is difficult to compact in the field because it tends to move laterally under the roller. Mixes tend to stiffen as the \( P_{0.075} \) increases, but too much will also result in a tender mix. A mix with a high \( P_{0.075}/P_{bc} \) will often exhibit a multitude of small stress cracks during the compaction process, called check-cracking. This property is usually calculated for dense-graded mixes only.

(c) Determination of mixing and compaction temperature—the temperature to which the asphalt must be heated to produce viscosities of 170 ± 20 centistokes kinematic and 280 ± 30 centistokes kinematic should be established as the mixing temperature and compaction temperatures, respectively. These temperatures can be estimated from a plot of the viscosity (log-log centistokes scale) versus temperature relationship for the asphalt concrete to be used. An example plot is shown in Figure 3.2

![Mixing and Compaction Temperature Chart](attachment:image.png)

Figure 3.2 Determination of Mixing and Compaction Temperatures
(d) **Preparation of mold and hammer**—thoroughly clean the specimen mold assembly and the face of the compaction hammer and heat them in a water bath or on the hot plate to a temperature between 95 and 150°C.

(e) **Preparation of mixtures**—weigh into separate pans for each test specimen the amount of each aggregate size fraction required to produce the required gradation and a batch that will result in a compacted specimen 63.5 ± 1.27 mm (2.5 ± 0.05 in.) in height. This will normally be about 1.2 kg. It is generally desirable to prepare a trial specimen prior to preparing the aggregate batches. If the trial specimen height falls outside the height limits, the amount of aggregate used for the specimen should be adjusted using:

\[
\text{Adjusted mass of aggregate} = 63.5 \times \left(\frac{\text{mass of aggregate used}}{\text{Specimen height (mm) obtained}}\right)
\]

Place the pans in the oven or on the hot plate and heat to a temperature not exceeding 28°C above the mixing temperature specified in (c). (If a hot plate is used, provision should be made for dead space, baffle plate or a sand bath beneath the pans and the hot plate to prevent local overheating.) Charge the mixing bowl with the heated aggregates and dry mix thoroughly. Form a crater in the dry blended aggregate and weigh the required amount of asphalt concrete into the mixture in accordance with the calculated batch weights. At this point the temperature of the aggregate and the asphalt must be within the limits of the mixing temperatures established in (c). Asphalt concrete should not be held at mixing temperatures for more than one hour before using. Mix the aggregate and asphalt cement, preferably with a mechanical mixer or by hand with a trowel, as quickly and thoroughly as possible to yield a mixture having a uniform distribution of asphalt.

Mixing is typically done with either a planetary mixer with wire whips or a five-gallon bucket mixer (Figure 3.3).

![Figure 3.3 Planetary mixer with wire whips (Left), a five-gallon bucket mixer (Right)](image)

The following points are important to remember in the mixing operation:

- Place the aggregate and binder in the oven at the mixing temperature for at least two hours before mixing. To avoid excessive aging of the binder, do not allow it to stay at the mixing temperature for much over the time needed to bring it to temperature and complete the mixing operation.
• Place all mixing bowls, whips and molds in the oven 30 minutes to an hour before mixing. Keep enough molds in the oven to rotate their use, always keeping a hot mold available.

• Keep the binder in smaller containers (no more than a gallon) to avoid aging it from constant reheating. Transfer the hot binder to quart cans or other small containers as needed to make it safer and easier to pour. Small stainless steel pitchers from commercial restaurant supply stores work very well.

• Place the spatula blade on a hot plate, making sure that the wooden handle does not touch the hot plate (usually a heavier nonflammable object is placed on the blade to keep the spatula from slipping off).

• Keep a stack of paper squares next to the scale to intercept the poured binder stream when it is about to reach the proper weight and to dip out excess binder.

• It is good practice to place something on the scale to protect the electronics from overheating when the hot bowl/bucket is placed on it.

• “Butter” the mixing bowl and whip by mixing a dummy batch before subsequent design batches to coat the equipment with binder as an aid in maintaining consistent binder contents.

• Make sure to have an oven set at the compaction temperature ready to receive the freshly mixed batches.

When we are ready to mix, place the mixing bowl/bucket on the scale and tare it. Pour the heated aggregate batch into the bowl and verify the required weight. Form a crater in the center of the aggregate to receive the binder and keep it from flowing to the edges of the bowl. Add the correct number of grams of binder, dipping out any excess binder with a folded paper dipper.

Mix until all of the aggregate is thoroughly coated. ASTM D6926 suggests mixing for approximately 60 seconds for single specimen batches and approximately 120 seconds for multiple specimen batches. When transferring the mixture from the mixing bowl to the conditioning pans, make sure to thoroughly scrape the mixed fines and asphalt from the bowl and whips into the conditioning pans with a hot spatula.

Mixture conditioning

Current ASTM and AASHTO procedures do not require any aging or curing of the mixture prior to Marshall compaction. The Asphalt Institute recommends that Marshall mixes be conditioned according to AASHTO R30.

