EXPERIMENT NO: 17

ASPHALT CONCRETE MIX DESIGN BY MARSHALL METHOD

(ASPHALT INSTITUTE MANUAL SERIES NO. 2 (MS-2), Ch. 4 & Ch. 6, SIXTH EDITION 1997)



VOLUMETRIC PROPERTIES OF COMPACTED PAVING MIXTURES

1.1 GENERAL

The volumetric properties of a compacted paving mixture [air voids (V_a), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and effective asphalt content (P_{be})) provide some indication of the mixture's probable pavement service performance. The intent of laboratory compaction is to simulate the in place density of HMA after it has endured several years of traffic. How well the laboratory compaction procedure simulates either the compacted state immediately after construction or after years of service can be determined by comparing the properties of an undisturbed sample removed from a pavement with the properties of a sample of the same paving mixture competed in the laboratory.

HMA: Hot Mix Asphalt

It is necessary to understand the definitions and analytical procedures described here to be able to make informed decisions concerning the selection of the design asphalt mixture. The information here applies to both paving mixtures that have been compacted in the laboratory, and to undisturbed samples that have been removed from a pavement in the field.

A comparison of field and laboratory compacted mix properties has been made in several research studies. Statistical analysis of these data has failed to establish one laboratory compaction method that consistently produces the closest simulation to the field for all of the measured properties. However, there is a trend toward the gyratory method of compaction based on these findings and other subjective factors. This is a very complicated issue. Compaction method, level of compaction, structural concerns, construction conditions and other influences can all make a difference in these comparisons. Assuming that a reasonable degree of simulation is achieved by whatever compaction procedures are used, it is universally agreed that the air void analysis is an important part of mix design.

1.2 DEFINITIONS

Mineral aggregate is porous and can absorb water and asphalt to a variable degree. Furthermore, the ratio of water to asphalt absorption varies with each aggregate. The three methods of measuring aggregate specific gravity take these variations into consideration. The methods are ASTM bulk, ASTM apparent and effective specific gravities. The differences among the specific gravities come from different definitions of aggregate volume.

Bulk Specific Gravity, G_{sb} - the ratio of the weight in air of a unit volume of permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water at a stated temperature. See Figure 17.1.

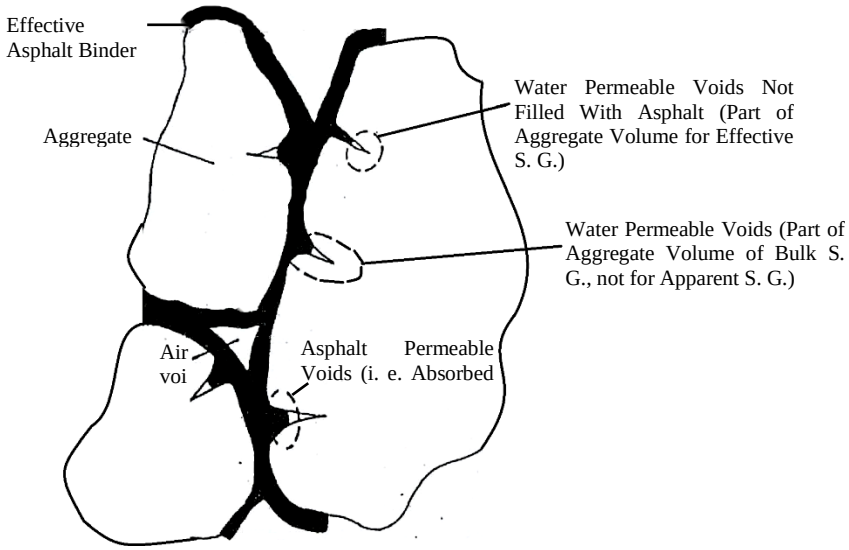


Figure 17.1 Illustrating bulk, effective, and apparent specific gravities; air voids and effective, asphalt content in compacted asphalt paving mixture

Apparent Specific Gravity, G_{sa} - the ratio of the weight in air of a unit volume of an impermeable material at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water at a stated temperature. See Figure 17.1.

Effective Specific Gravity, G_{se} - the ratio of the weight in air of a unit volume of a permeable material (excluding voids permeable to asphalt) at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water at a stated temperature. See Figure 17.1.

NOTE: The accuracy of specific gravity measurements for mix design is important. Unless specific gravities are determined to four significant figures (three decimal places) an error in air voids value of as much as 0.8 percent can occur. Therefore, the Asphalt Institute recommends the use of weigh scales whose sensitivity will allow a mix batch weighing 1000 to 5000 grams to be measured to an accuracy of 0.1 gram.

V_{ma} = Volume of voids in mineral aggregate
V_{mb} = Bulk volume of compacted mix
V_{mm} = Void less volume of paving mix
V_{fa} = Volume of voids filled with asphalt
V_a = Volume of air voids
V_b = Volume of asphalt
V_{ba} = Volume of absorbed asphalt
V_{sb} = Volume of mineral aggregate (by bulk specific gravity)
V_{se} = Volume of mineral aggregate (by effective specific gravity)

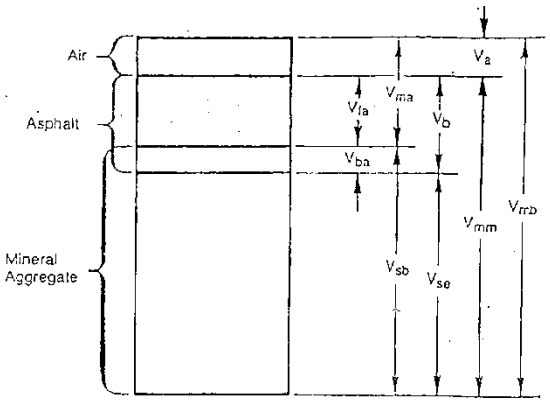


Figure 1.2 Representation of volumes in a compacted asphalt specimen

The definitions for voids in the mineral aggregate (VMA), effective asphalt content (P_{be}), air voids (V_a) and voids filled with asphalt (VFA) are:

Voids in the Mineral Aggregate, VMA - the volume of inter granular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of the total volume of the sample. See Figure 17.2.

Effective Asphalt Content, Pbe - the total asphalt content of a paving mixture minus the portion of asphalt that is lost by absorption into the aggregate particles. See Figure 17.2.

Air Voids, V_a - the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as percent of the bulk volume of the compacted paving mixture. See Figure 17.2.

Voids Filled with Asphalt, VFA - the portion of the volume of intergranular void space between the aggregate particles (VMA) that is occupied by the effective asphalt. See Figure 17.2.

The Asphalt Institute recommends that VMA values for compacted paving mixtures should be calculated in terms of the aggregate's bulk specific gravity, G_{sb}. The effective specific gravity should be the basis for calculating the air voids in a compacted asphalt paving mixture.

Table 1 illustrates that the type of aggregate specific gravity used in the analysis of a compacted paving mixture can have a very dramatic effect on the values reported for air voids and VMA. These differences are enough to make it appear that a mixture may satisfy or fail the design criteria for air voids and VMA depending on the aggregate specific gravity used for analysis. Asphalt Institute mix design criteria do not apply unless VMA calculations are made using bulk specific gravity and air void content calculations are made using effective specific gravity.

Voids in the mineral aggregate (VMA) and air voids (V_a) are expressed as percent by volume of the paving mixture. Voids filled with asphalt (VFA) is the percentage of VMA that is filled by the effective asphalt. Depending on how asphalt content is specified, the effective asphalt content may be expressed either as percent by weight of the total weight of the paving mixture, or as percent by weight of the aggregate in the paving mixture.

Because air voids, VMA and VFA are volume quantities and therefore cannot be weighed, a paving mixture must first be designed or analyzed on a volume basis. For design purposes, this volume approach can easily be changed over to a weight basis to provide a job mix formula.

1.3 OUTLINE OF PROCEDURE FOR ANALYZING A COMPACTED PAVING MIXTURE

This list delineates all the measurements and calculations needed for a void analysis:
(a) Measure the bulk specific gravities of the coarse aggregate (AASHTO T 85 or ASTM C 127) and of the fine aggregate (AASHTO T 84 or ASTM C 128).
(b) Measure the specific gravity of the asphalt cement (AASHTO T 228 or ASTMD 70) and of the mineral filler (AASHTO T 100 or ASTM D 854).
(c) Calculate the bulk specific gravity of the aggregate combination in the paving mixture.
(d) Measure the maximum specific gravity of the loose paving mixture (ASTMD 2041).
(e) Measure the bulk specific gravity of the compacted paving mixture (ASTM D 1188 or ASTM D 2726).
(f) Calculate the effective specific gravity of the aggregate.
(g) Calculate the maximum specific gravity of the mix at other asphalt contents.
(h) Calculate the asphalt absorption of the aggregate.

