10.9 Marshall Stability and Flow

10.9.1 Introduction

The Marshall test method is widely used for the design and control of asphaltic concrete and hot rolled asphalt materials, it cannot be applied to open textured materials such as bitumen macadam. Materials containing aggregate sizes larger than 20 mm, are liable to give erratic results.

The full Marshall method is a method of bituminous mix design in addition to being a quality control test. The details given below related mainly to its use as a quality control test. The suitability of materials for the design of Marshall asphalt requires that a numbers of tests are performed on the materials. Tests normally performed are:

1. Asphalt :
   (a) Penetration  (b) Viscosity  (c) Solubility (d) Specific gravity  (e) Fire & flash point  (f) Softening point.

2. Aggregates :
   (a) Percent wear  (b) Unit weight (c) Sieve analysis  (d) Specific gravity  (e) Absorption.

The preliminary mix designs, the scheme for analysing aggregate will be governed, to some extent, by method of producing the gradation during construction.

10.9.2 Scope

The basic Marshall test consists essentially of crushing a cylinder of bituminous material between two semi-circular test heads and recording the maximum load achieved (i.e. the stability) and the deflection at which the maximum load occurs (i.e. the flow).

In common with many other tests, the bulk of the work is involved in preparing the samples for testing.

10.9.3 Apparatus

The samples are prepared in 100 mm diameter moulds which are fitted with a base and collar (Figure 10.9.1) the sample is compacted using a hammer consisting of a sliding weight which falls onto a circular foot (Figure 10.9.2) during compaction the mould is held on a hardwood block which is rigidly fixed to a concrete base (Figure 10.9.3).

The sample is removed from the mould using an extraction plate and press (Figure 10.9.1) and heated to the test temperature of  60° C in a water bath.

The cylindrical specimens are tested on their sides between test heads similar to those shown in Fig. 10.9.4. The flow is measured with a dial gauge and the stability is measured with a proving ring. A motorised load frame is required for the test.
Figure 10.9.1 Marshall Test Compaction and Extraction Equipment

Dimensions are in millimetres.
Figure 10.9.2  Marshall Compaction Hammer

Mandatory requirements:
- Diameter of foot: 98.5 ± 0.125
- Length of free fall: 457
- Mass of sliding mass: 4.535 kg
(Other dimensions are approximate)

- Handle screwed and pinned
- Foot screwed and locked
- Hard face
- Finger guard
- Compression spring:
  - Free length: 51
  - Wire diameter: 3.175
  - Mean diameter: 27.0 - 28.6
  - Number of coils: 4
- Rod-nut screwed and riveted on end
- Sliding mass: 4.535 kg
  - 457 free fall
- Handle screwed and pinned
Figure 10.9.3 Marshall Compaction Pedestal

Dimensions are in millimetres.

NOTE. A suitable framework is secured to the pedestal to ensure that the compaction hammer is kept vertical.
Figure 10.9.4  Marshall Testing Heads

NOTE. Frequent checks on inner radius of segments and on alignment of guide posts are necessary as high loads may permanently distort the testing head.

Dimensions are in millimetres.
10.9.4 Sampling

Due to the various uses which may be made of Marshall tests, the materials for test may be obtained in one of the following forms:

a) 100 mm diameter bituminous cores cut from an existing pavement using a core cutting machine.

b) Ready-mixed bituminous material obtained from a mixing plant or at the point of laying, and sampled in accordance with Chapter 2.

c) A sample of mixed aggregate obtained from the mixing plant together with a separate sample of bitumen obtained from the storage tank at the mixing plant in accordance with Chapter 2.

Note. A sample of mixed aggregate may be obtained from a mixing plant by batching the specified aggregate weights into the mixer but not allowing any bitumen to be batched. The aggregate sample is then discharged into a clean lorry where it may be sampled in accordance with Chapter 2.

d) Samples of the various sized aggregates in use at the mixing plant sampled in accordance with Chapter 2 together with a separate sample of bitumen sampled in accordance with Chapter 2.