The absorptive characteristics of aggregates used in asphalt mixes can greatly impact laboratory tests and resulting volumetric calculations. R 30 specifies a 2-hour conditioning period prior to laboratory compaction. Aggregate absorption characteristics can impact both $G_{mb}$ and $G_{mm}$ values. The maximum theoretical specific gravity test procedure, AASHTO T 209, requires a mixture conditioning period of at least 2 hours. In an effort to provide the most accurate mixture design results, the Asphalt Institute recommends that all $G_{mb}$ and $G_{mm}$ mixture samples be conditioned a minimum of 2 hours prior to the compaction of $G_{mb}$ samples and the cooling and testing of $G_{mm}$ samples, regardless of the mix design procedure utilized. Aggregate sources that have high water absorption values (above 2.0 percent) should be conditioned for an extended period of time (up to 4 hours). Figure 3.4 demonstrates how different levels of absorption in the aggregate can greatly affect the increase of $G_{mm}$ over time. AASHTO R 30 gives the standard practice for mixture conditioning. It differentiates between mixture conditioning for volumetric mix design, short-term conditioning for mixture mechanical property testing and long-term conditioning for mixture mechanical property testing. The purpose of the conditioning for volumetric mix design is to allow for binder absorption during the mix design process.
The short-term conditioning for mixture mechanical property testing is designed to simulate the plant-mixing and construction effects on the mixture. The long-term conditioning for mixture mechanical property testing is designed to simulate the aging that the mixture would experience over 7–10 years of service life.

**Figure 3.4 Effects of absorption on $G_{mm}$**

The equipment required for conditioning the mixture includes: oven—a forced-draft oven capable of maintaining the desired temperature setting within ± 5.4°F; thermometers—having a range of 50°C to 260°C, readable to 1°C; and miscellaneous—a shouldow metal pan for heating uncompacted asphalt mix, a metal spoon or spatula, timer and gloves for handling hot materials.

Place the mixture in a shouldow metal pan and spread it to an even thickness between 25 and 50 millimeters in depth. Place the mixture and pan, in the oven for 2 hours ± minutes at a temperature equal to the mixture’s compaction temperature ± 3°C. Note that the conditioning time may need to be increased to be more representative of field conditions when higher absorptive aggregates (more than 2 percent) are used, subject to client approval.

Stir the loose mixture every 60 ± 5 minutes to maintain uniform conditioning. Remove the mixture and pan from the oven after 2 hours ± 5 minutes. The mixture is now conditioned for further testing.

The procedure for short-term conditioning for mixture mechanical property testing is similar to that for volumetric mix design, but the conditioning time is 4 hours ± 5 minutes, and the oven temperature, 135°C ±3°C.

**(f) Packing the mold**—place a filter or nonabsorbent paper disk cut to size in the bottom of the mold. Place the entire batch in the mold with collar, and then spade the mixture vigorously with a heated spatula or towel 15 times around the perimeter and 10 times over the interior. Smooth the surface to a slightly rounded shape. The temperature of the mixture immediately prior to compaction should be within the limits of the compaction temperature established in (c); otherwise, it should be discarded. In no case should the mixture be reheated.

**(g) Compaction of specimens**—place a paper disk on top of the mix and place the mold assembly on the compaction pedestal in the mold holder. As specified according to the design traffic category (Table 3.7), apply 35, 50 or 75 blows with the compaction hammer using a free fall of 457 mm. Hold the axis of the compaction hammer as nearly perpendicular to the base of the mold assembly as possible during compaction. Remove the base plate and collar, and reverse and reassemble the mold. Apply the same number of compaction blows to the face of the reversed specimen. After compaction, remove the
base plate and the paper disks and allow the specimen to cool at room temperature until no deformation will result when removing it from the mold. When more rapid cooling is desired, electric fans may be used, but not water unless the specimen is in a plastic bag. Remove the specimen from the mold by means of an extrusion jack or other compression device, and then place on a smooth, level surface until ready for testing. Normally, specimens are allowed to cool overnight.

**Correlation of the manually and mechanically operated hammers**

There is a tendency for manually operated hammers to yield a higher specimen density than mechanically operated hammers. It has been theorized that a slight kneading effect takes place when the manually operated hammer is dropped at a slight angle from the true-vertical action of the automated hammers. If variations of the standard manual Marshall hammer (e.g., mechanical lift, slanted face and rotating base) are used, correlations with the standard Marshall compaction procedure must be made. This is equally the case if mix samples are reheated before compaction.

*The Asphalt Institute recommends using only mechanical hammers for mix design and field verification. The Asphalt Institute also recommends that the asphalt pavement owner establish a governing compactor which establishes the job mix formula parameters and resulting construction tolerances.*

*The Asphalt Institute further recommends that all laboratory compactors utilized in the quality control, acceptance or assurance of field constructed pavements be correlated to the governing compactor utilized in the mixture design approved by the pavement owner.*

An example of such a correlation is adjusting the number of blows to result in the same volumetric properties. Using the same mix and compaction temperature as in the mix design, compact triplicate specimens at five different blow counts.

As a minimum, specimens should be compacted at the mix design number of blows, ± 5 blows and ± 10 blows. Draw a “number of blows vs. $G_m$ curve” and determine the number of blows required to get the same $G_m$ obtained by the governing compactor used in the mix design. This new correlated blow count should be used for all further testing when utilizing this correlated compactor. The range of blow counts must be large enough to include the results of the governing compactor without extrapolation of the correlation curve. An example of a correlation curve is shown below in **Figure 3.5**.

![Figure 3.5 Compactor correlation curve](image)

**Figure 3.5 Compactor correlation curve**
C3.6 Test procedure

In the Marshall method, each compacted test specimen is subjected to these tests and analysis in the order listed:

- specimen height determination;
- bulk specific gravity determination;
- theoretical maximum specific gravity
- density and voids analysis; and
- stability and flow test.

C3.6.1 Bulk specific gravity determination

The bulk specific gravity test may be performed as soon as the freshly compacted specimens have cooled to room temperature. This test is performed according to ASTM D1188, “Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens” or ASTM D2726, “Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens.”

