PRINCIPLES AND DESIGN OF PAVEMENTS

Flexible Pavement: Introduction, composition, factors governing design, design of flexible pavements as per IRC;

Bituminous mix design (Marshall method), IIT Pave Software; Case study - Design Problem

Rigid pavement: Introduction, composition, factors governing design, DLC and PQC mix design; design of concrete

pavements as per IRC; Joints; Case study – Design Problem.

EVOLUTION OF MIX DESIGN

- As per Das et al.(2004); During 1900's, the bituminous paving technique was first used on rural roads – so as to handle rapid removal of fine particles in the form of dust, from Water Bound Macadam, which was caused due to rapid growth of automobiles. At initial stage, **heavy oils** were used as **dust palliative**. An eye estimation process, called pat test was used to estimate the requisite quantity of the heavy oil in the mix

- The first formal mix design method was **Habbard field method**, which was originally developed on **sand-asphalt mixture**. Mixes with large aggregates could not be handled in Hubbard field method. This was one of the limitations of this procedure. Hveem used the surface area calculation concept (which already existed at that time for cement concrete mix design), to estimate the quantity of bitumen required. Moisture susceptibility and sand equivalent tests were added to the Hveem test in 1946 and 1954 respectively.

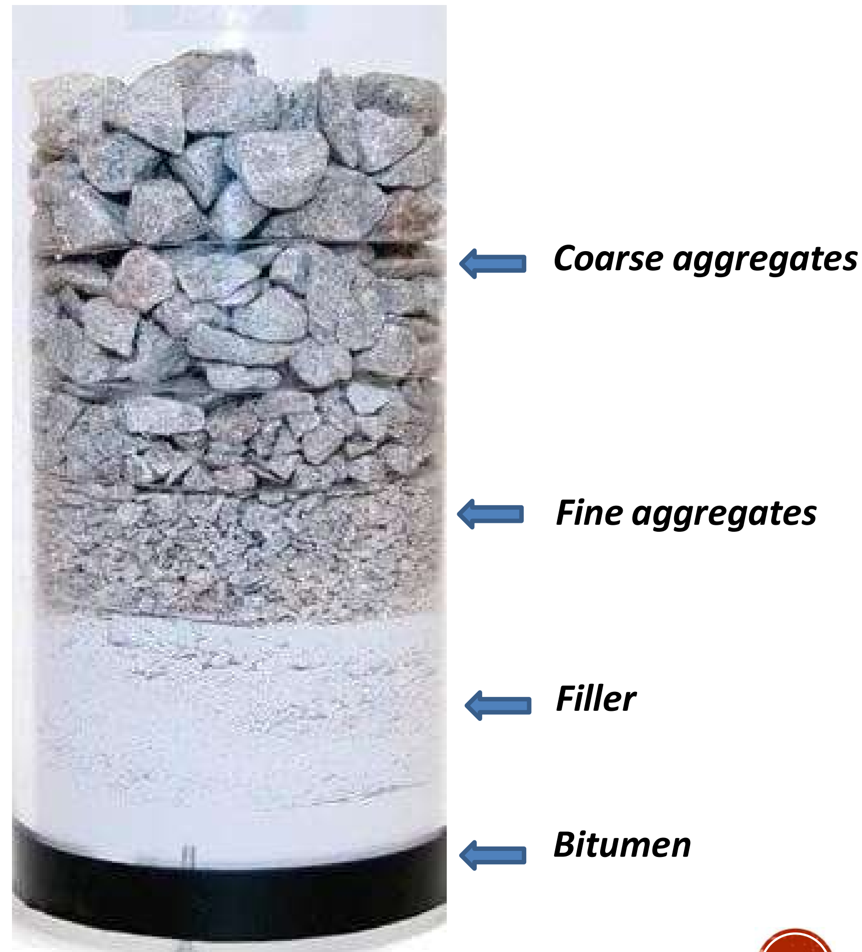
- Bruce Marshall developed the **Marshall testing machine** just before the World War-II. It was adopted in the US Army Corpes of Engineers in 1930‟s and subsequently modified in 1940's and 50's

BITUMINOUS MIXES

- Asphaltic/Bituminous concrete consists of a mixture of aggregates continuously graded from maximum size, typically less than 25 mm, through the fine filler that is smaller than 0.075 mm.

- Sufficient bitumen is added to the mix so that the compacted mix is effectively impervious and will have acceptable dissipative and elastic properties.