In the case of a sample of type (a), the core may be tested without further preparation. It must, however, be of the correct diameter and height. It is doubtful if samples obtained in this manner give results which are closely comparable to laboratory compacted specimens; however, the taking of cores is a valuable way to check the compacted density of the ‘as laid’ material and the small amount of additional work in determining the stability and flow is justified. If the densities obtained from cores (or sand replacement tests) are significantly below those of laboratory compacted specimens, attention should be paid to the methods of laying and compacting.

For many quality control purposes samples of type (b) are the most useful as they may be compacted, after re-heating in an oven to the required temperature. The delay between initial mixing and compacting should be as short as possible. With this type of sample separate test on the mixed aggregate will be required to determine the void content.

It is essential to make frequent checks on the combined aggregate from an asphalt plant. The most important factors to be checked are the aggregate temperature at the time of mixing and the grading of the mixed aggregate. It may, therefore, be convenient to obtain separate samples of aggregate and bitumen (type (c) sample) and mix them in the required proportions in the laboratory. As the aggregate will be discharged from the mixer in a dry state, there is considerable risk of segregation and the greatest care should be taken in obtaining a representative sample. If there are reasons to suspect that the bitumen at the mixing plant has been overheated, it may be worth while to check the penetration as excessive heating hardens the bitumen. One particular use of this method of sampling is that if some adjustment is required to the bitumen content, a number of samples may be made at various bitumen contents to determine which is the most satisfactory.

To maintain the quality of a bituminous material, it is necessary to check, at regular intervals, the various sizes of aggregate for grading, cleanliness, shape, strength etc. If it is required to study the effects of varying the aggregate, or bitumen proportions, it will be necessary to obtain separate samples of each
aggregate size to be used in addition to a sample of the bitumen (a type (d) sample).

10.9.5 Sample Preparation

If necessary, the aggregates should be oven-dried at 150°C before testing commences. (Sample types (c) and (d)).

For samples of type (d) it is first necessary to combine the various sample sizes to give the required grading for the mixed aggregate. Several different gradings may be tried if a full Marshall mix design is to be carried out.

When it is required to determine the most satisfactory bitumen content, given a sample of mixed aggregate, an initial estimate of the required bitumen content can be made from a knowledge of the compacted density of the Mixed Aggregate (CDMA). The CDMA is most conveniently determined using a standard 100 mm. diameter compaction mould and a 2.5 kg compaction hammer. The sample of dry aggregate is compacted in the mould in four layers, each layer being given 20 blows of the hammer. The density of the aggregate is then calculated in an identical manner to the bulk density in a compaction tests. The average of two determinations is taken as the CDMA, as shown in Form 10.9.1.

It is also necessary to carry out separate determinations of the specific gravity of the mixed aggregate (SGMA), and the specific gravity of bitumen.

The voids in mixed aggregate VMA are then determined from the formula:

\[
VMA = \frac{(SGMA - CDMA)}{SGMA} \times 100\%
\]

The VMA should normally be between 17 and 20% for a satisfactory mix. An initial estimate of the optimum bitumen content (B) is obtained from the formulae:

\[
B_{100} = \frac{(VMA - VIM) \times S.G.\ Bitumen}{CDMA}
\]

Where, \( B_{100} \) is expressed in parts per 100 parts of mixed aggregate (p.h.a) and VIM = the specified percentage of air voids in the compacted mix.

Note. In bitumen calculations, it is usual to express all densities and specific gravities in gram/ml; gram/cc or Mg/cu.m.

Having completed the required tests on the mixed aggregates, the bituminous material is then produced by mixing the aggregates with the bitumen in the correct proportions.