The SSD method is intended to be used for compacted mixture specimens with water absorption less than or equal to 2.0 percent of the specimen volume as designated in AASHTO T 166 or ASTM D2726.

The water absorption can be determined as follows:

\[
\% \text{ water absorbed by volume} = 100 \times \frac{(B - A)}{(B - C)}
\]

where:

A = dry mass of the specimen in air
B = saturated surface-dry mass of the specimen in air
C = mass of the specimen in water

This calculation must be done on samples suspected of excessive absorption in order to determine which method to use for calculation of \( G_{mb} \). Consideration should be given to preparing an extra specimen for absorption determination. If the specimen is absorptive, and the internal voids become wetted, the sample will not be usable in CoreLok testing.

After mixing, aging and compacting the mixture, the mass of the sample is determined in air (dry), while submerged in water, and then in air again after drying the surface (saturated surface dry). The mass of the oven-dry specimen is being determined in Figure 3.6.

![Figure 3.6 Determination of dry mass of specimen](image)
The next step is to place the specimen in the water bath directly below the scale (not shown) and determine its mass under water. The last step is to determine the mass of the saturated surface dry specimen in air. The saturated surface dry (SSD) mass is obtained by quickly blotting the sample so that the surface is not shiny (Figure 3.7). The bulk specific gravity is the mass of the sample divided by the mass (volume) of water it displaces.

Figure 3.7 Determination of SSD mass of specimen

\[ G_{mb} = \frac{A}{B - C} \]

where:

A = dry mass of the specimen in air
B = saturated surface-dry (SSD) mass of the specimen in air
C = mass of the specimen in water at 25°C

The “mass” part of the standard specific gravity formula is the dry mass of the specimen in air. The “volume” part of the formula is determined in the denominator of the above formula, “(B – C).” The surface of the specimen has thousands of small irregularities, so the volume cannot be accurately computed by the standard formula for the volume of a cylinder. Archimedes’ Principle is used in this method to determine the volume. It says that the buoyant force on an object is equal to the mass of the water it displaces. The buoyant force plus the immersed mass equals the SSD mass in air. When tested at 25°C, the mass of displaced water in grams is equal to the volume of water in cubic centimeters, therefore the formula “(B–C)” accurately represents the volume of the specimen.

C3.6.2 Theoretical specific gravity determination

The theoretical maximum specific gravity of an asphalt mixture (G\text{mm}), is the specific gravity of the binder coated aggregate only, with no air voids. Determining the theoretical maximum specific gravity (G\text{mm}) of loose asphalt mixtures is another fundamental component of asphalt mix design and testing that involves a mass divided by a volume multiplied by the unit mass of water. In this case, the mass includes both the mass of the aggregate and the mass of the binder. The volume includes only the effective volume of the aggregate and the volume of the binder. If G\text{mb} and G\text{mm} samples had the same dry weight in air, the numerators of the specific gravity equation would be the same for G\text{mb} and G\text{mm}, but the denominator of the G\text{mm} calculation is smaller because it does not include the volume of air.
Therefore, $G_{mm}$ must always be a larger number than $G_{mb}$. Theoretically, if a $G_{mb}$ sample could be compacted until 0 percent air voids remain, the $G_{mb}$ and $G_{mm}$ would be equal.

The most commonly used practice for determining the theoretical maximum specific gravity is standardized in the following ASTM and AASHTO test methods:

- ASTM D2041 Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures; and
- AASHTO T 209 Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA).

There are three basic steps in determining the theoretical maximum specific gravity. The loose mix is warmed and separated into loose, individually coated aggregates. A minimum mass, specified in T 209, of the dry loose mix is split out and placed in a metal bowl or calibrated pycnometer and covered with water. A vacuum lid is fitted and secured to the bowl or pycnometer and placed on a vibratory shaker table. A vacuum pump is started and the manometer or absolute pressure gauge reading is used to determine the proper vacuum adjustment. Once the proper (almost absolute, 27.5 mm Hg) vacuum is obtained, the shaker table is started. This provides gentle agitation to help in the removal of any air between particles. The agitation ensures that the air in the mixture is as close as possible to zero. The theoretical maximum specific gravity is calculated using the equation for the specific procedure utilized. $G_{mm}$ is the mass of the coated aggregate divided by the volume of coated aggregate. Air voids are calculated from the bulk and maximum specific gravities ($G_{mb}$ and $G_{mm}$). The ratio of these two specific gravities is actually the percent by volume of solids (in decimal form).

A common source of error with this test is that technicians do not calibrate (verify) the mass of the vacuum container filled with water often enough. This is not usually a problem in labs where only distilled water is used for the test, but field labs often have water tanks that serve the entire lab and are refilled periodically, sometimes from different sources. Because it only takes a few minutes to calibrate, more consistent results will be generated if the vacuum containers are calibrated daily or even before each test.

In order to calculate the volumetric properties of a mixture, a $G_{mb}$ and $G_{mm}$ must be determined at each trial binder percentage utilized in the mix design.

Compaction procedures provide the $G_{mb}$ values for each sample, which are then averaged for each trial binder content. The appropriate $G_{mm}$ value must also be determined at each trial binder percentage. Some designers elect to prepare samples and conduct $G_{mm}$ testing at each trial binder percentage. As previously discussed, the $G_{mm}$ directly accounts for the volume of asphalt binder absorbed by the aggregate. The Asphalt Institute considers the asphalt absorption constant and not dependent on the amount of binder added to the mix, as long as the binder content added to the mixture exceeds the absorption value of the aggregate. This position allows the designer to prepare and determine the $G_{mm}$ at one laboratory trial binder content. The $G_{mm}$ values for the remaining trial binder contents, or at any binder content, can then be calculated by computing an effective specific gravity of the aggregate, $G_{se}$. $G_{se}$ is a constant that can be used to back-calculate $G_{mm}$ at any asphalt binder content.