Table 17.1: Influence of type of specific gravity on determination of VMA, VFA and air voids

Specific gravity Employed for Aggregate		Allowance For Absorption of Asphalt by Aggregate	Void Properties Compacted Mixture		
			Percent Voids in Mineral Aggregate	Percent Air Voids	Percent Voids Filled With Asphalt
ASTM Bulk	2.651	Yes	13.6	1.1	92
ASTM Bulk	2.651	No	13.6	-0.8	106
ASTM Bulk (sat. surf. dry)	2.716	Yes	15.6	3.2	79
ASTM Bulk (sat. surf. dry)	2.716	No	15.6	1.3	92
ASTM Apparent	2.834	No	19.1	4.9	74
Effective	2.708	No	15.4	1.1	93

Bulk Specific Gravity of Compacted Mixture, G_{mb} 2.436
Density of Compacted Mixture, W_r, Mg/m^3 (lb/ft^3) 2.435 (152.0)
Asphalt Content, percent by weight of total mix 5.9
Asphalt Absorbed by Aggregate Particles, percent 0.8
Specific Gravity of Asphalt Cement, G_b 1.011
(i) Calculate the effective asphalt content of the paving mixture.
(j) Calculate the percent voids in the mineral aggregate in the compacted paving mixture.
(k) Calculate the percent air voids in the compacted paving mixture.
(l) Calculate the percent voids filled with asphalt.

Equations for these calculations are found in Articles 1.5 through 1.11 and theirapplication may be expedited by use of the appropriate worksheet.

1.4 PAVING MIXTURE DATA FOR SAMPLE CALCULATIONS

Table 17.2 illustrates the basic data fora sample of paving mixture. These design data are used in the sample calculations used in the remainder of this chapter.

1.5 BULK SPECIFIC GRAVITY OF AGGREGATE

When the total aggregate consists of separate fractions of coarse aggregate, fine aggregate and mineral filler, all having different specific gravities, the bulk specific gravity for the total aggregate is calculated using:

$$G_{sb} = \frac{P_1 + P_2 + \ldots + P_n}{P_1/G_1 + P_2/G_2 + \ldots + P_n/G_n}$$

Where, G_{sb}= bulk specific gravity for the total aggregate
P_1, P_2, P_n= individual percentages by weight of aggregate
G_1, G_2, G_n= individual bulk specific gravities of aggregate

Table 17.2: Basic data for sample of paving mixture:

a) Constituents

Material	Specific Gravity				Mix Composition	
		Bulk	AASHTO Method	ASTM Method	Percent By Weight of Total Mix	Percent By Weight of Total Aggregate
Asphalt Cement	1.030 (G_b)		T 228	D 70	5.3 (P_b)	5.6 (P_b)
Coarse Aggregate		2.716 (G_1)	T 85	C 127	47.4 (P_1)	50.0 (P_1)
Fine Aggregate		2.689 (G_2)	T 84	C 128	47.3 (P_2)	50.0 (P_2)
Mineral Filler	----		T 100	D 854	----	----

b) Paving Mixture

Bulk specific gravity of compacted paving mixture sample, G_{mb} (ASTM D 2726) = 2.442
Maximum specific gravity of paving mixture sample, G_{mm} (ASTM D 2041) = 2.535

The bulk specific gravity of mineral filler is difficult to determine accurately. However, if the apparent specific gravity of the filler is substituted, the error is usually negligible.
Using the data in Table 17.2:

$$G_{sb} = \frac{50.0 + 50.0}{50.0/2.716 + 50.0/2.689} = 2.703$$

1.6 EFFECTIVE SPECIFIC GRAVITY OF AGGREGATE

When based on the maximum specific gravity of a paving mixture, G_{mm}, as measured using ASTM D 2041, the effective specific gravity of the aggregate, G_{se}, includes all void spaces in the aggregate particles except those that absorb asphalt. G_{se} is determined using:

$$G_{se} = \frac{P_{mm} - P_b}{P_{mm}/G_{mm} - P_b/G_b}$$

Where, G_{se} = effective specific gravity of aggregate
G_{mm} = maximum specific gravity (ASTM D 2041) of paving mixture (no air voids)
P_{mm} = percent by weight of total loose mixture = 100
P_b = asphalt content at which ASTM D 2041 test was performed, percent by total weight of mixture
G_b= specific gravity of asphalt

Using the data in Table 17.2:

$$G_{se} = \frac{100 - 5.3}{100/2.535 - 5.3/1.030} = 2.761$$

NOTE: The volume of asphalt binder absorbed by an aggregate is almost invariably less than the volume of water absorbed. Consequently, the value for the effective specific gravity of an aggregate should be between its bulk and apparent specific gravities. When the effective specific gravity falls outside these limits, its value must be assumed to be incorrect. The calculations, the maximum specific gravity of the total mix by ASTM D 2041, and the composition of the mix in terms of aggregate and total asphalt content should then be rechecked for the source of the error.
The apparent specific gravity, G_{sa}, of the total aggregate can be calculated by the same formula as the bulk by using the apparent specific gravity of each aggregate constituent.

1.7 MAXIMUM SPECIFIC GRAVITY OF MIXTURES WITH DIFFERENT ASPHALT CONTENTS

In designing a paving mixture with a given aggregate, the maximum specific gravity, G_{mm}, at each asphalt content is needed to calculate the percentage of air voids for each asphalt content. While the maximum specific gravity can be determined for each asphalt content by ASTM D 2041, the precision of the test is best when the mixture is close to the design asphalt content. Also, it is preferable to measure the maximum specific gravity in duplicate or triplicate. After calculating the effective specific gravity of the aggregate from each measured maximum specific gravity (see Article 1.6) and averaging the G_{se} results, the maximum specific gravity for any other asphalt content can be obtained as shown below. For all practical purposes, the effective specific gravity

of the aggregate is constant because the asphalt absorption does not vary appreciably with variations in asphalt content.

$$G_{mm} = \frac{P_{mm}}{P_s/G_{se} + P_b/G_b}$$

Where, G_{mm} = maximum specific gravity of paving mixture (no air voids)
P_{mm} = percent by weight of total loose mixture = 100
P_s = aggregate content,percent by total weight of mixture
P_b = asphalt content,percent by total weight of mixture
G_{se} = effective specific gravity of aggregate
G_b= specific gravity of asphalt

Using the specific gravity data from Table 2, and the effective specific gravity, G_{se}, determined in article 1.6, the G_{mm} at an asphalt content, P_b, of 4 percent would be:

$$G_{mm} = \frac{100}{96/2.761 + 4/1.030}$$

1.8 ASPHALT ABSORPTION

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

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

Where, P_{ba} = absorbed asphalt, percent by weight of aggregate
G_{se} = effective specific gravity of aggregate
G_{sb}= bulk specific gravity of aggregate
G_b= specific gravity of asphalt

Using the bulk and effective aggregate specific gravities determined in Articles 1.5 and 1. 6 and the asphalt specific gravity from Table 17.2:

$$P_{ba} = 100 \left(\frac{2.761 - 2.703}{2.761 \text{ x } 2.703} \right) 1.030 = 0.8$$

1.9 EFFECTIVE ASPHALT CONTENT OF A PAVING MIXTURE

The effective asphalt content, P_{be}, of a paving mixture is the total asphalt content minus the quantity of asphalt lost by absorption into the aggregate particles. It is the portion of the total asphalt content that remains as a coating on the outside of the aggregate particles and it is the asphalt content which governs the performance of an asphalt paving mixture. The formula is:

$$P_{be} = P_b - \frac{P_{ba}}{100} P_s$$

Where, P_{be} = effective asphalt content, percent by total weight of mixture
P_b = asphalt content, percent by total weight of mixture
P_{ba} = absorbed asphalt, percent by weight of aggregate
P_s = aggregate content, percent by total weight of mixture
Using the data from Table 2 and Article 1.8:

$$P_{be} = 5.3 - \frac{0.8}{100} \text{x } 94.7 = 4.5$$

1.10 PERCENT VMA IN COMPACTED PAVING MIXTURE

The voids in the mineral aggregate, VMA, are defined as the intergranular void space between the aggregate particles in a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of the total volume. The VMA is calculated on the basis of the bulk specific gravity of the aggregate and is expressed as a percentage of the bulk volume of the compacted paving mixture. Therefore, the VMA can be calculated by subtracting the volume of the aggregate determined by its bulk specific gravity from the bulk volume of the compacted paving mixture. A method of calculation is illustrated for each type of mixture percentage content.