- The bituminous mix design aims to *'determine the proportion of bitumen, filler, fine aggregates, and coarse aggregates to produce a mix which is workable, strong, durable and economical'*.



CONSTITUENTS OF MIX

Bituminous mix is a mixture of following materials

- Aggregates: Coarse and Fine
- Fillers
- Bitumen
- Additives

REQUIREMENTS BITUMINOUS MIXES

1. Stability: Resistance of the paving mix to deformation under traffic load.

Lack of stability leads to two typical failure:


a) Shoving


b) Rutting


c) Rutting

2. Durability: Resistance of the mix against weathering and abrasive actions.

Typical examples of failure are:


a) Stripping


b) Pot-holes

REQUIREMENTS OF BITUMINOUS MIXES

3. Flexibility: It is the property of the mix that measures the level bending strength. Shrinkage and brittleness is the main reasons for formation

- Shrinkage cracks are due to volume change in the binder due to aging
- Brittleness is due to repeated bending of the surface due to traffic loads

a) Hairline-cracks

4. Skid resistance: The resistance of the finished pavement against skidding which depends on the surface texture and bitumen content

b) Alligator cracks

5. Workability: Workability is the ease with which the mix can be laid and compacted, and formed to the required condition and shape. This depends on the gradation of aggregates, their shape and texture, bitumen content and its type

PROPERTIES OF BITUMINOUS MIXES

Thus, the desirable properties of a bituminous mix can be summarized as follows:

- Stability to meet traffic demand
- Bitumen content to ensure proper binding and water proofing
- Voids to accommodate compaction due to traffic
- Flexibility to meet traffic loads, especially in cold season
- Sufficient workability for construction
- Economical mix

OBJECTIVE OF THE MIX DESIGN:

To produce a bituminous mix by proportioning various components so as to have:

a) Sufficient strength to resist shear deformation under traffic at higher temperature

b) Sufficient air voids in the compacted bitumen to allow for additional compaction by traffic

c) Sufficient workability to permit easy placement without segregation

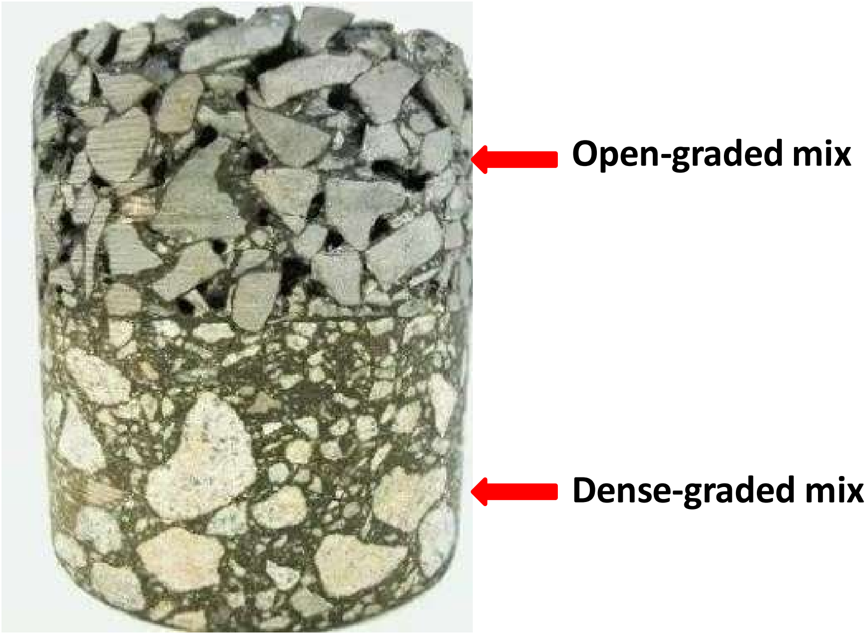
d) Sufficient flexibility to avoid premature cracking due to repeated bending by traffic

e) Sufficient flexibility at low temperature to prevent shrinkage cracks.

f) Sufficient bitumen to ensure a durable pavement

TYPES OF BITUMINOUS MIXES

- Bituminous Concrete (BC)
- Dense Bituminous Macadam (DBM)
- Bituminous Macadam (BM)
- Stone Matrix Asphalt (SMA)
- Mastic Asphalt (MA)
- Open Graded Friction Course (OGFC)
- Premix Carpet (PC)



****All about aggregate gradation, bitumen quantity, and method of mixing**

Types of Bituminous Mixes

Dense Bituminous Macadam (DBM)