For each test specimen, the required weight of mixed aggregate is weighed out and place in an oven at the temperature shown in the following Table 10.9.1 (Column 2):
BANGLADESH ROAD RESEARCH LABORATORY
HOTMIX DESIGN BY MARSHAL METHOD

Aggregate type: Crushed Gravel
Sand type: River Sand
Bitumen grade: 80/100
Date of test: 20/6/79

MAY 2001 Page 10.68

Name and designation of operator: 
Origin of aggregate / sand: Sylhet
Origin of bitumen: Store

Specific gravity of mixed aggregate (S.G.M.A)

\[
S.G.M.A = \frac{100}{W_1/G_1 + W_2/G_2 + W_3/G_3 \text{ etc.}} = 2.66
\]

Compacted density of mixed aggregate (C.D.M.A)

<table>
<thead>
<tr>
<th>Weight of agg. + mould</th>
<th>4043</th>
<th>4052</th>
<th>4047</th>
<th>4061</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of agg.</td>
<td>2040</td>
<td>2049</td>
<td>2044</td>
<td>2058</td>
</tr>
<tr>
<td>C. D. M. A</td>
<td>2.16</td>
<td>2.17</td>
<td>2.165</td>
<td>2.18</td>
</tr>
<tr>
<td>Average C. D. M. A</td>
<td>2.17</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mould Factor, \( F = \frac{1.059}{1000} \)

Voids in mixed aggregate (V. M. A)

\[
V.M.A = \frac{S.G.A \times C.D.M.A}{S.G.M.A} \times 100 = \frac{(2.660217) \times 100}{2.66} = 18.4\% 
\]

Optimum bitumen content (B)

\[
B = \frac{(V.M.A - V.I.M) \times S.G.bltumen}{C.D.M.A} \\
= \frac{(18.4 - 5.0) \times 0.99}{2.17} = 6.1 
\]

Specific gravity of mix (S.G.M.)

\[
B = \frac{100+B}{(100 / S.G.M.A) + (100 / S.G.bltumen)} = \frac{(100+6.1)}{(100/2.66) + (6.1/0.99)} = 2.42 
\]
Table 10.9.1 Temperatures required in the preparation of moulded specimens

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder grade pen (in mm)</td>
<td>Temperature</td>
<td>Heated aggregate</td>
<td>Heated binder bitumen</td>
<td>On Completion of mixing (approx.)</td>
</tr>
<tr>
<td>80 - 100</td>
<td>°C</td>
<td>155</td>
<td>150</td>
<td>140</td>
</tr>
<tr>
<td>60 - 70</td>
<td>°C</td>
<td>160</td>
<td>155</td>
<td>145</td>
</tr>
<tr>
<td>40 - 50</td>
<td>°C</td>
<td>165</td>
<td>160</td>
<td>150</td>
</tr>
</tbody>
</table>

The amount of aggregate required for each specimen is in the region of 1000 - 1500 grams, but the exact amount must be determined by an initial trial.

There are required for each bitumen content and the aggregate should be heated in the oven for at least 2 hours.

The weight of bitumen required for each specimen should be weighed out into a small metal container, and heated to the temperature shown in the Table 10.9.1 (Column 3), using an oven or a hot plate. When using a hot plate, the bitumen should be stirred whenever possible to prevent local overheating and heating should not continue for longer than 30 minutes. The temperature should be maintained for at least 10 minutes. When pouring a sample of bitumen it is inevitable that some bitumen adheres to the sides of the container, to account for this, it is useful to beat a sample of bitumen in the container and pour this away, thus coating the sides of the container before adding the exact weight of bitumen required for the specimen, the weight of bitumen adhering to the sides of the container will vary only slightly each time it is emptied. To establish the exact weight of bitumen used, the weight of the container should be taken before heating and after pouring.

The heated aggregate and bitumen should be thoroughly mixed together as quickly as possible. Mixing may be by hand or in a mechanical mixer. In either case the mixing pan and tools should be heated prior to use so that the temperature of the sample is maintained. When all the aggregate is evenly coated with the bitumen, the sample should be removed from the mixing pan and compacted as quickly as possible.