If the mix composition is determined as percent by weight of total mixture:

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

Where, VMA = voids in mineral aggregate, percent of bulk volume
G_{sb} = bulk specific gravity of total aggregate
G_{mb} = bulk specific gravity of compacted mixture (AASHTO T 166; ASTM D 1188 or D 2726)
P_s = aggregate content, percent by total weight of mixture

Using the data from Table 2 and Article 1.5:

$$VMA = 100 - \frac{2.442 \text{ x } 94.7}{2.703} = 14.4$$

Or if the mix composition is determined as percent by weight of aggregate:

$$VMA = 100 - \frac{G_{mb}}{G_{sb}} \text{ x } \frac{100}{100 + P_b} 100$$

Where, P_b = asphalt content, percent by weight of aggregate

Using the data from Table 2 and Article 1.5:

$$VMA = 100 - \frac{2.442}{2.703} X \frac{100}{100 + 5.6} X\ 100 = 14.4$$

1.11 PERCENT AIR VOIDS IN COMPACTED PAVING MIXTURE

The air voids, V_a, in the total compacted paving mixture consist of the small air spaces between the coated aggregate particles. The volume percentage of air voids in a compacted mixture can be determined using:

$$V_a = 100 \text{ x } \frac{G_{mm} - G_{mb}}{G_{mm}}$$

Where, V_a= air voids in compacted mixture, percent of total volume
G_{mm} = maximum specific gravity of paving mixture (as determined in Article 1.7 or as measured directly for a paving mixture by ASTM D 2041)
G_{mb} = bulk specific gravity of compacted mixture (AASHTO T 166; ASTM D 1188 or D 2726)

Using data from Table 2:

$$V_a = 100 \text{ x } \frac{2.535 - 2.442}{2.535} = 3.7$$

1.12 PERCENT VFA IN COMPACTED PAVING MIXTURE

The voids filled with asphalt, VFA, is the percentage of the intergranular void space between the aggregate particles (VMA) that are filled with asphalt. VFA, not including the absorbed asphalt, is determined using:

$$VFA = \frac{100 (VMA - V_a)}{VMA}$$

Where, VFA = voids filled with asphalt, percent of VMA
VMA = voids in mineral aggregate, percent of bulk volume
V_a = air voids in compacted mixture, percent of total volume

Using the data from Table 2 and Articles 1.10 and 1.11:

$$VFA = 100 \text{ x } \frac{14.4 - 3.7}{14.4} = 74.3 \text{ percent}$$

MARSHALL METHOD OF MIX DESIGN

A. GENERAL

2.1 DEVELOPMENT AND APPLICATION

The concepts of the Marshall method of designing paving mixtures were formulated by Bruce Marshall, a former Bituminous Engineer with the Mississippi State Highway Department. The U.S. Army Corps of Engineers, through extensive research and correlation studies, improved and added certain features to Marshall's test procedure, and ultimately developed mix design criteria. The Marshall test procedures have been standardized by the American Society for Testing and Materials. Procedures are given by ASTM D 1559, *Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus*.* Testing procedures presented here are basically the same as those of the ASTM method.

The original Marshall method is applicable only to hot mix asphalt (HMA) paving mixtures containing aggregates with maximum sizes of 25 mm (1 inch) or less. A modified Marshall method has been proposed for aggregates with maximum sizes up to 38 mm (1.5 inch). The differences between this proposed method and the Original are discussed in Article 2.16. The Marshall method is intended for laboratory design and field control (Chapter 8, MS-2) 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.

**AASHTO T 245 "Resistance to plastic Flow of Bituminous Mixtures Using Marshall Apparatus" agrees with ASTM D 1559 except for provision for mechanically operated hammer. AASHTO T 245 Par. 2.3 Note 2- Instead of hand operated hammer and associated equipment, a mechanically operated hammer may be used provided it has been calibrated to give results comparable to the hand operated hammer.*

2.2 OUTLINE OF METHOD

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

(a) All materials proposed for use meet the physical requirements of the project specifications.
(b)Aggregate blend combinations meet the gradation requirements of the project specifications.
(c) For performing density and voids analyses, the bulk specific gravity of all aggregates used in the blend and the specific gravity of the asphalt cement are determined.

These requirements are matters of routine testing, specifications, and laboratory technique that must be considered for any mix design method. Refer to Chapter 3 (MS-2), "Evaluation of Aggregate Gradation", for the preparation and analysis of aggregates.

The Marshall method uses standard test specimens of 64 mm (2 $\frac{1}{2}$ in.) height x 102mm (4 in.) diameter. These are prepared using a specified procedure for heating, mixing and compacting the asphalt aggregate mixture. The two principal 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 the test specimen is the maximum load resistance in Newton (lb.) that the standard test specimen will develop at 60^0 C (140^0 F) when tested as outlined.
The flow value is the total movement or strain, in units of 0.25 mm (1/100 in.) occurring in the specimen between no load and the point of maximum load during the stability test.

B. PREPARATION OF TEST SPECIMENS

2.3GENERAL

In determining the design asphalt content for a particular blend or 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 ½ 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, computational formula, or performing the centrifuge kerosene equivalency and oil soak tests in the Hveem procedure. Another quick method to arrive at a starting point is to use the dust-to-asphalt ratio guideline (0.6 to 1.2). 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 = approximate asphalt content of mix, percent by weight of mix
a = percent* of mineral aggregate retained on 2.36mm (No. 8) sieve
b = percent* of mineral aggregate passing the 2.36mm (No. 8) sieve and retained on the 75 μm (No. 200) sieve
c = percent of mineral aggregate passing 75 μm (No. 200) sieve
K = 0.15 for 11-15 percent passing 75 μm (No. 200) sieve
0.18 for 6-10 percent passing 75 μm (No. 200) sieve
0.20 for 5 percent or less passing 75 μm (No. 200) sieve
F = 0 to 2.0 percent. Based on absorption of light or heavy aggregate. In the absence of other data, a value of 0.7 is suggested.

*Expressed as a whole number

To provide adequate data, at least three test specimens are prepared for each asphalt content selected. Therefore, a Marshall mix design using six different asphalt contents will normally require at least eighteen test specimens. Each test specimen will usually require approximately 1.2 kg (2.7 lb) 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 (50 lb). About four liters (one gallon) of asphalt cement will be adequate.

2.4 EQUIPMENT

The equipment required for the preparation of test specimens is:

(a) Flat bottom metal pans for heating aggregates.
(b) Round metal pans, approximately 4 liter (4 qt.) capacity, for mixing asphalt and aggregate.
(c) Oven and Hot Plate, preferably thermostatically controlled, for heating aggregates, asphalt,and equipment.
(d) Scoop for batching aggregates.
(e) Containers: gill-type tins, beakers, pouring pots, or sauce pans, for heating asphalt.
(f) Thermometers: armored, glass, or dial type with metal stem, 10°C (50°F) to 235°C (450°F), for determining temperature of aggregates, asphalt and asphalt mixtures.
(g) Balances: 5 kg capacity, sensitive to 1 g, for weighing aggregates and asphalt and 2 kg capacity, sensitive 0.1 g, for weighing compacted specimens.
(h) Large Mixing Spoon or small trowel.
(i) Large spatula.
(j) Mechanical Mixer (optional): commercial bread dough mixer 4 liter (4 qt.) capacity or larger, equipped with two metal mixing bowls and two wire stirrers.
(k) Compaction Pedestal (Figure 2.1), consisting of a 200 x 200 x 460 mm (8 x 8 x 18 in.) wooden post capped with a 305 x 305 x 25 mm (12 x 12 x 1 in.) steel plate. The wooden post should be oak, pine or other wood having a dry weight of 670 to 770 kg/m^3 (42 to 48 pcf). 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.
*(l) Compaction Mold, consisting of a base plate, forming mold, and collar extension. The forming mold has an inside diameter of 101.6 mm (4 in.) and a height of approximately 75 mm (3 in.); the base plate and collar extension are designed to be interchangeable with either end of the forming mold.
*(m) Compaction Hammer, consisting of a flat circular tamping face. 98.4 mm (3 $^7/_8$ in.) in diameter and equipped with a 4.5 kg (10 lb.) weight constructed to obtain a specified 457 mm (18 in.) height of drop.
*(n) Mold Holder, consisting of spring tension device designed to hold compaction mold centered in place on compaction pedestal.

(o) Paper disks, 100mm (4 in.), for compaction.
(p) Steel specimen extractor, in the form of a disk with a diameter not less than 100 mm (3.95 in.) and 13 mm (0.5 in.) thick for extruding compacted specimens from mold.
(q) Welders gloves for handling hot equipment. Rubber gloves for removing specimens from water bath.
(r) Marking Crayons, for identifying test specimens.

* Marshall test apparatus should conform to requirements of ASTM D 1559

(Note: See additional equipment requirements in Article 2.7)



Mechanical compaction hammer assembly Manual compaction hammer assembly

Figure 17.3 Pedestal, hammer and mold used in preparing Marshall test specimens

2.5 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 asphalt content.

(b) Preparation of Aggregates - Dry aggregates to constant weight at 105°C to 110°C (220°F to 230°F) and separate the aggregates by dry sieving into the desired size fractions. These size fractions are recommended:

25.0 to 19.0 mm (1 to $^3/_4$ in.)

19.0 to 9.5 mm ($^3/_4$ to $^3/_8$ in.)

9.5 to 4.75 mm ($^3/_8$ in. to No. 4)

4.75 to 2.36 mm (No. 4 to No. 8)

passing 2.36 mm (No. 8)

(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 shall be established as the mixing temperature and compaction temperature, respectively. These temperatures can be estimated from a plot of the viscosity (log-log centistokes scale) versus temperature (log degrees Rankine scale, $^0R=^0F+459.7$) relationship for the asphalt cement to be used. An example plot is shown in Figure 2.2.