**Determining the $G_{se}$ — effective specific gravity of the aggregate**

The effective specific gravity is the ratio of the oven dry mass of a unit volume of aggregate (including both the solid volume of the aggregate and the water permeable voids not filled with absorbed asphalt as shown in Figure 3.8) to the mass of the same volume of water. When only one $G_{mm}$ is conducted in the laboratory, the designer should select a binder content that is equal to or greater than the anticipated design binder content in order to assure thorough coating and minimize water intrusion into the
aggregate during vacuum testing. After finding the average of two $G_{mm}$ samples at a single binder content (or if desired, at every trial binder percentage), $G_{se}$ can be calculated using the following equation:

$$G_{se} = \frac{P_s}{100} \frac{P_b}{G_{mm}} - \frac{P_b}{G_b}$$

where:

- $G_{se}$ = effective specific gravity of aggregate
- $P_s$ = percentage of aggregate by total mix weight
- $P_b$ = percentage of binder by total mix weight, at which the $G_{mm}$ test was performed
- $G_{mm}$ = maximum specific gravity of paving mixture
- $G_b$ = specific gravity of binder

### Determining $G_{mm}$ at other binder contents

The $G_{se}$ is then used to calculate $G_{mm}$ at each of the other binder contents. This step is not necessary if the designer has performed $G_{mm}$ testing at each trial binder percentage. $G_{mm}$ can be visually determined from the phase diagram in Figure 3.9 and is defined by the following relationship:

$$G_{mm} = M_{mb} \rho / V_{mm}$$

The calculation of $G_{mm}$ at other binder contents, utilizing $G_{se}$, is accomplished with the following equation:

$$G_{mm} = \frac{100}{G_{se} + \frac{P_b}{G_b}}$$
where:

\[ P_s + P_b = 100 \]

\[ M_{mb} = \text{bulk mass of paving mixture (which would be the same as } M_{mm}, \text{ since the air has no mass), typically in g} \]

\[ V_{mm} = \text{volume of aggregate and binder, typically in cm}^3 \]

\[ \rho = \text{density of water, } 1.000 \text{ g/cm}^3 \]

Note that as the binder content increases, \( G_{mm} \) always decreases. This is because the percentage of aggregate, which has a higher specific gravity, necessarily decreases for a unit volume with an increase in the percentage of binder, which has a lower specific gravity.

**C3.7 Marshall testing**

**C.3.7.1 Equipment for stability and flow tests**

The equipment required for the testing of the 101.6-mm (4-in.) diameter by 63.5-mm (2.5-in.) height specimens is as follows:

- The Marshall testing machine is a compression testing device conforming to ASTM D6927.

It is designed to apply loads to test specimens through cylindrical segment testing heads [inside radius of curvature of 51 mm] at a constant loading rate of 51 mm per minute. Two perpendicular guide posts are included to allow the two segments to maintain horizontal positioning and free vertical movement during the test.

It is equipped with a calibrated proving ring for determining the applied testing load, a Marshall stability testing head for use in testing the specimen, and a Marshall flow meter (or automatic recording device) for determining the amount of deformation at the maximum load in the test. A universal testing machine equipped with suitable load and deformation indicating devices may be used instead of the Marshall testing frame.

- The water bath must be at least 150 mm deep and thermostatically controlled to 60°C ± 1°C. The tank should have a perforated false bottom or be equipped with a shelf for suspending specimens at least 50 mm above the bottom of the bath.

**C.3.7.2 Stability and flow test procedures**

After the bulk specific gravity of the test specimens has been determined, the following stability and flow tests are performed:

(a) determination of specimen height;

(b) immerse specimen in water bath at 60°C ± 1°C (140°F ± 1.8°F) for 30 to 40 minutes before testing, or in an oven at the same temperature for 120 to 130 minutes; and

(c) use an automatic recording device, or use a proving ring and flow meter (as shown in Figure 3.8).
Place the flow meter over the marked guide rod and “zero” the flow meter while holding it firmly against the upper segment of the testing head while the load is being applied.

The same assembly of the testing head and flow meter must be used in testing all specimens. Specimens should be 101.6 ± 0.25 mm (4.00 ± 0.01 in.). Otherwise, an initial and final reading of the flow meter is required for the determination of the flow value.

(d) Thoroughly clean the inside surfaces of the testing heads. Temperature of heads should be maintained between 21.1 and 37.8°C using a water bath, when required.

Lubricate guide rods with a thin film of oil so that the upper test head will slide freely without binding. If a proving ring is used to measure applied load, check to see that the dial indicator is firmly fixed and “zeroed” for the “no-load” position.

(e) With the testing apparatus ready, remove the test specimen from water bath and carefully dry surface with a towel. Place specimen in lower testing head and center; then fit upper testing head into position and center complete assembly in loading device. Place flow meter over marked guide rod as noted in (c) above.

(f) Apply testing load to specimen at a constant rate of deformation, 51 mm per minute, until failure occurs. The point of failure is defined when the maximum load reading is obtained. The total force in Newtons (N) required to produce failure of the specimen should be recorded as its Marshall stability value.