When using a sample of mixed bituminous material (type (b)), this should be divided into the required specimen weights as quickly as possible after sampling and then brought back to the required mixing temperature by heating in an oven. The time of heating will depend on the initial temperature of the sample and should not exceed one hour. On removal from the oven, the sample should be compacted as soon as possible.

The compaction moulds, collars and bases should be cleaned, lightly oiled and placed in an oven, at the temperature shown in column 5 of the Table 10.9.1, for a period of at least one hour. The hammer base should also be heated in a similar manner.

The base, mould and collar should then be assembled and a 100 mm. diameter disc of tough non-absorbent paper (such as greaseproof) placed in the base of the mould. The whole of the mixed material is then transferred into the mould as quickly as possible and levelled by prodding with a spatula 15 times round the perimeter and 10 times over the interior of the sample. At the end of this process, the upper surface of
the sample should be slightly domed. At this stage the temperature should be checked, using a previously warmed thermometer, to save time, and must be within the range shown in column 5, Table 10.9.1.

A disc of non-absorbent paper is then placed on the top of the sample, the mould assembly is placed on the compaction pedestal and located in the mould clamp.

Compaction is then given to the top of the sample using 50 blows of the hammer. The hammer must be maintained perfectly vertical during this operation and the rate of compaction should be about 60 - 70 blows per minute.

On completion of 50 blows, the collar and base are carefully removed, the mould is turned over and the base and collar re-fixed so the bottom of the sample is now facing upwards. The assembly is re-fixed in the pedestal mould holder and given another 50 blows of the hammer.

On completion of compaction, the collar is removed and the mould and base are immersed in cold water for at least 15 minutes.

When completely cool the base is removed and the sample ejected from the mould using the extraction apparatus. The specimen must be extracted from the mould without shock or distortion. Any burrs may be removed with a spatula or sharp knife.

The specimen should be placed on a flat surface and the average height measured, preferably with a dial gauge, the height must be between 62.0 and 65.0 mm. (2.7/16" - 2.9/16) otherwise the sample should be discarded.

The specimen is then dried with a cloth and stored on a piece of absorbent paper on a flat surface for at least 16 hours. Ensure the different specimens are clearly marked.

The mould, base and collar should be thoroughly cleaned before re-use or storage.

10.9.6 Measurement of Density

Prior to testing, it is necessary to determine the density of the specimen, this is done by weighing in water.

The weight of the dry specimen is first determined to an accuracy of 0.1 grams. Weight C.

The specimen is then weighed in water, weight d, using a wire basket suspended from a suitable balance. Care should be taken to ensure that there are no air bubbles attached to the wire basket or the specimen prior to weighing.

These weights are recorded on the data sheet Form 10.9.2 and the calculations relating to volume and voids in the mix may then be completed.
## Tests For Bitumen & Bituminous Materials

### Standard Test Procedures

**Bangladesh Road Research Laboratory**

**Analysis of Bituminous Materials**

**Marshall Stability**

<table>
<thead>
<tr>
<th>Location</th>
<th>Inner Circular Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract</td>
<td>No. 3</td>
</tr>
<tr>
<td>Date of sample</td>
<td>29/9/2000</td>
</tr>
<tr>
<td>Time of sample</td>
<td>15:30</td>
</tr>
<tr>
<td>Remarks</td>
<td>Sampled at</td>
</tr>
<tr>
<td>Supplier</td>
<td>Dacca Circle</td>
</tr>
<tr>
<td>Date of test</td>
<td>30/6/2000</td>
</tr>
<tr>
<td>Name and designation of operator</td>
<td></td>
</tr>
<tr>
<td>Marshall Stability</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extraction</th>
<th>Sheet No. 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet No.</td>
<td>82</td>
</tr>
</tbody>
</table>

### Table

| a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t |
| 

### Formulas

S.G.M = \( \frac{x}{100} \)

where:

- \( x \) = (\% binder / S.G. binder) + (\% agg. / S.G. agg.)