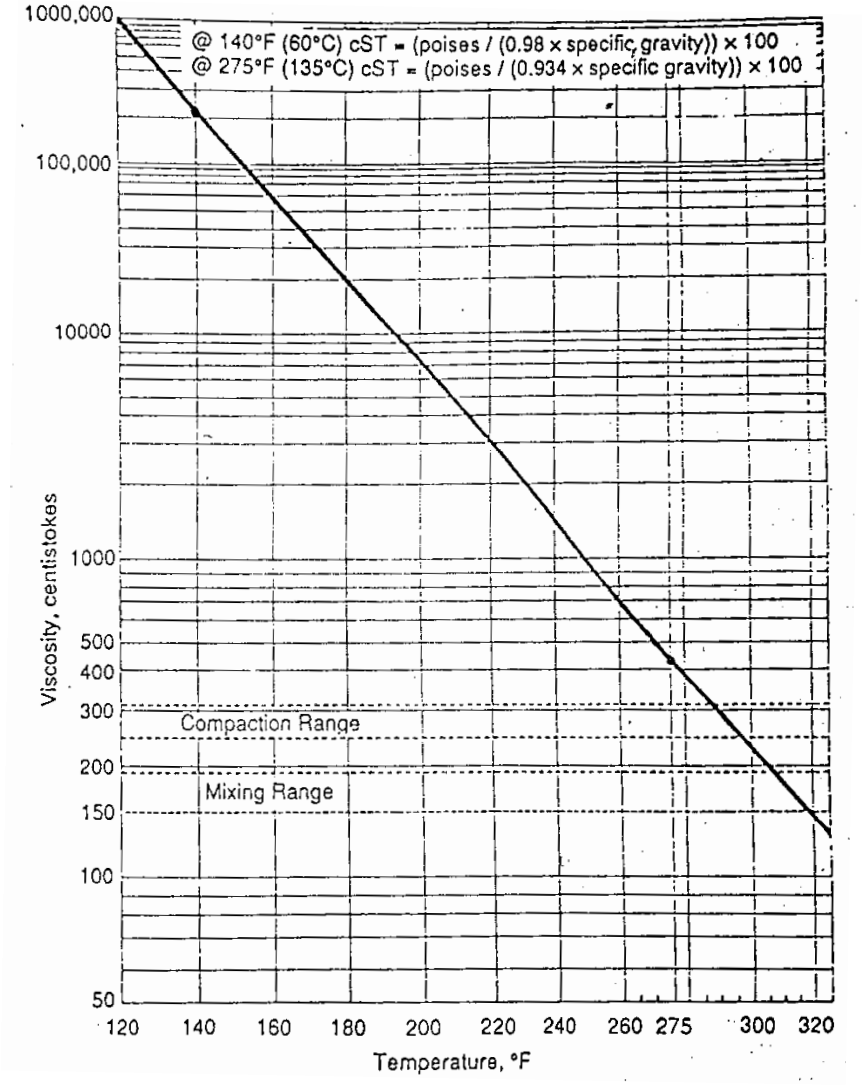


Figure 17.4 Determination of Mixing and Compaction Temperatures

(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°C and 150°C (200°F and 300°F). Place a piece of filter or waxed paper, cut to size, in the bottom of the mold before the mixture is placed in the mold.

(e) Preparation of Mixtures - Weigh into separate pans for each test specimen the amount of each size fraction required to produce 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 (2.7 lb.). It is generally desirable to prepare a trial specimen prior to preparing the aggregate batches. If the trial specimen height falls outside the limits, the amount of aggregate used for the specimen may be adjusted using:

For International System of Units (SI),

*Adjusted mass of aggregate -63.5 (mass of aggregate used) / Specimen height (mm) obtained

U.S. Customary Units,

*Adjusted weight of aggregate - 2.5 (weight of aggregate used) / Specimen height (in.) obtained

Place the pans in the oven or on the hot plate and heat to a temperature not exceeding 28°C (50°F) 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 heated aggregates and dry mix thoroughly. Form a crater in the dry blended aggregate and weigh the required amount of asphalt cement into the mixture in accordance with the calculated batch weights. At this point the temperature of the aggregate and asphalt must be within the limits of the mixing temperature established in paragraph (c). Asphalt cement 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.

Note: Currently, there is no standardized or recommended procedure for aging or curing the mixture prior to Marshall compaction. A number of suggested methods have been proposed; however, a consensus of opinion has not yet been reached. The Hveem procedure recommends a 2 to 3 hour cure period to allow for both aging and absorption to occur. If severe climates or absorptive aggregates are involved, some consideration should be given to this behavior.

(f) Packing the Mold - Place a paper disk in the mold. Place the entire batch in the mold, spade the mixture vigorously with a heated spatula or trowel 15 times around the perimeter and ten times over the interior. Smooth the surface to a slightly rounded shape. The temperature of the mixture immediately prior to compaction shall be within the limits of the compaction temperature established in paragraph (c); otherwise, it shall be discarded. In no case shall the mixture be reheated.

(g) Compaction of Specimens - Place a paper 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 (see Table 2.2), apply either 35, 50 or 75 blows with the compaction hammer using a free fall of 457 mm (18 in.). 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 in air 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, then place on a smooth level surface until ready for testing. Normally, specimens are allowed to cool overnight.

Note: ASTM D1559 specifies that hand lifting of a flat faced compaction hammer be used for specimen compaction. If variations (e.g. mechanical lift, slanted face, and rotating base) of the flat face, hand-lifted hammer are used, correlations with the standard Marshall compaction procedure must be made.

C. TEST PROCEDURE

2.6 GENERAL

In the Marshall method, each compacted test specimen is subjected to thesetestsand analysis in theorder listed:
(a) Bulk Specific Gravity Determination
(b) Stability and Flow Test
(c) Density and Voids Analysis

2.7 EQUIPMENT

The equipment required for the testing of the 102 mm (4 in.) diameter x 64 mm (2 $^1/_2$ in.) height specimens is:

*(a) Marshall Testing Machine, a compression testing device. It is designed to apply loads to test specimens through cylindrical segment testing heads (inside radius of curvature of 51 mm (2 in.)) at a constant rate of vertical strain of 51 mm (2 in.) 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 for determining the amount of strain 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.

**Marshall test apparatus should conform to requirements of ASTM D 1559*

(b) Water Bath, at least 150 mm (6 in.) deep and thermostatically controlled to 60°C ± 1°C (140°F±1.8°F). The tank should have a perforated false bottom or be equipped with a shelf for suspending specimens at least 50 mm (2 in.) above the bottom of the bath.

2.8 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 D 1188, *Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-coated Specimens* or ASTM D 2726, *Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens*.

2.9 STABILITY AND FLOW TESTS

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

(a) Immerse specimen in water bath at 60°C ± 1°C (140°F ± 1.8°F) for 30 to 40 minutes before test.

(b) If not using an automatic recording device (as shown in Figure 17.5). "Zero" the flow meter by inserting a 101.6 mm (4.00 in.) diameter metal cylinder in the testing head, placing the flow meter over the guide rod and adjusting the flow meter to read "zero."

Note: This adjustment should be made on the guide post marked with an "0" and with the side of the upper segment of the testing head marked with an "0" being placed on the same side as the guide post so marked. The same assembly of testing head and flow meter must then be used in testing the specimens. Specimens should be 101.6± 0.25 mm (4.00 in. ± 0.01 in.); otherwise, an initial and final reading of flow meter is required for the determination of the flow value.



Figure 17.5 Marshall stability and flow test

(c) Thoroughly clean the inside surfaces of testing head. Temperature of head shall be maintained between 21.1°to 37.8°C (70° to 100°F) using a water bath when required. Lubricate guide rods with a thin film of oil so that upper test head will slide freely without binding. If a proving ring is used

to measure applied load, check to see that dial indicator is firmly fixed and "zeroed" for the "no-load" position.

(d) With testing apparatus ready, remove test specimen from water bath and carefully dry surface. 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 (b) above.

(e) Apply testing load to specimen at constant rate of deformation, 51 mm (2 in.) per minute, until failure occurs. The point of failure is defined by the maximum load reading obtained. The total number of Newtons (lb.) required to produce failure of the specimen shall be recorded as its Marshall stability value.

(f)While the stability test is in progress, if not using an automatic recording device, hold the flow meter firmly in position over guide rod and remove as 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 (1/100 in.). For example, if the specimen deformed 3.8 mm (0.15 in.) the flow value is 15.

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

2.10 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.

(The calculations for the voids analysis are fully described in previous chapter)

(a) Average the bulk specific gravity values for all test specimens of given asphalt content; values obviously in error shall not be included in the average. These values of bulk specific gravity shall 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/m^3 (62.4 pcf)).

(c) Determine the theoretical maximum specific gravity (ASTM D 2041) 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. This value may then be used for calculation of the maximum specific gravity of mixtures with different asphalt contents, as discussed in previous chapter.

(d) Using the effective and bulk specific gravity of the total aggregate, the average bulk specific gravities of the compacted mix, the specific gravity of the asphalt, and the maximum specific gravity of the mix determined above in (c), calculate the percent absorbed asphalt by weight of dry aggregate, percent air voids (V_a), percent voids filled with asphalt (VFA) and percent voids in mineral aggregate (VMA). These values and calculations are more fully described in previous chapter.