Bituminous Concrete (BC)

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Open Graded Friction Course (OGFC)

Stone Matrix Asphalt (SMA)

****All about aggregate gradation, bitumen quantity, and method of mixing**

DESIGN OF BITUMINOUS MIXES

The following steps may be followed for a rational design of a bituminous mix:

i) Selection of Aggregates

ii) Selection of Aggregate Grading

iii) Determination of Specific Gravity

iv) Proportioning of Aggregates

v) Preparation of Specimen or Sample

vi) Determination of Specific Gravity of Compacted Specimen

vii) Determination of volume of voids, voids in mineral aggregates and voids filled with bitumen

viii) Stability Tests on Compacted Specimens

ix) Selection of Optimum Bitumen Content

SELECTION OF AGGREGATE GRADING

Table: Grading of Aggregates

Sieve size in mm	Percentage Passing	
	Grade 1	Grade 2
20	-	100
12.5	100	80-100
104.75	80-100	55-75
2.36	55-75	35-50
0.6	35-50	18-29
0.3	18-29	13-23
0.15	13-23	8-16
0.75	8-16	4-10
Binder Content (% by weight of mix)	5-7.5	5-7.5

If the available gradation is not satisfying the specification or specified gradation proper blending of different grades is to be adopted for this purpose, either by the method of trials or Rothfuch's method

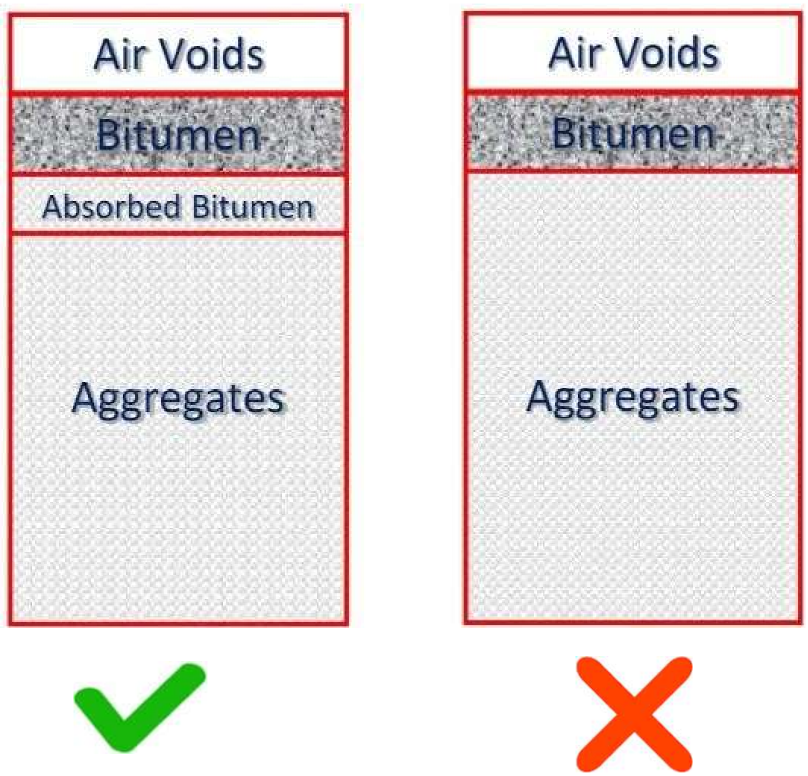
ROTHFUTCH'S METHOD OF AGGREGATE BLENDING

1. Determine the proportion of aggregates A, B and C to be mixed together for obtaining desired gradation using Rothfuth's method

Sieve size	Percentage passing				
	Sample A	Sample B	Sample C	Specification	Mid specification
3/4 inch (19)	100	100	100	94-100	97
½ inch (12.5)	63	100	100	70-85	78
No. 4 (4.75)	19	100	100	40-55	48
No. 8 (2.38)	8	93	100	30-42	36
No. 50 (0.3)	5	55	100	20-30	36
No. 100 (0.15)	3	36	97	12-22	17
No. 200 (0.75)	2	3	88	5-11	8

PHASE DIAGRAM OF BITUMINOUS MIX SAMPLE

Aggregate absorbs bitumen – important to consider this aspect, otherwise there will be less effective bitumen, and may result in stripping, poor bond, raveling and failure of pavement.