'y' - see conversion Figure 9.12

### Notes

- **Location**: Inner Circular Road
- **Contract**: No. 3
- **Date of sample**: 29/9/2000
- **Time of sample**: 15:30
- **Remarks**: Sampled at
- **Supplier**: Dacca Circle
- **Date of test**: 30/6/2000
- **Name and designation of operator**: |
- **Marshall Stability**: |
- **Extraction**: Sheet No. 80
- **Sheet No**: 82
From the weight of bitumen and aggregates used in the mix, the proportion of binder is calculated as follows:

\[
\text{Proportion of binder, } B = \frac{\text{Weight of bitumen}}{\text{Weight of mixed aggregate}} \times 100 \quad \text{(a)}
\]

Where \( B \) is expressed in parts of bitumen per 100 parts of aggregate (p.h.a). This is the most convenient method of expressing binder content.

The binder content as a true percentage of the mixed material, is given by:

\[
B' = \frac{\text{Weight of bitumen}}{(\text{Weight of mixed aggregate}) + (\text{Weight of bitumen})} \times 100\%
\]

Note that

\[
B' = B \times \frac{100}{(100 + B)} \% \quad \text{............... (b)}
\]

Where, \( B \) is in p.h.a.

From the weight in air and weight in water:

Total Volume of specimen, \( V = (\text{Weight } c - \text{Weight } d) \times \text{S.G. water} = (\text{Weight } c - \text{Weight } d) \text{ ml} \quad \text{(f)} \)

The density of the compacted specimen is then given by, Compacted density of mix,

\[
\text{CDM} = \frac{\text{Weight } C}{V} \text{ gram/ml} \quad \text{............... (g)}
\]

The maximum theoretical density of the specimen if there were no air voids would be:

Max. theoretical specimen density,

\[
'X' = \frac{100}{\text{S.G.Bitumen} + \frac{\text{S.G. Aggregate}}{\text{S.G.M.A}}} \quad \text{(h)}
\]

or, \( 'X' = \frac{100 B'}{\text{S.B.Bitumen} + \frac{(100 - B')}{\text{S.G.M.A}} \quad \text{gram/ml}} \quad \text{............... (h)} \)

From the above results it is possible to derive a number of factors concerning the volumetric proportions of the mix and the void content:

\[
\text{Volume of binder, } V_b = \frac{B' \times \text{CDM}}{\text{S.G. Bitumen}} \% \quad \text{............... (i)}
\]

(as % of total volume)
Volume of aggregate, \( V_{agg} = \frac{(100 - B') \times CDM}{S.G.M.A} \% \) .............. (j)

Volume of air voids, \( V_{IM} = (100 - V_{b} - V_{agg}) \% \) ....................... (k)
(as % of total volume)

The voids in the mixed aggregate are given by:
\[ V_{MA} = (100 - V_{agg}) \% \] ............... (l)
and this value may be compared with that calculated previously using the CDMA.

The percentage of voids filled with bitumen are given by:
\[ V_{FB} = 100 \times \frac{V_{b}}{V_{MA}} \% \] ....................................................... (m)
and the percentage of air voids in the compacted mix,
\[ V_{IM} = 100 \times (1 - \frac{CDM}{X'}) \% \] ........ (n)

This alternative method of calculating VIM may be used as a check. The values of VIM achieved should be compared with the specified value.

If the test is being repeated using a number of different bitumen contents, it is usual to plot, graphs of compacted density of mix, CDM, Voids in Mix, VIM, and Voids filled with bitumen, VFB, against binder content, B.

10.9.7 Test procedure

On completion of density measurements, the specimens are heated in a thermostatically controlled water bath at a temperature of 60 ± 0.5°C for a period of 60 minutes the specimens should be completely immersed in the water.

The inside faces of the testing heads should be thoroughly cleaned and the guide rods lightly oiled, so that the upper head slides freely. The heads should then be immersed in the water bath at 60 ± 0.5°C so they are heated to the correct test temperature.