D. INTERPRETATION OF TEST DATA

2.11 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 (2 $^{1}/_{2}$ in.) thickness shall be converted to an equivalent 63.5 mm (2 $^{1}/_{2}$ in.) value by means of a conversion factor. Applicable correlation ratios to convert the measured stability values are set forth in Table 17.3. Note that the conversion may be made on the basis of either measured thickness or measured volume.

Table 17.3: Stability correlation ratios

Volume of specimen, cm^3	Approximate thickness of specimen		Correlation ratio
	mm	in.	
200 to 213	25.4	1	5.56
214 to 225	27.0	1 1/16	5.00
226 to 237	28.6	1 1/8	4.55
238 to 250	30.2	1 3/16	4.17
251 to 264	31.8	1 1/4	3.85
265 to 276	33.3	1 5/16	3.57
277 to 289	34.9	1 3/8	3.33
290 to 301	36.5	1 7/16	3.03
302 to 316	38.1	1 1/2	2.78
317 to 328	39.7	1 9/16	2.50
329 to 340	41.3	1 5/8	2.27
341 to 353	42.9	1 11/16	2.08
354 to 367	44.4	1 3/4	1.92
368 to 379	46.0	1 13/16	1.79
380 to 392	47.6	1 7/8	1.67
393 to 405	49.2	1 15/16	1.56
406 to 420	50.8	2	1.47
421 to 431	52.4	2 1/16	1.39
432 to 443	54.0	2 1/8	1.32
444 to 456	55.6	2 3/16	1.25
457 to 470	57.2	2 1/4	1.19
471 to 482	58.7	2 5/16	1.14
483 to 495	60.3	2 3/8	1.09
496 to 508	61.9	2 7/16	1.04
509 to 522	63.5	2 1/2	1.00
523 to 535	64.0	2 9/16	0.96
536 to 546	65.1	2 5/8	0.93
547 to 559	66.7	2 11/16	0.89
560 to 573	68.3	2 3/4	0.86
574 to 585	71.4	2 13/16	0.83
586 to 598	73.0	2 7/8	0.81
599 to 610	74.6	2 15/16	0.78
611 to 625	76.2	3	0.76

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 (2 $^{1}/_{2}$ in.) specimen.
2. Volume-thickness relationship is based on a specimen diameter of 101.6 mm (4 in.).

(b) Average the flow values and the final converted stability values for all specimens of a given asphalt content. Values that are obviously in error shall not be included in the average.

(c) Prepare a separate graphical plot for these values and connects plotted points with a smooth curve that obtains the "best fit" for all values, as illustrated in Figure 2.4:

- Stability vs. Asphalt Content
- Flow vs. Asphalt Content
- Unit Weight of Total Mix vs. Asphalt Content
- Percent Air Voids (V_a) vs. Asphalt Content
- Percent Voids Filled with Asphalt (VFA) vs. Asphalt Content
- Percent Voids in Mineral Aggregate (VMA) vs. Asphalt Content

These graphs are used to determine the design asphalt content of the mix.

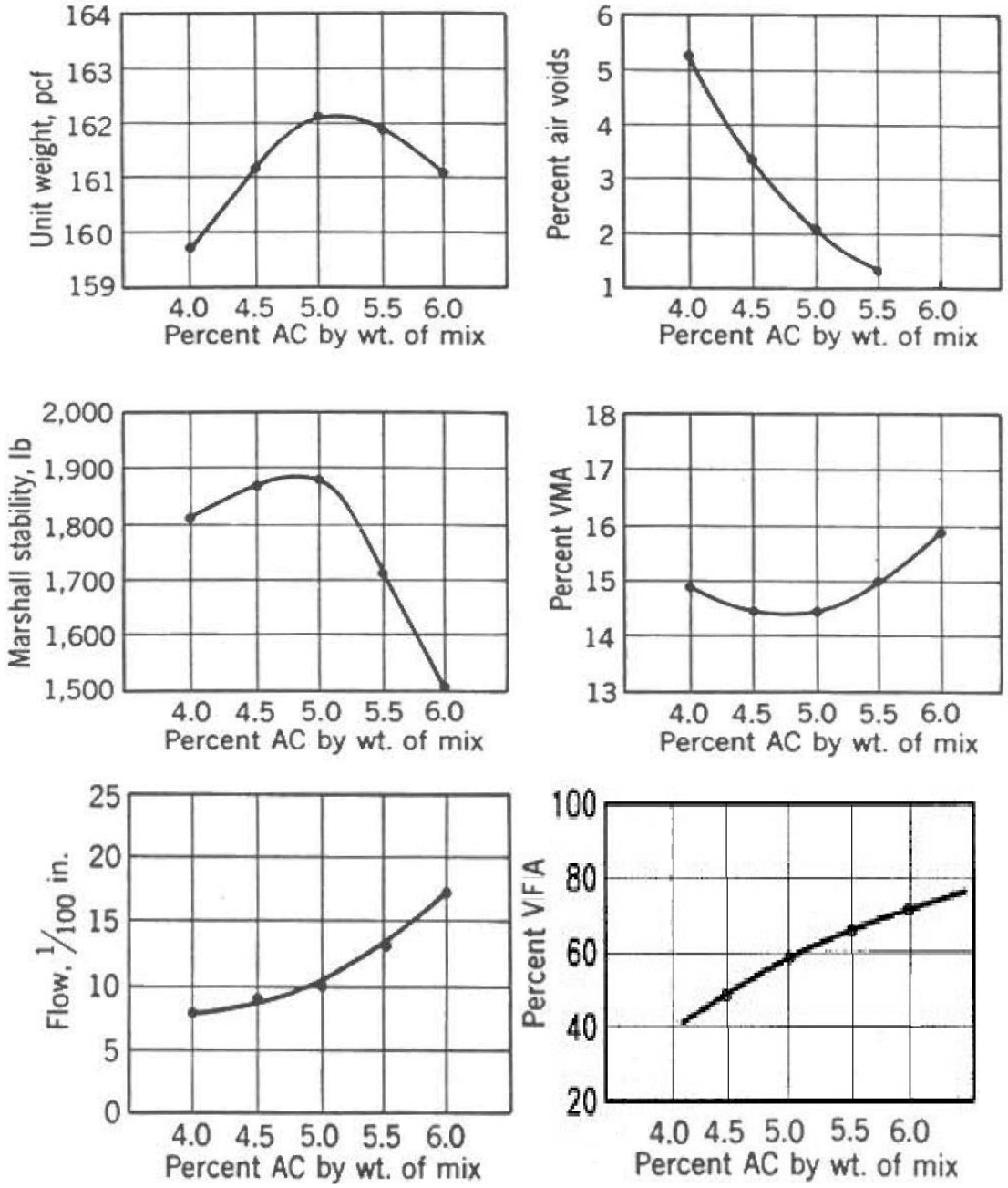


Figure 17.6 Test property curves for hot-mix design data by the Marshall method
(Reference book: "Highway Materials" by Robert D. Kerbs& Richard D. Walker. Figure 12.3, Page-398)

2.12 TRENDS AND RELATIONS OF TEST DATA

By examining the test property curves plotted for Article 2.11, 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 will and do occur. Trends generally noted are:

(a) The stability value increases with increasing asphalt content up to a maximum after which the stability decreases.
(b) The flow value consistently increases with increasing asphalt content.
(c) 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.
(d) The percent of air voids, V_a, steadily decreases with increasing asphalt content, ultimately approaching a minimum void content.
(e) The percent voids in the mineral aggregate, VMA, generally decreases, to a minimum value then increases with increasing asphalt content.
(f) The percent voids filled with asphalt, VFA, steadily increases with increasing asphalt content, because the VMA is being filled with asphalt.

2.13 CRITERIA FOR SATISFACTORY PAVING MIX

Deciding whether the asphalt paving mix will be satisfactory at the selected design asphalt content is guided by applying certain limiting criteria to the mixture test data. The Marshall method mix design criteria in Table 2.2 are recommended by the Asphalt Institute.

Table 17.4: Marshall mix design criteria

Marshall Method Mix Criteria	Light Traffic Surface & Base		Medium Traffic Surface & Base		Heavy Traffic Surface & Base	
Compaction, Number of blows on each end of specimen	35		50		75	
Stability, N (lb)	3336 (750)	–	5338 (1200)	–	8006 (1800)	–
Flow, 0.25 mm (0.01 in)	8	18	8	16	8	14
Percent Air Voids	3	5	3	5	3	5
Percent Voids in Mineral (VMA)	See Table 2.3					
Percent Voids Filled with Asphalt (VFA)	70	80	65	78	65	75

NOTES

1. All criteria, not just stability value alone, must be considered in designing an asphalt pavement mix. Hot mix asphalt bases that do not meet the criteria when tested at 60^0 C (140^0 F) are satisfactory if they meet the criteria when tested at 38^0C (100^0F) and are placed 100 mm (4 inches) or more below the surface. This recommendation applies only to regions having range of climate conditions similar to those prevailing throughout most of the United States. A different lower test temperature may be considered in regions having more extreme climate conditions.
2. Traffic classification: Light Traffic condition resulting in a Design EAL < 10^4
   Medium Traffic condition resulting in a Design EAL between 10^4 and 10^6
   Heavy Traffic condition resulting in a Design EAL > 10^6
3. Laboratory compaction efforts should closely approach the maximum density obtained in the pavement under traffic.
4. The flow value refers to the point where the load begins to decrease.
5. The portion of asphalt cement lost by absorption into the aggregate particles must be allowed for when calculating percent of air voids.
6. Percent voids in the mineral aggregate is to be calculated on the basis of the ASTM bulk specific gravity for the aggregates.