Absorbs bitumen fills pore of aggregate

(does not contribute in any performance)

Effective bitumen = Total - Absorbed

BASIC TERMINOLOGY

Bulk Specific Gravity of Mix Sample

$$\text{Bulk specific gravity of mix } (G_{mb}) = \frac{\text{Weight of sample in air}}{\text{Bulk volume of sample}}$$

Say, weight of compacted sample in air: 1260 gm

Bulk volume of aggregates: Saturated surface dry weight – weight in water = 1264 gm– 719 gm = **545 cc**

Bulk specific gravity (G_{mb}): $\frac{1260}{545}$ = 2.312

**Bulk volume - total volume of samples including air voids within

BASIC TERMINOLOGY

Percentage Air voids (V_a)

Percentage air voids: Percentage volume of air voids in the sample.

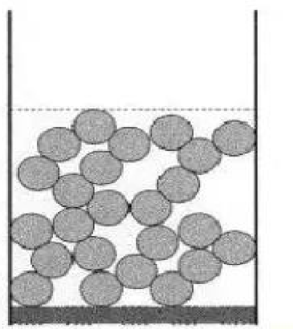
Percentage Compaction (% density): 100 - Percentage air voids (Say, if air voids: 4.5%, compaction: 95.5%)

- High air voids means, sample of too loose, so water ingress, easily deform, air/temperature impact
- Low air voids means sample is highly compacted. Bitumen will over flow on surface of roads after traffic compaction, failure of pavement

Standard: **Maximum air voids should be 8% (or in other words, minimum compaction should be 92%)**

BASIC TERMINOLOGY

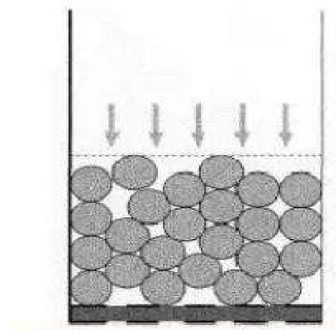
Voids in Mineral Aggregates (VMA)



Voids in compacted aggregates without bitumen

Total Voids =Volume of air voids

Example: **20%**



Voids in compacted aggregates after addition of bitumen (bituminous mix): mobility of aggregate increase, better compaction

Total Voids = Volume of bitumen + air voids

VMA: Volume of effective bitumen + air voids

Example: VMA = **16%**

i.e., 11.5% effective bitumen + 4.5% air voids

BASIC TERMINOLOGY

Voids Filled with Bitumen(VFB)

Out of total voids (VMA) available after compaction (air voids+ effective bitumen), what % of voids are filled with effective bitumen/asphalt

Example: VMA: 16% (total voids, effective volume of bitumen + air voids)

Volume filled with effective bitumen: 11.5%, Air voids: 4.5%

VFB: $\frac{11.5}{16} \times 100 = 71.8\%$

VFB indicates volume of bitumen available to coat the aggregates

- Very high VFB indicates, excess amount of bitumen, may pose bleeding of mix.
- Low VFB indicates, not enough bitumen to coat aggregates, and hence raveling or poor bond or durability.

Standard: **VFB should have a low and high range (typically it is 65-75%)**

BASIC TERMINOLOGY

Binder absorbed and Effective Binder

Binder absorbed (M_{ba}):

Amount of bitumen filled in pore of aggregate

Percentage of absorbed bitumen,

$$P_b = \frac{M_{ba}}{M_s} \times 100$$

Example:

Mass of aggregates: M_s = 1200 gm

Mass of bitumen: M_b = 60 gm

Mass of bitumen absorbed into aggregates: M_{ba}= 12 gm

$$P_b = \frac{12}{1200} \times 100 = 1\%$$

Effective Bitumen

total bitumen – absorbed bitumen = $M_b - M_{ba}$

Percentage of effective binder,

$$P_b = \frac{M_{be}}{M_{mb}} \times 100$$

Example:

Mass of mix: M_{mb} = 1260 gm

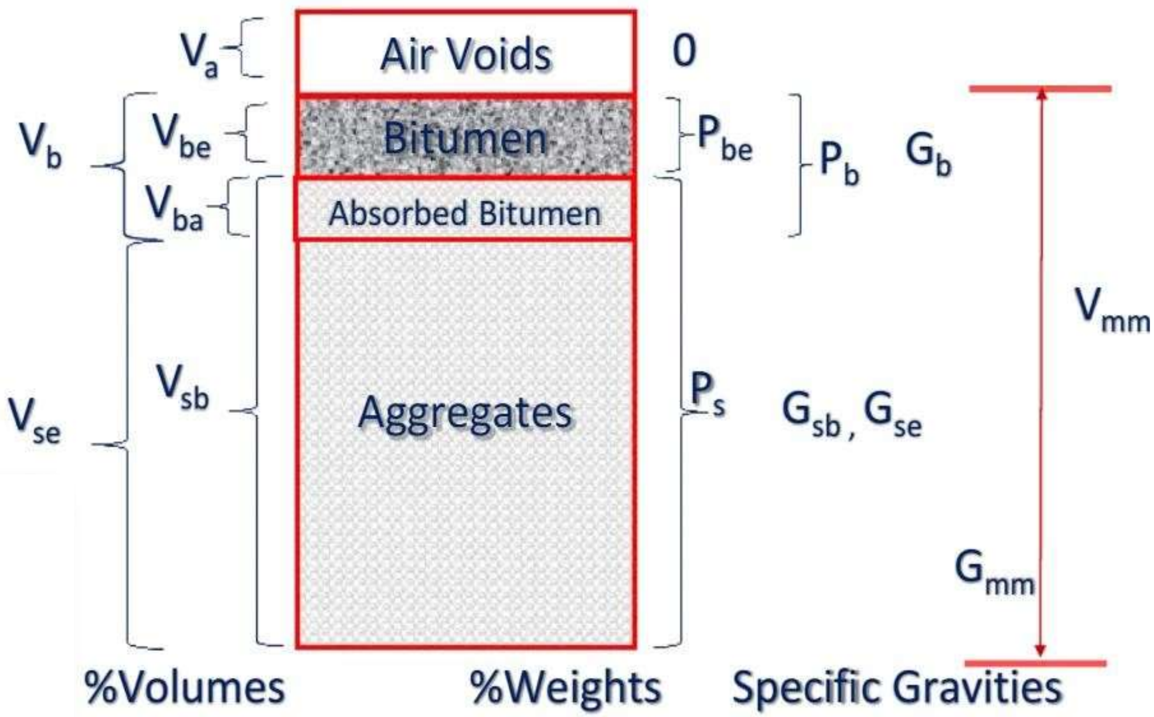
Mass of bitumen: M_b = 60 gm

Mass of bitumen absorbed into aggregates: M_{ba}= 12 gm

Mass of effective bitumen = 60-12 =48gm

$$P_{be} = \frac{48}{1260} \times 100 = 3.8\%$$

PHASE DIAGRAM



Voids in mineral aggregates

$$VMA = \frac{V_a + V_{be}}{V} \times 100$$

Voids Filled with Bitumen

$$VFB = \frac{V_{be}}{V_a + V_{be}} \times 100$$

$$\mathbf{VFB} = \frac{\mathbf{V_b}}{\mathbf{VMA}} \times \mathbf{100}$$

**Absorbs bitumen does not count towards total

BITUMINOUS MIX DESIGN BY MARSHALL METHOD

PREPARATION OF SPECIMEN

- The coarse aggregates, fine aggregates and the filler material should be proportioned and mixed as per the dry mix design(1200gm).
- The dry mix of aggregates and filler is heated to a temperature of 150° to 170°C.
- The compacted mould assembly and rammer are cleaned and kept preheated to a temperature of 100°C to 145°C.
- The bitumen is heated to a temperature of 150°C to 165°C and the required quantity of the first trial percentage of bitumen is added to the heated aggregates and thoroughly mixed.
- The mixing temperature of the 60/70 grade is about 165°C.

MARSHALL STABILITY TEST

Preparation of Specimen Mould

- For preparing specimens of 10cm diameter and 6.35 cm height for Marshall testing.
- Consists of base plate, forming mould and collar
- Interchangeable base plate and collar can be used on either end of compaction mould.

Compaction of the Specimen

- The mix is placed in the mould and compacted by a rammer with about 75 blows on each side.
- The weight of hammer is 4.54 kg and height of fall is 45.7 cm.
- The compacting temperature may be about 135°C for 60/70 grade bitumen.
- The compacted specimen should have a thickness of 63.5 ± 3.0mm.