(g) While the stability test is in progress (if not using an automatic recording device), hold the flow meter firmly in position over the guide rod and remove immediately when the load begins to decrease, take reading and record.

This reading is the flow value for the specimen, expressed in units of 0.25 mm. For example, if the specimen deformed 3.8 mm, the flow value is 15.

(h) The entire procedure for both the stability and flow measurements, starting with the removal of the specimen from the water bath, should be completed within a period of 30 seconds.

(i) The Marshall stability is corrected for specimens with a height different than 63.5 mm (Table 3.6).

Table 3.6 Stability Correlation Ratios

<table>
<thead>
<tr>
<th>Volume of Specimen, cm³</th>
<th>Approximate Thickness of Specimen, mm</th>
<th>Correlation Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 to 213</td>
<td>25.4</td>
<td>5.56</td>
</tr>
<tr>
<td>214 to 225</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>226 to 237</td>
<td>28.6</td>
<td>4.55</td>
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<tr>
<td>238 to 250</td>
<td>30.2</td>
<td>4.17</td>
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<tr>
<td>251 to 264</td>
<td>31.8</td>
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<td>265 to 276</td>
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<td>3.57</td>
</tr>
<tr>
<td>277 to 289</td>
<td>34.9</td>
<td>3.33</td>
</tr>
<tr>
<td>290 to 301</td>
<td>36.5</td>
<td>3.03</td>
</tr>
<tr>
<td>302 to 316</td>
<td>38.1</td>
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<td>2.27</td>
</tr>
<tr>
<td>341 to 353</td>
<td>42.9</td>
<td>2.08</td>
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<tr>
<td>354 to 367</td>
<td>44.4</td>
<td>1.92</td>
</tr>
<tr>
<td>368 to 379</td>
<td>46</td>
<td>1.79</td>
</tr>
<tr>
<td>380 to 392</td>
<td>47.6</td>
<td>1.67</td>
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</tbody>
</table>
### C.3.7.3 Marshall Method of HMA Mix Design

**Table C.3.7.3**

<table>
<thead>
<tr>
<th>Volume of Specimen, cm³</th>
<th>Approximate Thickness of Specimen, mm</th>
<th>Correlation Ratio</th>
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</thead>
<tbody>
<tr>
<td>393 to 405</td>
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<tr>
<td>406 to 420</td>
<td>50.8</td>
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<tr>
<td>421 to 431</td>
<td>52.4</td>
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<td>432 to 443</td>
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<td>444 to 456</td>
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<td>457 to 470</td>
<td>57.2</td>
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<td>471 to 482</td>
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<td>483 to 495</td>
<td>60.3</td>
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<td>496 to 508</td>
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<tr>
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</tr>
<tr>
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<td>536 to 546</td>
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<td>0.93</td>
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<td>560 to 573</td>
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<tr>
<td>574 to 585</td>
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<td>586 to 598</td>
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<tr>
<td>599 to 610</td>
<td>74.6</td>
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</tr>
<tr>
<td>611 to 625</td>
<td>76.2</td>
<td>0.76</td>
</tr>
</tbody>
</table>

**Notes:**

1. The measured stability of a specimen multiplied by the ratio for the thickness of the specimen equals the corrected stability for a 63.5-mm specimen.

2. Volume-thickness relationship is based on a specimen diameter of 101.6 mm.

**C.3.7.3 Marshall stability and flow considerations**

Marshall stability is the peak resistance load obtained during a constant rate of deformation. Marshall flow is a measure of the deformation (elastic plus plastic) of the specimen determined during the stability test. The determination of the Marshall flow with an automatic recording device will typically produce a plot comparable to the stylized Figure 3.9.

![Marshall Stability Curve](image)

**Figure 3.9 Determining Marshall Flow**

The bottom portion of the Marshall stability versus Marshall flow curve shows the effects of irregularities on the specimen surface until full contact (seating) of the testing heads and the specimen surface is achieved. Therefore, when using an automatic recording device, the recorded Marshall flow
must be corrected by subtracting the flow portion during “seating” of the specimen (as shown in Figure 3.9). To determine the correct start of the flow reading, a tangent line should be drawn connecting two points on the stability–flow curve, representing 25 percent and 75 percent of Marshall stability. Where this tangent line intersects the x-axis is the start of Marshall flow.

No correction is necessary when using a proving ring and flow meter, since the flow meter has been “zeroed out” on a calibrated 4.00-inch metal disk or specimen.

If the flow at the selected optimum binder content is above the upper specified limit, the mix is considered too plastic or unstable. If the flow is below the lower specified limit, the mix is considered too brittle. The stability and flow results are highly dependent on binder grade, binder quantity and aggregate structure.

C3.8 Density and voids analysis

After the completion of the stability and flow test, a density and voids analysis is made for each series of test specimens.

(a) Average the bulk specific gravity values for all test specimens of a given asphalt content; values obviously in error should not be included in the average. The average value of bulk specific gravity for each binder content should be used in further computations of voids data.

(b) Determine the average unit weight for each asphalt content by multiplying the average bulk specific gravity value by the density of water (1,000 kg/m³)

(c) Determine the theoretical maximum specific gravity (Gₘₘₐₓ by ASTM D2041) for at least two asphalt contents, preferably on mixes at or near the design asphalt content. An average value for the effective specific gravity of the total aggregate is then calculated from these values.