Table 17.5: Minimum percent voids in mineral aggregate (VMA)

Nominal Maximum Particle Size 1,2		Minimum VMA, Percent		
		Design Air Voids, Percent 3		
mm	in	3.0	4.0	5.0
1.18	No. 16	21.5	22.5	23.5
2.36	No. 8	19	20	21
4.75	No. 4	16	17	18
9.5	3/8	14	15	16
12.5	½	13	14	15
19	¾	12	13	14
25	1	11	12	13
37.5	1.5	10	11	12
50	2	9.5	10.5	11.5
63	2.5	9	10	11

1. Standard specification for Wire Cloth Sieves for testing purposes. ASTM E11 (AASHTO M92)
2. The nominal maximum particle size larger than the first sieve to return more than 10 percent.
3. Interpolate minimum voids in the mineral aggregate (VMA) for design air voids between those listed.

2.14 DETERMINATION OF PRELIMINARY DESIGN ASPHALT CONTENT

The design asphalt content of the asphalt paving mix is selected by considering all of the data discussed previously. As an initial starting point, the Asphalt Institute recommends choosing the asphalt content at the median of the percent air voids limits, which is four percent. All of the calculated and measured mix properties at this asphalt content should then be evaluated by comparing them to the mix design criteria in Table 17.4. If all of the criteria are met, then this is the preliminary design asphalt content. If all of the design criteria are not met, then some adjustment or compromise is necessary or the mix may need to be redesigned. A number of considerations are discussed in the next article that should be weighed even if all the design criteria are met.

2.15 SELECTION OF FINAL MIX DESIGN

The final selected mix design is usually the most economical one that will satisfactorily meet all of the established criteria. However, the mix should not be designed to optimize one particular property. Mixes with abnormally high values of stability are often less desirable because pavements with such mixes tend to be less durable and may crack prematurely under heavy volumes of traffic. This situation is especially critical where the base and subgrade materials beneath the pavement are weak and permit moderate to relatively high deflections under the actual traffic.

The design asphalt content should be a compromise selected to balance all of the mix properties. Normally the mix design criteria will produce a narrow range of acceptable asphalt contents that

pass all of the guidelines as shown by the example in Figure 2.5. The asphalt content selection can be adjusted within this narrow range to achieve a mix property that will satisfy a requirement of a specific project.

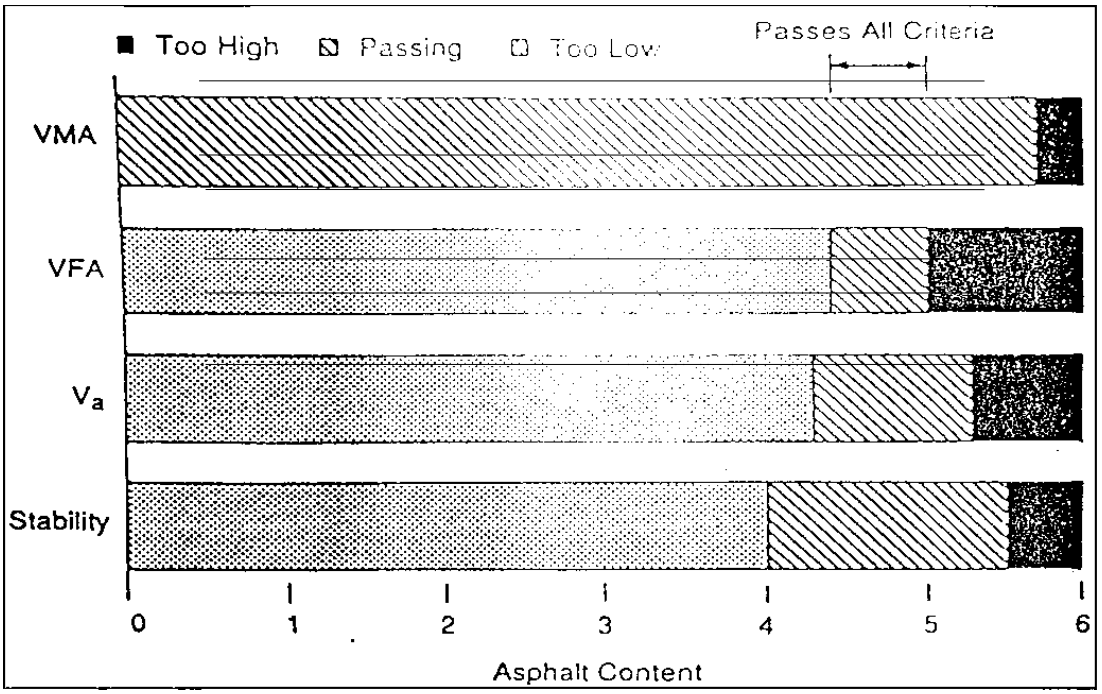


Figure 17.7 An example of the narrow range of acceptable asphalt contents

Different properties are more critical for different circumstances, depending on traffic, structure, climate, construction equipment and other factors. Therefore, the balancing process is not the same for every pavement and every mix design. These are some considerations for adjustment that should be evaluated prior to establishing the final design asphalt content:

Evaluation of VMA Curve

In many cases the most difficult mix design property to achieve is a minimum amount of voids in the mineral aggregate. The goal is to furnish enough space for the asphalt cement so it can provide adequate adhesion to bind the aggregate particles, but without bleeding when temperatures rise and the asphalt expands. Normally the curve exhibits a flattened U-shape, decreasing to a minimum value and then increasing with increasing asphalt content, shown in Figure 17.8 (a).

This dependency of VMA on asphalt content appears to be a contradiction to the definition. One might expect the VMA to remain constant with varying asphalt content, thinking that the air voids would simply be displaced by asphalt cement. In reality the total volume changes across the range

of asphalt contents; the assumption of a constant unit volume is not accurate. With the increase in asphalt the mix actually becomes more workable and compacts more easily, meaning more weight can be compressed into less volume. Therefore, up to a point, the bulk density of the mix increases and the VMA decreases.

At some point as the asphalt content increases (the bottom of the U-shaped curve) the VMA begins to increase because relatively more dense material (aggregate) is displaced and pushed apart by the less dense material (asphalt cement). It is recommended that asphalt contents on the "wet" or right-hand increasing side of this VMA curve be avoided, even if the minimum air void and VMA criteria is met. Design asphalt contents in this range have a tendency to bleed and/or exhibit plastic flow when placed in the field. Any amount of additional compaction from traffic leads to inadequate room for asphalt expansion, loss of aggregate to aggregate contact, and eventually rutting and shoving in high traffic areas. Ideally, the design asphalt content should be selected slightly to the left of the low point of the VMA curve, provided none of the other mixture criteria are violated.

In some mixes, the bottom of the U-shaped VMA curve is very flat, meaning that the compacted mixture is not as sensitive to asphalt content in this range as some other factors. In the normal range of asphalt contents, compact ability is influenced more by aggregate properties. However, at some point the quantity of asphalt will become critical to the behavior of the mix and the effect of asphalt will dominate as the VMA increases drastically.

When the bottom of the U-shaped VMA curve falls below the minimum criteria level required for the nominal maximum aggregate size of the mix [Figure 17.8 (b)], this is an indication that changes to the job mix formula are necessary. Specifically, the aggregate grading should be modified to provide additional VMA.