MARSHALL STABILITY TEST

Sample Extraction

Sample is being extracted after 24hr using Marshall machine

Marshall Stability and Flow Test

- The specimens to be tested are kept immersed in water in a thermostatically controlled water bath at 60 ± 1°C for 30 to 40 minutes.
- Take out the specimen from the water bath and place it in the breaking head.
- Place the breaking head in Marshall testing machine.
- Load is applied on the breaking head by the loading machine at the rate of 5 cm per minute.
- **Stability value** is the load taken by the specimen at failure.
- **Flow value** is the deformation of the specimen at failure.
- Apply **correction factor** to the stability value if the height of specimen is different from 6.35 cm.

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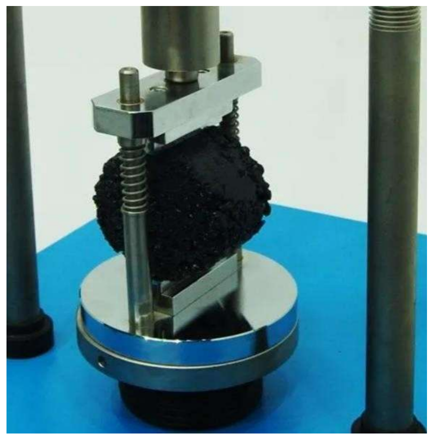
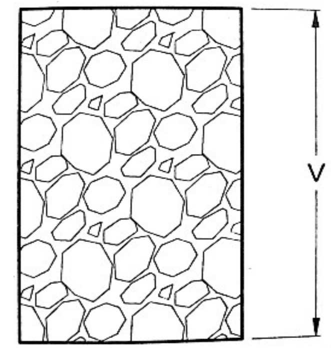
MARSHALL STABILITY TEST



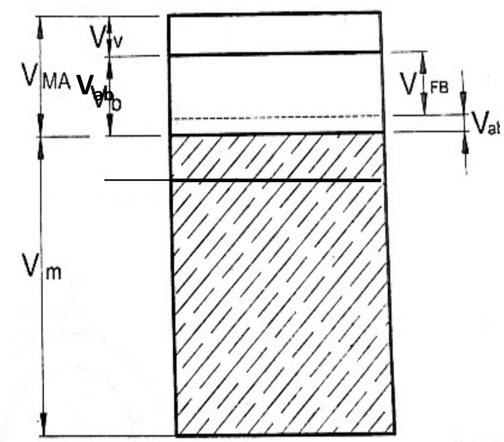
Correction Factors		
Volume of specimen in cm^3	Approximate Thickness of Specimen in mm	Correction Factors
457-470	57.1	1.19
471-482	58.7	1.14
483-495	60.3	1.09
496-508	61.9	1.04
509-522	63.5	1.00
523-535	65.1	0.96
536-546	66.7	0.93
547-559	68.3	0.89
560-573	69.9	0.86

VOLUMETRIC ANALYSIS

The volumetric composition of compacted bituminous mix is as given in figure:



BITUMINOUS MIX OF WEIGHT, W



VOLUME OF COMPONENTS

Let the weight of compacted specimen (weight in air) be W_g

Let the volume of compacted specimen be V cm^3

Total or bulk volume of compacted specimen = **V**

Solid/void-less volume all the mineral aggregate and filler = $\mathbf{V_m}$

Volume of Voids in Mineral Aggregates, VMA = $\mathbf{V - V_m}$

Total volume of bituminous binder in the mix = $\mathbf{V_b}$

Part of volume of binder absorbed by the aggregates = $\mathbf{V_{ab}}$

Rest of binder filled in part of voids in mineral aggregates = $\mathbf{V_{bf}}$

Therefore, $\mathbf{V_b = (V_{ab} + V_{bf})}$

MARSHALL METHOD OF MIX DESIGN

Volume of air voids in mix, $\mathbf{V_v}$ = V – (V_m + V_{bf})

Volume of voids filed with bitumen, **VFB** = (VMA - V_v)

Void-less volume of paving mix = (V - V_v)

Theoretical specific gravity

$$G = \frac{100}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_b}{G_b}}$$

Where,

W_1, W_2, W_3, W_b = percent by weight of coarse aggregates, fine aggregates, filler and bitumen respectively

G_1, G_2, G_3, G_b = specific gravity of coarse aggregates, fine aggregates, filler and bitumen respectively

BULK SPECIFIC GRAVITY/ ACTUAL SPECIFIC GRAVITY

$$G_b = \frac{W_m}{W_m - W_w}$$

where, W_m is the weight of mix in air, W_w is the weight of mix in water

Void Analysis:

Volume of voids, $V_v(\%) = \frac{100(G_t - G_b)}{G_t}$

Volume of bitumen, $V_b = \frac{W_b}{G_b} \times \frac{G_m}{W_m}$

Voids in Mineral Aggregates, VMA = $V_v + V_b$

Voids Filed with Bitumen, VFB = $\frac{100 V_b}{VMA} = \frac{100 V_b}{(V_v + V_b)}$

DETERMINATION OF SPECIFIC GRAVITY

The specific gravity of aggregate mix is represented as bulk specific gravity/apparent specific gravity/effective specific gravity of mix

When the different aggregate are mixed to obtain required gradation, the specific gravity of combined mixture denoted as 'G_a' is determined using equation:

$$G_a = \frac{100}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_4}{G_4} + \cdots}$$

Where,

W_1, W_2, W_3, W_4 = percent by weight of aggregates

G_1, G_2, G_3, G_4 = specific gravity of each material used in mix

When the total weight of aggregate mix is considered:

$$\boldsymbol{G_a = \frac{W_1 + W_2 + W_3 + \cdots}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \cdots}}$$

DETERMINE OPTIMUM BITUMEN CONTENT:

The average values of the above properties are determined for each mix with different bitumen content and the following graphical plots are prepared:

- Binder content versus corrected Marshall stability
- Binder content versus Marshall flow
- Binder content versus percentage of void (V_v) in the total mix
- Binder content versus voids filled with bitumen (VFB)
- Binder content versus unit weight or bulk specific gravity (G_m)

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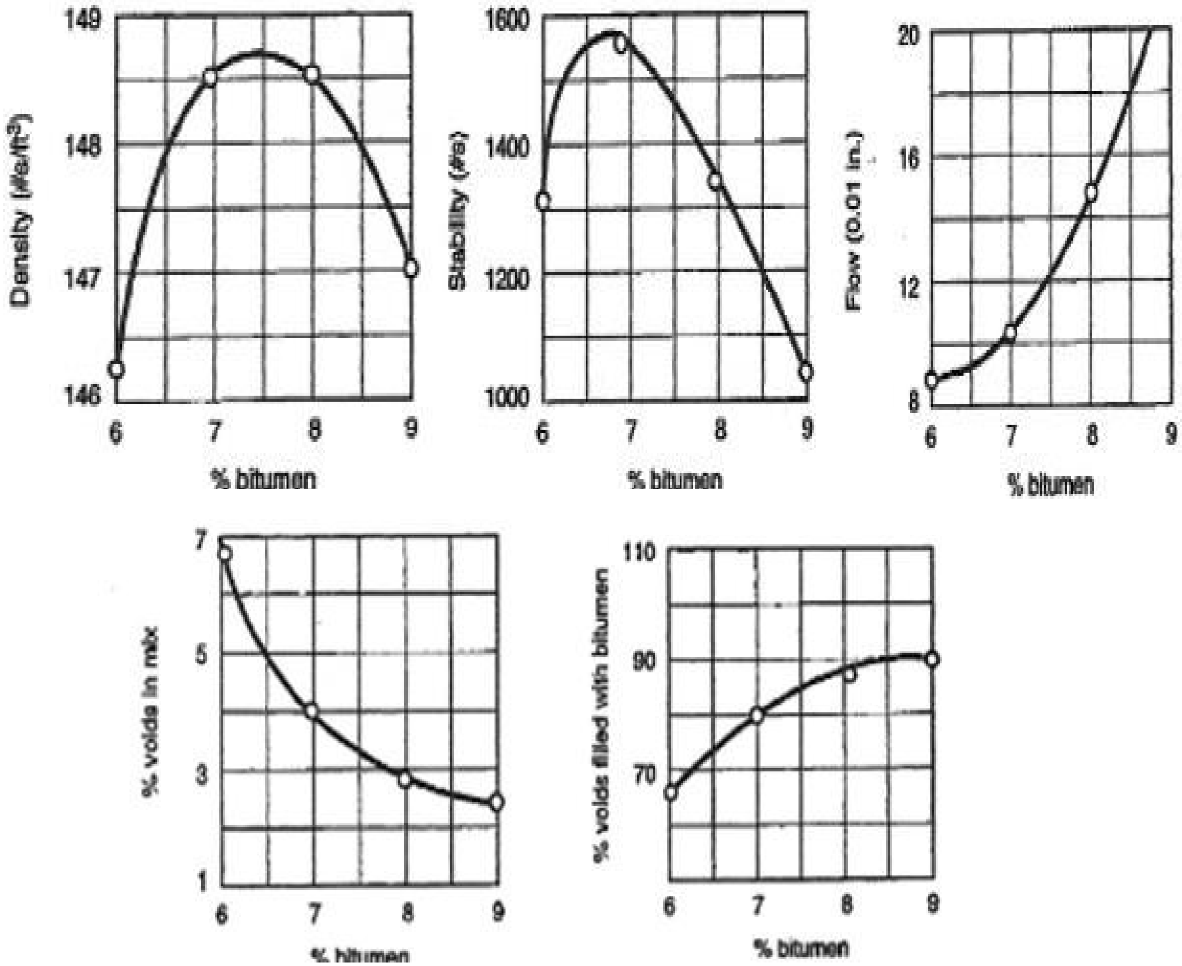
DETERMINE BINDER CONTENT