(d) Using the effective (Gₑ) and bulk specific gravity (Gₘₜₜ) of the total aggregate, the average bulk specific gravities of the compacted mix (Gₑₘ), the specific gravity of the asphalt (Gₐ), and the maximum specific gravity of the mix (Gₘₘₐₓ) determined above in (c), calculate the percent absorbed asphalt (Pₐₐ) by weight of dry aggregate, percent air voids (Pₐ), percent voids filled with asphalt (VFA) and percent voids in the mineral aggregate (VMA).

Percent air voids in compacted mixture

Keep in mind that this manual defines Pₐ as the percentage of air voids by volume and Vₐ as the measured volume of air voids. They consist of the small air spaces between coated aggregate particles. The property Pₐ can be visually determined from the phase diagram and is defined by the following relationship:

\[ Pₐ = 100 \times \frac{Vₐ}{Vₘₜₜ} \]

Although the Pₐ can be calculated several different ways, the following equation is most commonly used:

\[ Pₐ = 100 - \left( 100 \times \frac{Gₘₜₜ}{Gₘₘₐₓ} \right) \]

where:

Pₐ = air voids in compacted mixture, percentage of total volume

Gₘₘₐₓ = maximum specific gravity of paving mixture

Gₘₜₜ = bulk specific gravity of paving mixture
In a laboratory-compacted mixture is an important part of selecting the proper binder content of the asphalt mixture. A reasonable rule of thumb says that for each 1.0 percent decrease in the air void content for a given aggregate structure, the design binder content increases 0.3 to 0.4 percent.

**Percent VMA in compacted mixture**

The voids in the mineral aggregate, VMA, are defined as the inter-granular 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. VMA can be visually determined from the phase diagram and is defined by the following relationship:

\[
VMA = 100 \times \frac{V_a + V_{be}}{V_{mb}}
\]

VMA is most readily calculated utilizing the following equation:

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

where:

- **VMA** = voids in the mineral aggregate
- **G_{mb}** = bulk specific gravity of paving mixture
- **P_s** = percentage of aggregate by total mix weight
- **G_{sb}** = bulk (dry) specific gravity of the aggregate
- **V_a** = volume of voids in compacted mixture, typically in cm\(^3\)
- **V_{be}** = volume of the effective (nonabsorbed) binder, typically in cm\(^3\)
- **V_{mb}** = total volume of compacted mixture, typically in cm\(^3\)

The equations shown above are for analyzing mixture compositions that are determined as percent by weight of the total mixture. If the mixture composition is determined as percent by weight of aggregate, the following equation must be utilized to calculate VMA:

\[
VMA = 100 - \frac{G_{mb} \times 100}{G_{sb}} \times \frac{100 + P_b}{100} \times 100
\]

**Because the VMA does not include the water permeable voids in the aggregate, the bulk dry G_{sb} must be utilized in calculating VMA.** Table 3.7 illustrates the effects of using other aggregate.

**Table 3.7 Proper Aggregate Specific Gravity for Use in VMA Calculation**

<table>
<thead>
<tr>
<th>Example Asphalt Mixture Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Specific Gravity of Compacted Mixture (G_{mb})</td>
<td>2.406</td>
</tr>
<tr>
<td>Max. Theoretical Specific Gravity of Compacted Mixture (G_{mm})</td>
<td>2.494</td>
</tr>
<tr>
<td>Asphalt Content, percentage by weight of total mix (P_b)</td>
<td>5.1</td>
</tr>
<tr>
<td>Specific Gravity of Asphalt Cement (G_b)</td>
<td>1.011</td>
</tr>
<tr>
<td>Aggregate Specific Gravity Test Parameters:</td>
<td></td>
</tr>
<tr>
<td>A = 3357.8 g (Mass of oven-dry aggregate in air)</td>
<td></td>
</tr>
<tr>
<td>B = 3439.8 g (Mass of saturated surface-dry aggregate in air)</td>
<td></td>
</tr>
<tr>
<td>C = 2173.1 g (Mass of saturated aggregate in water)</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3 Marshall Method of HMA Mix Design

<table>
<thead>
<tr>
<th>Aggregate Specific Gravity</th>
<th>Specific Gravity Calculation</th>
<th>Example Value</th>
<th>Resulting VMA (%)</th>
<th>Calculated VMA Filled With:</th>
<th>Correct? (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Dry - Gsb (Determined from Aggregate Test)</td>
<td>( \frac{A}{B - C} )</td>
<td>2.651</td>
<td>13.9</td>
<td>Air + Effective Binder</td>
<td>Yes</td>
</tr>
<tr>
<td>Bulk SSD - Gsb, SSD (Determined from Aggregate Test)</td>
<td>( \frac{B}{B - C} )</td>
<td>2.716</td>
<td>15.9</td>
<td>Not Applicable (SSD aggregate weight in numerator results in inaccurate volume calculation)</td>
<td>No</td>
</tr>
<tr>
<td>Effective - Gse (Calculated from ( G_{mm} ))</td>
<td>( \frac{P_s}{100 \left( \frac{G_{mm}}{G_{ssd}} \right) - P_b G_b} )</td>
<td>2.708</td>
<td>15.7</td>
<td>Air + Effective Binder + Absorbed Binder</td>
<td>No</td>
</tr>
<tr>
<td>Apparent - Gsa (Determined from Aggregate Test)</td>
<td>( \frac{A}{A - C} )</td>
<td>2.834</td>
<td>19.4</td>
<td>Air + Effective Binder + Water- Permeable Voids in Aggregate</td>
<td>No</td>
</tr>
</tbody>
</table>

As the nominal maximum aggregate size of the mix decreases, the surface area of the total aggregate structure increases. Therefore, the percentage of binder necessary to adequately coat the particles increases. Since the target air voids (\( P_a \)) typically remains the same, the VMA must increase to allow sufficient room for the additional asphalt binder.