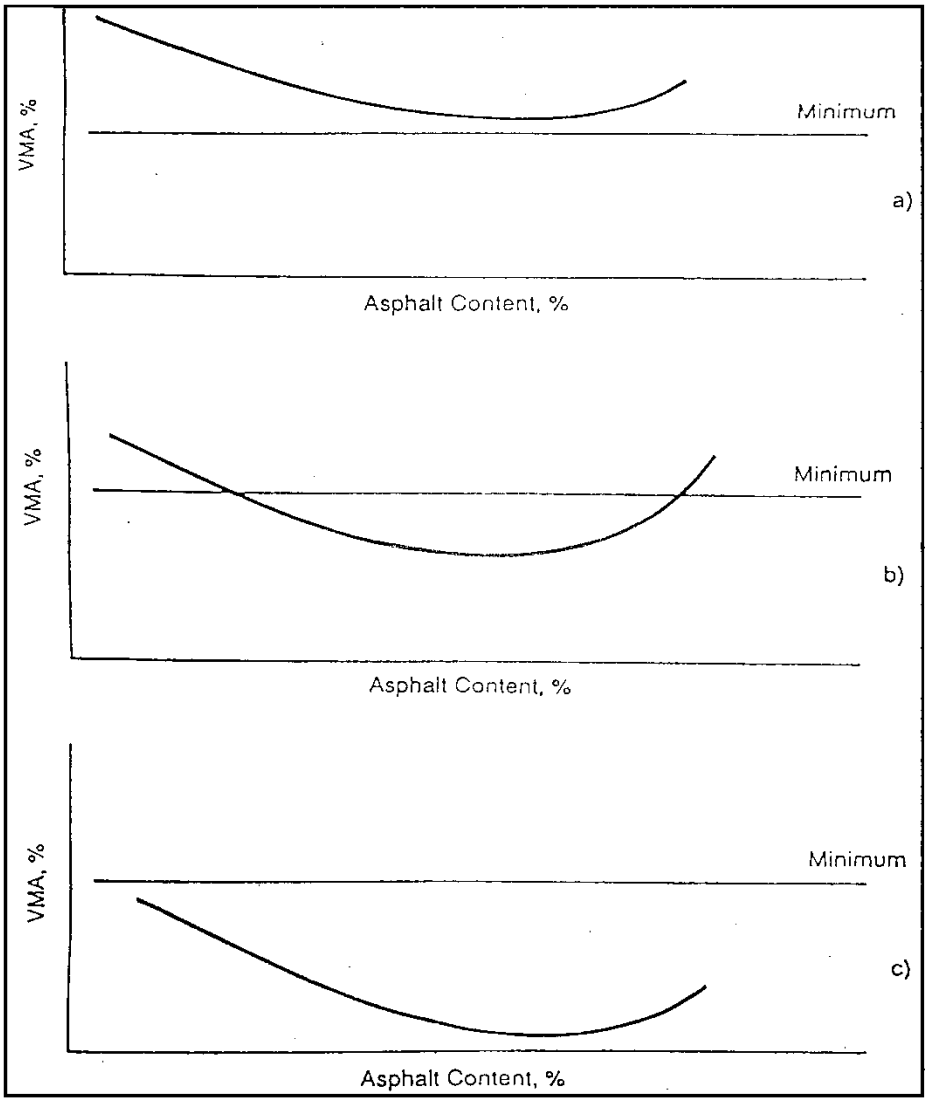


Figure 17.8 Relationship between VMA and specification limit

The design asphalt content should not be selected at the extremes of the acceptable range even though the minimum criteria are met. On the left-hand side, the mix would be too dry, prone to segregation and would probably be too high in air voids. On the right-hand side, the mix would be expected to rut.

If the minimum VMA criteria are completely violated over the entire asphalt content range [curve is completely below minimum, Figure 2.6(c)], a significant redesign and/or change in material sources is warranted.

Effect of Compaction Level

At the same asphalt content, both air voids (V_a) and voids in the mineral aggregate (VMA) decrease with higher compactive effort. The three levels of compaction of the Marshall mix procedure can

be used to illustrate the consequences of this fact. As shown in Figure 17.9(a), not only do the magnitudes of the values change but the asphalt content value at the minimum VMA shifts.

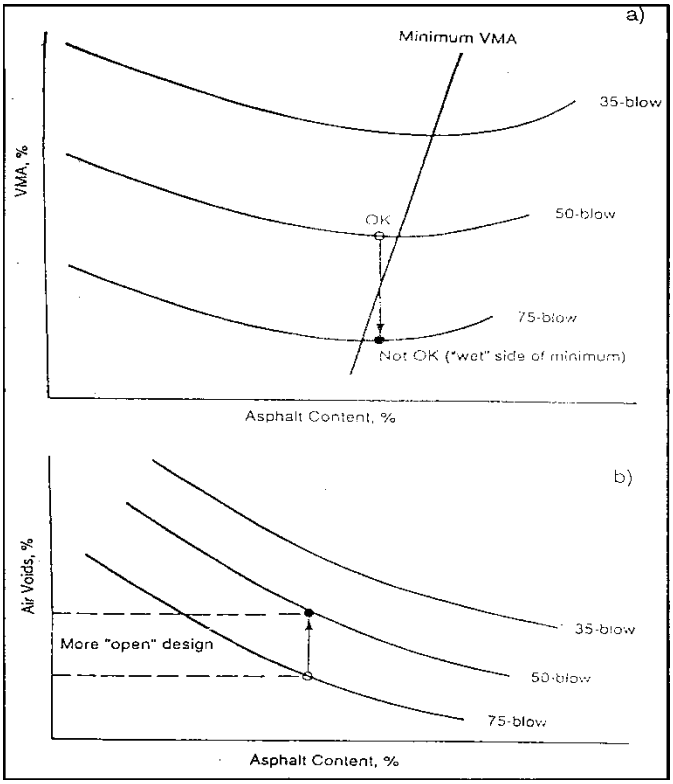


Figure 17.9 Effect of Marshall compactive effort on VMA and air voids

If a mix is designed slightly to the left of minimum VMA at a compaction level of 50 blows and the pavement actually endures heavier traffic than expected (closer to 75 blow design level); then, the same asphalts content now plots on the right hand or "wet" side of the minimum VMA point for a mix designed using 75 blow compactions. Ultimately, a mix susceptible to rutting is the result.

This scenario can also work in the opposite direction. If a mix, designed at a compaction level of 75 blows as shown in Figure 2.7(b), is placed in a pavement with much lower volumes of traffic, then the final percentage of air voids (V_a) will be considerably higher than planned. This condition could lead to a more open, permeable mix allowing air and water to pass through easily. The consequence of this situation is a mix that hardens prematurely, becomes brittle and cracks at an early age or the aggregate ravels out of the mix because of the loss of asphalt adhesion. This condition may also lead to stripping.

For this reason, it is important that the compactive effort used to simulate the design traffic expected in the pavement be selected accordingly in the laboratory. Also, the mixture must be constructed with appropriate compaction equipment in the field to produce adequate initial density regardless of climatic conditions.

It is also important to note that the VMA criteria do not change based on the level of compaction. The reasoning for having sufficient VMA (providing space for the asphalt and air voids) is consistent regardless of the traffic level for which the mixture is being designed.

Effect of Air Voids

It should be emphasized that the design range of air voids (3 to 5 percent) is the level desired after several years of traffic. This goal does not vary with traffic as seen in Table 2.2; the laboratory compactive effort is supposed to be selected for the expected traffic. This design air void range will normally be achieved if the mix is designed at the correct compactive effort and the percent air voids after construction is about 8 percent. Some consolidation with traffic is expected and desired.

The consequence of a change in any factor orany detour in the procedure that offsets the total process will be a loss of performance or service life. It has been shown that mixtures that ultimately consolidate to less than three percent air voids can be expected to rut and shove if placed in heavy traffic locations. Several factors may contribute to this occurrence, such as an arbitrary or accidental increase in asphalt content at the mixing facility or an increased amount of ultra-fine particles passing the 75 µm (No. 200) sieve beyond that used in the laboratory, which will act as an asphalt extender. Similarly, problems can occur if the final air void content is above five percent or if the pavement is constructed with over eight percent air voids initially. Brittleness, premature cracking, raveling and stripping are all possible under these conditions. The overall objective is to limit adjustments of the design asphalt content to less than 0.5 percent air voids from the median of the design criteria (four percent), especially on the low side of the range and to verify that the plant mix closely resembles the laboratory mix.

Effect of Voids Filled with Asphalt

Although VFA, VMA and V_a are all interrelated and only two of the values are necessary to solve for the other, including the VFA criteria helps prevent the design of mixes with marginally acceptable VMA. The main effect of the VFA criteria is to limit maximum levels of VMA and subsequently maximum levels of asphalt content. VFA also restricts the allowable air void content for mixes that are near the minimum VMA criteria. Mixes designed for lower traffic volumes will not pass the VFA criteria with a relatively high percent air voids (five percent) even though the air void criteria range is met. The purpose is to avoid less durable mixes in light traffic situations.

Mixes designed for heavy traffic will not pass the VFA criteria with relatively low percent air voids (less than 3.5 percent) even though that amount of air void is within the acceptable range. Because low air void contents can be very critical in terms of permanent deformation (as discussed previously), the VFA criteria helps to avoid those mixes that would be susceptible to rutting in heavy traffic situations.

The VFA criteria provide an additional factor of safety in the design and construction process in terms of performance. Since changes can occur between the design stage and actual construction, an increased margin for error is desirable.

Influence of Structure and Climate

Mix design is a compromise of many factors. The asphalt content that provides the best overall performance in addition to passing the previously discussed conventional criteria would be considered the design value. The CAMAS computer program contained in the Asphalt Institute *Computer Assisted Asphalt Mix Analysis System package*, provides an additional tool for evaluating the predicted performance of a specific mix placed in a particular situation. The various mathematical models contained in the program have not been fully verified and the program is currently considered only a research tool. However, models are included for examining fatigue life, subgrade deformation and asphalt concrete deformation of the pavement and mix for the actual climatic and traffic conditions. If any of these levels of performance are not acceptable, then either the mix or the structure could be modified and a subsequent evaluation performed.