- corresponding to maximum stability
- corresponding to maximum bulk specific gravity (G_m)
- median of designed limits of percent air voids (V_v) in the total mix (i.e. 4%)

DETERMINE BINDER CONTENT

The stability value, flow value, and VFB are checked with Marshall mix design specification chart given in Table

Table: Marshall Mix Design Specifications

Test Property	Specified Value
Marshal Stability, kg	340(minimum)
Flow Value, 025 mm units	8-17
Percentage of air voids in mix, V_v %	3-5
Voids filled with bitumen, VFB %	75-85

Mixes with very high stability value and low flow value are not desirable as the pavements constructed with such mixes are likely to develop cracks due to heavy moving loads.

Numerical 1: The specific gravities and weight proportions for aggregate and bitumen are as under for the preparation of Marshall mix design. The volume and weight of one Marshall specimen was found to be 475cc and 1100 gm. Assuming absorption of bitumen in aggregate is zero, find V_v, V_b, VMA and VFB

Item	A_1	A_2	A_3	A_4	B
Wt (gm)	825	1200	325	150	100
Sp. Gr	2.63	2.51	2.46	2.43	1.05

Solution:

Theoretical specific gravity value of bituminous mix specimen,

$$G = \frac{100}{\frac{W_1}{G_1}+\frac{W_2}{G_2}+\frac{W_3}{G_3}+\frac{W_3}{G_3}+\frac{W_b}{G_b}}$$

$$G_t = \frac{100}{\frac{825}{2.63}+\frac{1200}{2.51}+\frac{325}{2.46}+\frac{150}{2.43}+\frac{100}{1.05}}$$

= 2.406

Bulk specific gravity, $G_m = \frac{W_m}{W_m - W_w}$

$= \frac{1100}{475}$

$= 2.316$

Volume of voids, $V_v(\%) = \frac{100(G_t - G\ \ )}{G_t}$

$= \frac{100(2.406-2.316)}{2.406}$

$= 3.714\%$

Volume of bitumen, $V_b = \frac{W_b}{G_b} \times \frac{G_m}{W_m}$

$= \frac{100}{1.05} \times \frac{2.316}{1100}$

$= 20.052\%$

Voids in Mineral Aggregates, VMA = $V_v + V_b$

$= 3.714 + 20.052$

$= 23.793\%$

Voids Filed with Bitumen, VFB = $\frac{100 V_b}{VMA}$

$= \frac{100 \times 20.052}{23.793}$

$= 84.277\%$

Numerical 2: The results of Marshall test for five specimens is given below. Find the optimum bitumen content of the mix

Bitumen	Stability	Flow	V_v	VFB	G_m
content	(kg)	(units)	(%)	(%)	
3	499.4	9.0	12.5	34	2.17
4	717.3	9.6	7.2	65	2.21
5	812.7	12.0	3.9	84	2.26
6	767.3	14.8	2.4	91	2.23
7	662.8	19.5	1.9	93	2.18

Solution:

Plot the graphs:

- Binder content versus corrected Marshall stability
- Binder content versus Marshall flow
- Binder content versus percentage of void (V_v) in the total mix
- Binder content versus voids filled with bitumen (VFB)
- Binder content versus unit weight or bulk specific gravity (G_m)

Optimum binder content is determined by considering average of:

- Binder content corresponding to maximum stability = 5%
- Binder content corresponding to maximum bulk specific gravity (G_m) = 5%
- Binder content corresponding to 4% air voids (V_v) =3% The

optimum bitumen extent is the average of above = **4.33%**