**Percent VFA in compacted mixture**

The voids filled with asphalt(VFA) is the percentage by volume of the VMA that is filled with the effective binder. VFA, like VMA, also tends to increase as the mix becomes finer and gains more total aggregate surface area. The VFA can be calculated with either of the following equations.

VFA can be visually determined from the phase diagram and is defined by the following relationship:

\[
VFA = 100 \times \frac{V_{be}}{V_{be} + V_a}
\]

VFA is most readily calculated with the following equation:

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

where:

VFA = voids filled with asphalt

VMA = voids in the mineral aggregate

\( P_a \) = air voids in compacted mixture, percentage of total volume

\( V_{be} \) = volume of the effective (non absorbed) binder, typically in cm³

\( V_a \) = volume of voids in compacted mixture, typically in cm³

**C3.9 Interpretation of test data**

**C.3.9.1 Preparation of test data**

Prepare the stability and flow values and void data.

(a) Measured stability values for specimens that depart from the standard 63.5 mm thickness should be converted to an equivalent 63.5mm value by means of a conversion factor. Applicable correlation ratios to convert the measured stability values are set forth in Table 3.6. Note that the conversion may be made on the basis of either measured thickness or measured volume.
(b) Average the flow values and the final converted stability values for all specimens of given asphalt content. Values that are obviously in error should not be included in the average.

(c) Prepare separate graphical plots for the following values and connect plotted points with a smooth curve that obtains the “best fit” for all values, as illustrated in Figure 3.10

- percent air voids (Pa) versus asphalt content;
- percent voids in mineral aggregate (VMA) versus asphalt content;
- percent voids filled with asphalt (VFA) versus asphalt content;
- unit weight of total mix versus asphalt content;
- stability versus asphalt content; and
- flow versus asphalt content.

Figure 3.10 Test Property Curves for Hot Mix Design Data by the Marshall Method
(d) Determine the optimum binder content and properties of the mix by using these graphs.

The Asphalt Institute recommends that the final selected mix design should be one whose aggregate structure and binder content, compacted to the design number of blows, results in 4 percent air voids and satisfactorily meets all of the other established criteria in Table 3.8. Deviations from the recommended design criteria should be clearly specified in the project documents and must be appropriate for the intended use of the asphalt mixture. The mixture should contain as much asphalt binder as possible to maximize durability, while also maintaining the stability required to support the intended loads for the life of the pavement.

**Table 3.8 Marshall Mix Design Criteria**

<table>
<thead>
<tr>
<th>Marshall Method Criteria</th>
<th>As per MS-2</th>
<th>As per DOR Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light Traffic&lt;sup&gt;2&lt;/sup&gt; Surface &amp; Base</td>
<td>Medium Traffic&lt;sup&gt;2&lt;/sup&gt; Surface &amp; Base</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Compaction, number of blows each end of specimen</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>Stability, N</td>
<td>3336</td>
<td>-</td>
</tr>
<tr>
<td>Flow&lt;sup&gt;3,4&lt;/sup&gt;, 0.25 mm (0.01 in.)</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Percent Air Voids&lt;sup&gt;6&lt;/sup&gt;</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>NMAS, mm</td>
<td>13.2</td>
<td>13</td>
</tr>
<tr>
<td>Minimum VMA, percent</td>
<td>26.5</td>
<td>11</td>
</tr>
<tr>
<td>Percent Voids Filled With Asphalt (VFA)</td>
<td>70</td>
<td>80</td>
</tr>
</tbody>
</table>

**Notes:**
1. All criteria, not just stability value alone, must be considered in designing an asphalt paving mix.
2. Traffic classifications
   - Light Traffic conditions resulting in a 20-year Design ESAL < 10<sup>4</sup>
   - Medium Traffic conditions resulting in a 20-year Design ESAL between 10<sup>4</sup> and 10<sup>6</sup>
   - Heavy Traffic conditions resulting in a 20-year Design ESAL > 10<sup>6</sup>
3. The flow value refers to the point where the load begins to decrease. When an automatic recording device is used, the flow should be corrected.
4. The flow criteria were established for neat asphalts. The flow criteria are often exceeded when polymer modified or rubber-modified binders are used. Therefore, the upper limit of the flow criteria should be waived when polymer modified or rubber-modified binders are used.
5. Percent voids in the mineral aggregate are to be calculated on the basis of the ASTM bulk specific gravity for the aggregate.
6. Percent air voids should be targeted at 4 percent. This may be slightly adjusted if needed to meet the other Marshall criteria.

A usage with much lighter loads, such as a bike path, may specify 3 percent air voids and reduce the compaction to only 35 blows for increased durability.
C.3.9.2 Trends and relations of test data

By examining the test property curves plotted on Figure 3.10, information can be learned about the sensitivity of the mixture to asphalt content. The test property curves have been found to follow a reasonably consistent pattern for dense-graded asphalt paving mixes, but variations do and will occur. Trends generally noted are:

- The stability value increases with increasing asphalt content up to a maximum, after which the stability decreases.
- The flow value consistently increases with increasing asphalt content.
- The curve for unit weight of total mix follows the trend similar to the stability curve, except that the maximum unit weight normally (but not always) occurs at slightly higher asphalt content than the maximum stability.
- The percent of air voids, Pa, steadily decreases with increasing asphalt content, ultimately approaching a minimum void content.
- The percent voids in the mineral aggregate, VMA, generally decreases (because of better compaction) to a minimum value, and then increases with increasing asphalt content, because the aggregate is starting to be pushed apart by excessive binder in the mix.
- The percent voids filled with asphalt, VFA, steadily increases with increasing asphalt content because the VMA is being filled with asphalt.