The decision-making process for selecting the design asphalt content in the mix varies with the circumstances involved in the specific case. Depending on the particular structure or agency policy, certain factors may be more important than others. Although it was found that it is not feasible, suitable, or practical to directly trade-off thickness for better mix compaction or a change in asphalt content, there are other advantages to integrating structural design and mix design.

The type of structure can alter the engineer's evaluation in many ways. For example, in an asphalt concrete overlay of a Portland cement concrete pavement, there would be little concern for fatigue, since the tensile strains in the bottom of the AC overlay would be minimal. This is also true for the subgrade deformation related to the compressive strain on the top of the subgrade. The main consideration would be how to limit the AC rutting as well as any supplementary treatments for minimizing reflective cracking. In this particular case, it may be worthwhile to look at the effects of altering the compactive effort in the lab and field while changing the asphalt content. Depending on the environmental conditions during construction, it may be worthwhile to use heavier rollers or a longer period of rolling to achieve more or the same density with less asphalt in the mix. Mixes with asphalt contents on the high side of the acceptable range are usually avoided in this situation.

In an asphalt pavement, all three performance indicators need to be evaluated in terms of future maintenance. Initially, it is important that the subgrade be adequately protected by the structure; the number of allowable repetitions based on subgrade deformation should exceed that expected or the pavement's performance may have little to do with proper mix design. In some cases, depending on location and traffic volume, the engineer may consider whether cracking or rutting is less of a future maintenance concern and the mix design can be selected accordingly. With all other factors being equal, mixes with asphalt contents on the high side of the range are less prone to cracking because of the additional flexibility. Similarly, mixes on the low side of the range are less susceptible to rutting.

Finally, climate can have a major impact on mix and pavement performance for a given pavement structure. Mix designs do not usually consider this factor except in selecting the category or grade of asphalt cement. Table 17.6 gives recommended asphalt grades for various temperature conditions.

Table 17.6: Selecting Asphalt Grade

Temperature Condition	Asphalt Grades	
Cold, Mean Annual Temperature $\leq 7^0$ C (45^0 F)	AC-5 AR-2000 120/150 pen.	AC-10 AR-4000 85/100 pen.
Warm, Mean Annual Temperature between 7^0 C (45^0 F) and 24^0 C (75^0 F)	AC-10 AR-4000 85/100 pen.	AC-20 AR-8000 60/70 pen.
Hot, Mean Annual Temperature between $\geq$ 24^0 C (75^0 F)	AC-20 AR-8000 60/70 pen.	AC-40 AR-16000 40/50 pen.

In hot climates, harder, more viscous asphalts are normally used to obtain more stability from asphalt adhesion as well as from aggregate interlock. If the mix is designed and constructed to maximize aggregate to aggregate contact, then the properties of the asphalt cement are less important. Regardless, asphalt contents on the low side of the acceptable range are recommended for these areas.

In colder climates, softer, less viscous asphalts are recommended to produce a mix which is less susceptible to low temperature shrinkage cracking. Rutting is less of a concern; therefore, additional stability from asphalt adhesion is not necessary. Usually asphalt contents on the high side of the acceptable range are recommended to furnish a mix which is more elastic and resilient.

Specific Project Conditions

The season of the year when the pavement is being constructed can be another factor to be considered when selecting the final design asphalt content. Summer paving would usually call for lower asphalt contents, while fall or early spring construction would dictate higher asphalt contents to assist compaction in cooler temperatures. Any shift in asphalt content is only a minor amount within the narrow range that passes all the previous criteria.

The amount and handling of traffic can also influence the final decision. If the actual traffic is at the low or high end of the broad traffic categories for selecting the laboratory compactive effort and mix design criteria, then the asphalt content could be slightly modified accordingly. Higher traffic areas would demand the lower asphalt contents within the acceptable range. Mixes to be used in overlay situations with reduced lane detours, where the pavement will undergo severe loading concentrations such as highly channelized wheel passes, very slow speeds or steep upgrades, demand additional attention in all phases of production. The design asphalt content

should be selected from the low end of the acceptable range and initial compaction requirements must be met. Traffic should be held off of the pavement as long as possible while the mix is cooling to normal temperatures. This cooling allows the asphalt to contribute more to the mix stability and less as a compaction lubricant.

2.16 MODIFIED MARSHALL METHOD FOR LARGE AGGREGATE

A modified Marshall method has been developed by Kandhal of the National Center for Asphalt Technology for mixes composed of aggregates with maximum size up to 38 mm (1.5 in.). This procedure is documented in draft form in the 1990 Proceedings of the Association of Asphalt Paving Technologists (AAPT). The procedure is basically the same as the original method except for these differences that are due to the larger specimen size that is used:

(a) The hammer weighs 10.2 kg (22.5 lb.) and has a 149.4 mm (5.88 in.) flat tamping face. Only a mechanically operated device is used for the same 457 mm (18 in.) drop height.

(b) The specimen has a 152.4 mm (6 in.) diameter by 95.2 mm (3.75 in.) height.

(c) The batch weights are typically 4 kg.

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

(e) The mix is placed in the mold in two approximately equal increments, with spading performed after each increment to avoid honey combing.

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

(g) 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 same criteria listed in Table 2.2 for the normal sized specimens.

(h) Similar to the normal procedure, these values should be used to convert the measured stability values to an equivalent value fora specimen with a 95.2 mm (3.75 in.) thickness, if the actual thickness varies:

Table 17.7: Height of Marshall specimen and Correlation Ratio

Approximate Height (mm)	Approximate Height (in.)	Specimen Volume (cc)	Correlation Ratio
88.9	3 1/2	1608 to 1626	1.12
90.5	3 9/16	1637 to 1665	1.09
92.1	3 5/8	1666 to 1694	1.06
93.7	3 11/16	1695 to 1723	1.03
95.2	3 3/4	1724 to 1752	1.00
96.8	3 13/16	1753 to 1781	0.97
98.4	3 7/8	1782 to 1810	0.95
100.0	3 15/16	1811 to 1839	0.92
101.6	4	1840 to 1868	0.90

Composition of Paving Mixtures
(ASTM D3515) for Marshal Method of Mix Design

Type of Mix: Dense Mix
Mix Designation: ¾" (19 mm)
Course Aggregate: Stone Chips
Bitumen: 80/100 pen. grade Bitumen
Fine Aggregate and Mineral Filler: Fine Fraction of Course Aggregate
Traffic Category: Medium Traffic (Compaction: 50 blows per face)

Sieve Size	% Passing	% Retained (Cumulative)	% Retained (Individual)	Batch Weight (gm)
1 in (25 mm)	100	0	0	0
¾ in (19 mm)	95	5	5	57
$^3/_8$ in (9.5 mm)	68	32	27	312
# 4 (4.75 mm)	50	50	18	208
# 8 (2.36 mm)	36	64	14	162
# 50 (300 μm)	12	88	24	277
# 200 (75 μm)	5	95	7	81
M.F.	0	100	5	58
Total			**100**	**1155**

% of Bitumen (of Total Mix), P_b

4.0% = 48.13 gm, 4.5% = 54.42 gm, 5.0% = 60.79 gm
5.5% = 67.22 gm, 6.0% = 73.72 gm

Specific Gravity

C.A. (1 inch - #8) (G_1) : 2.68 (ASTM C-127)
F.A. (#8 - #200) (G_2) : 2.68 (ASTM C-128)
M.F. (Passing #200) (G_3) : 2.77 (ASTM D-854)
Bitumen (G_b) : 1.02 (ASTM D-5)

Mixing Criteria:

Temperature: 148 – $153^0 \Rightarrow 150^0$ C, Time: 2.5 min.
Compaction Temp.: 138 – $142^0 \Rightarrow 140^0$ C
Oven Temperature for Bitumen and Aggregate: 155^0 C, Time: 2 hrs.

Experiment No: 17

Determination of Optimum Asphalt Content by Marshall Method of Mix Design

Name : **Student No**:

Asphalt content (P_b)%	Specimen wt. in air (W_a) gm	Specimen wt. in water (W_w) gm	Specimen wt. in air (SSD) (W_s) gm	G_{mb}	Unit wt. (lb/cft) G_{mb}x62.4	G_{mm}	P_S	G_{sb}	$\%V_a$	%VMA	%VFA	Height of specimen (mm)	Correction factor	Stability observed (lbs.)	Corrected stability (lbs.)	Flow value (0.25 mm)

$$G_{mb} = \frac{W_a}{Ws - W_w}; \qquad G_{mm} = \frac{P_{mm}}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}}; \qquad P_s = 100 - P_b; \qquad P_{mm} = 100; \qquad G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}}; \qquad G_{sb} = \frac{P_1 + P_2 + P_3}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3}}$$

$$\%V_a = 100\frac{G_{mm} - G_{mb}}{G_{mm}}; \qquad \%VMA = 100 - \frac{G_{mb} * P_s}{G_{sb}}; \qquad \%VFA = \frac{\%VMA - \%V_a}{\%VMA} * 100$$