It is important that the test is carried out quickly and efficiently such that the total time between removing the specimen from the water bath and completion of the test should not exceed 40 seconds. It is, therefore, essential that the test machine, gauges etc., are all prepared ready for use before removing the specimens from the water bath.

On completion of the heating period, the specimen and heads should be quickly removed from the bath and the specimen placed on its side centrally in the lower test head, the upper head is then located on the slides and brought into contact with the specimen. The whole assembly is then placed on the test machine directly below the plunger.

The deformation dial gauge should be placed into position and either zeroed or the initial reading taken. The load ring dial gauge should previously have been zeroed.

The load is then applied to the specimen by the machine at a rate of 50.8 mm/minute ± 5%. The reading on the load ring gauge should be observed and the instant the load stops increasing, the machine should be switched off. The maximum load gauge
reading should be taken. The corresponding reading on the deformation (flow) gauge may then be taken.

The heads should be wiped clean before testing further specimens.

10.9.8 Calculation

The calculations concerned with densities and voids have already been described in section 10.9.6

From the maximum load gauge reading, the maximum load applied may be determined using a calibration chart or proving ring factor. This is the measured stability.

It will be noted that the height of the specimen may vary somewhat and the measured stability will tend to increase as the height of the specimen increases. To reduce all measurements to a common height of 63.5 mm. (£\frac{1}{2} ins.) a stability correction factor is applied to the measured value such that:

Corrected stability = (Measured stability) x (Adjustment factor)

The adjustment factor is determined from the specimen volume in accordance with Figure 10.9.5. The stability is expressed in kN (or 1bf).

The flow value is simply the reading on the deformation gauge at the point of maximum load, and is expressed in mm. (or 0.01 inch).

A useful factor in the assessment of mix quality is the stability to flow ratio which is given by:

\[
\text{Stability flow ratio} = \frac{\text{Corrected stability}}{\text{Flow}}
\]

The stability to flow is expressed in kN/mm or lb/(0.01 inch). The average value of the three specimens should be quoted.

As mentioned previously the Marshall test is often carried out as a mix design procedure and specimens will be made at various bitumen contents to determine which is the most satisfactory (i.e. the optimum binder content).

To determine the optimum binder content graphs of CDM, VIM, VFB, Stability and Flow against binder content are normally plotted as shown in Figure 10.9.6.

The values of some these factors may be specified and the most satisfactory values for the other factors are generally known; it is, therefore, possible to obtain the most desirable bitumen content relating to each of these factors from the relevant graph. These values are not likely to be exactly the same, but are generally fairly close. The optimum bitumen content may than be determined by taking an average of these different values.
### 10.9.9 Reporting of results

The stability should be reported to the nearest 0.1 kN (20 lbsf) and the flow should be reported to the nearest 0.5 mm (0.01 inch).

The bitumen content of the specimen, the grade of bitumen and the proportions of the various aggregate sizes used should be given.

<table>
<thead>
<tr>
<th>Height of specimen, mm</th>
<th>Volume of specimen, ml</th>
<th>Stability correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>502 - 503</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>504 - 506</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>507 - 509</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>510 - 512</td>
<td>1.01</td>
</tr>
<tr>
<td>63.5</td>
<td>513 - 517</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>515 - 520</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>512 - 523</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>524 - 526</td>
<td>0.97</td>
</tr>
<tr>
<td>65</td>
<td>527 - 528</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Figure 10.9.5 Correction factors for stability values with variations in height or volume
Figure 10.9.6 (10.9.8) Marshall Test Results

<table>
<thead>
<tr>
<th>Binder Content (p.h.a.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max CDM</td>
</tr>
<tr>
<td>Max Stab</td>
</tr>
<tr>
<td>VIM - 5%</td>
</tr>
<tr>
<td>VFB - 80%</td>
</tr>
<tr>
<td>Flow II</td>
</tr>
<tr>
<td>Mean</td>
</tr>
</tbody>
</table>

Hence optimum binder content = 6.6 p.h.a.