C3.10 Selection of Design Binder Content (OBC)

The Asphalt Institute recommends that the final selected mix design should be one whose aggregate structure and binder content, compacted to the design number of blows, results in 4 percent air voids and satisfactorily meets all of the other established criteria in Table 3.8. Deviations from the recommended design criteria should be clearly specified in the project documents and must be appropriate for the intended use of the asphalt mixture. The mixture should contain as much asphalt binder as possible to maximize durability, while also maintaining the stability required to support the intended loads for the life of the pavement.

<table>
<thead>
<tr>
<th>Composition for</th>
<th>BC</th>
<th>DBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMAS 19 mm</td>
<td>13.2 mm</td>
<td>26.5 mm</td>
</tr>
<tr>
<td>Bitumen content % by mass of total mix</td>
<td>Min 5.2</td>
<td>Min 5.4</td>
</tr>
</tbody>
</table>

Corresponds to specific gravity of aggregates being 2.7. In case aggregate have specific gravity more than 2.7, the minimum bitumen content can be reduced proportionately. Further the region where highest daily mean air temperature is 30°C or lower and lowest daily air temperature is -10°C or lower, the bitumen content may be increased by 0.5 percent.

C3.10 Modified Marshall method for large aggregate

The procedure is basically the same as the original Marshall mix design method except for these differences that are due to the larger specimen size:

- The hammer weighs 10.2 kg and has a 149.4-mm flat tamping face. Only a mechanically operated device is used for the same 457-mm drop height.
- The specimen has a 152.4-mm diameter by 95.2-mm height.
• The batch weights are typically 4,050 g.

• The equipment for compacting and testing (molds and breaking heads) are proportionately larger to accommodate the larger specimens.

• The mix is placed in the mold in two approximately equal increments, with spading performed after each increment.

• The number of blows needed for the larger specimen is 1.5 times (75 or 112 blows) of that required for the smaller specimen (50 or 75 blows) to obtain equivalent compaction.

• The design criteria should be modified as well. The minimum stability should be 2.25 times, and the range of flow values should be 1.5 times the criteria listed in Table 3.8.

• The correction values as listed in Table 3.10 should be used to convert the measured stability values to an equivalent value for a specimen with a 95.2 thickness.

**Table 3.10 Stability Corrections for Large Stone Marshall Mixes in 6” Molds**

<table>
<thead>
<tr>
<th>Approximate Height, mm</th>
<th>Specimen Volume,(cc)</th>
<th>Correlation Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.9</td>
<td>1608 to 1626</td>
<td>1.12</td>
</tr>
<tr>
<td>90.5</td>
<td>1637 to 1665</td>
<td>1.09</td>
</tr>
<tr>
<td>92.1</td>
<td>1666 to 1694</td>
<td>1.06</td>
</tr>
<tr>
<td>93.7</td>
<td>1695 to 1723</td>
<td>1.03</td>
</tr>
<tr>
<td>95.2</td>
<td>1724 to 1752</td>
<td>1.00</td>
</tr>
<tr>
<td>96.8</td>
<td>1753 to 1781</td>
<td>0.97</td>
</tr>
<tr>
<td>98.4</td>
<td>1782 to 1810</td>
<td>0.95</td>
</tr>
<tr>
<td>100</td>
<td>1811 to 1839</td>
<td>0.92</td>
</tr>
<tr>
<td>101.6</td>
<td>1840 to 1868</td>
<td>0.9</td>
</tr>
</tbody>
</table>
# Test Report Showing Typical Lab Data for Design by the Marshall Method

<table>
<thead>
<tr>
<th>Name of Project:</th>
<th>Location:</th>
<th>Date:</th>
</tr>
</thead>
</table>

**Proportion of Aggregate fractions:**
- 38.0-25.0 mm
- 25.0 to 19.0 mm
- 19.0 to 13.2 mm
- 13.2 to 4.75 mm
- 4.75 to 2.36 mm
- Passing 2.36 mm

**Compaction:**

**Bitumen Viscosity Grade:**

**Sp.Gravity of Aggregate blend (Gs):**

**Theoretical max. Sp.Gravity of mix (Gmm):**

**Effective Sp. Gravity of Aggregate (Gse):**

**Absorbed Bitumen (Pb):**

**Specimen Diameter (in mm):**

<table>
<thead>
<tr>
<th>SN</th>
<th>Bitumen, % (Ps)</th>
<th>Filler/Dust %</th>
<th>Aggregate Mix, % (Pb)</th>
<th><strong>Specification</strong></th>
<th><strong>Mass, gm</strong></th>
<th>Bulk Volume, cm³</th>
<th>Bulk S.G. of Specimen (Gsb)</th>
<th>% Air Void (Pa)</th>
<th>% VMA</th>
<th>% VFA</th>
<th>Stability, N</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>In air</td>
<td>In water</td>
<td>SSD in air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

\[
P_s + P_b = 100\%
\]

\[
G_{mm} = \frac{100}{G_{se} + \frac{P_s}{G_b}}
\]

\[
G_{sb} = \frac{P_1}{G_1} + \frac{P_2}{G_2} + \ldots + \frac{P_n}{G_n}
\]

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

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

\[
VFA = 100 x \frac{VMA - P_a}{VMA}
\]