CONSTRUCTION AND QUALITY CONTROL OF FLEXIBLE AND RIGID PAVEMENTS

Bituminous Mix Design: Marshall Method

National Rural Infrastructure Development Agency

Ministry of Rural Development

National Institute of Technology

Warangal, Hyderabad

LECTURE-12

Bituminous Mix Design: Marshall Method

FLEXIBLE PAVEMENT DESIGN

- IRC:SP:72 (2015): up to 2 msa
  - Surface dressing as wearing course up to T5
  - OGPC as wearing course from T6 to T9
  - BM as binder course for T9
- IRC: 37 (2018): from 5 msa
- IRC:SP:20 (New Revision): 2 to 5 msa guidelines
  - T10: 2 to 3.5 msa, T11: 3.5 to 5 msa
  - BC or SDBC as wearing course
  - DBM as binder course

BITUMINOUS MIXES

- Bituminous Macadam
- Surface Dressing
- Open Graded Premix Carpet
- Mix Seal Surfacing
- Seal Coat
- Semi-Dense Bituminous Concrete
- Dense Bituminous Macadam
- Bituminous Concrete

BITUMINOUS MACADAM

- Single course of 50 mm to 75 mm
- VG bitumen

Property	Test	Specification
Cleanliness	Grain size analysis	Max. 5% passing 75 μm sieve
Particle shape	Flakiness index	Max. 25%
Strength	Aggregate impact value	Max. 30%
Durability	Soundness using Sodium Sulphate	Max. 12%
	Soundness using Magnesium Sulphate	Max. 18%
Water absorption	Water absorption	Max. 2%
Stripping	Stripping	Min. retained coating 95%

- When crushed gravel is used, not less than 90% by weight retained on 4.75 mm sieve shall have at least two fractured faces

BITUMINOUS MACADAM

- Aggregate grading and binder content:

IS Sieve size, mm	Percent passing
26.5	100
19	90 to 100
13.2	56 to 88
4.75	16 to 36
2.36	4 to 19
0.3	2 to 10
0.075	0 to 5
Bitumen content by weight of total mix	3.3 to 3.5

- Bitumen content may be up to 0.5% higher in cooler areas of the country subject to approval of the Engineer

BITUMINOUS MACADAM

- Mixing, laying and rolling temperatures for bituminous mixes:

Bitumen grade	Bitumen Temp., °C	Aggregate Temp., °C	Mixed Material Temp., °C	Laying Temp., °C	Rolling Temp., °C
VG 40	160 to 170	160 to 175	160 to 170	150 (Min.)	100 (Min.)
VG 30	150 to 165	150 to 170	150 to 165	140 (Min.)	90 (Min.)
VG 20	145 to 165	145 to 170	145 to 165	135 (Min.)	85 (Min.)
VG 10	140 to 160	140 to 165	140 to 160	130 (Min.)	80 (Min.)

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SURFACE DRESSING

- VG bitumen or CRS-2
- Single sized chips

Property	Test	Specification
Cleanliness	Grain size analysis	Max. 5% passing 75 μm sieve
Particle shape	Flakiness index	Max. 25%
Strength	Aggregate impact value	Max. 30%
Polishing	Polished stone value	Min. 60
Durability	Soundness using Sodium Sulphate	Max. 12%
	Soundness using Magnesium Sulphate	Max. 18%
Water absorption	Water absorption	**Max. 1%**
Stripping	Stripping	Min. retained coating 95%

- Size of aggregates depends on type of surface on which it is laid and traffic intensity

SURFACE DRESSING

Type of surface	NMAS, mm		
-	200 to 1000 CVPD per lane	20 to 200 CVPD per lane	< 20 CVPD per lane
Very hard	6	6	6
Hard	10	6	6
Normal	10	10	6
Soft	13	13	10
Very soft	19	13	10

- Very hard surfaces: cement concrete, very lean bituminous structures with dry stony surfaces into which negligible penetration of chippings will occur even under heaviest traffic
- Hard surfaces: chippings will penetrate only slightly under heavy traffic
- Normal: chippings will penetrate moderately under medium and heavy traffic
- Soft: chippings will penetrate considerably under medium and heavy traffic
- Very soft: Surfaces rich in binder into which even large aggregates will be submerged under heavy traffic

SURFACE DRESSING

- Precoated chips:
  - Alternative to use of adhesion agent (retained coating < 95%)
  - Chips precoated with binder except when sprayed binder film is bitumen emulsion
  - 0.75 to 1.0% bitumen by weight of chips
  - Cured for at least one week or until they become non sticky
  - Aggregate gradations depending on NMAS (see Table 500.6 of MoRD)

SURFACE DRESSING

NMAS, mm	Binder, kg/m²			Aggregates, m^3/m^2
	Uncoated aggregates		Coated aggregates	
	Bitumen	Bitumen emulsion	Bitumen	
19	1.2	1.8	1.0	0.014 to 0.015
13	1.0	1.5	0.8	0.009 to 0.011
10	0.9	1.3	0.7	0.007 to 0.009
6	0.75	1.1	0.6	0.003 to 0.005

- For 2-coat surface dressing using bitumen emulsion, bitumen emulsion quantity for each coat may be added and 40 to 45 percent is applied in the first coat and remaining in second coat
- Bitumen for coated aggregates excludes quantity of bitumen required for coating

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OPEN GRADED PREMIX CARPET

- VG bitumen or modified bitumen or bitumen emulsion

Property	Test	Specification
Cleanliness	Grain size analysis	Max. 5% passing 75 μm sieve
Particle shape	Flakiness index	Max. 25%
Strength	Aggregate impact value	Max. 30%
Durability	Soundness using Sodium Sulphate	Max. 12%
	Soundness using Magnesium Sulphate	Max. 18%
Water absorption	Water absorption	**Max. 1%**
Stripping	Stripping	Min. retained coating 95%

OPEN GRADED PREMIX CARPET

- Proportioning of materials:

Aggregate	Quantity
NMAS, 13.2 mm (22.4 mm to 11.2 mm)	0.18 m^3
NMAS, 11.2 mm (13.2 mm to 5.6 mm)	0.09 m^3
Total	0.27 m^3

Bitumen	Quantity
For 0.18 m^3 of 13.2 mm NMAS aggregates @ 52 kg/m^3	9.4 kg
For 0.09 m^3 of 11.2 mm NMAS aggregates @ 56 kg/m^3	5.2 kg
Total	14.6 kg

Bitumen Emulsion	Quantity
Total	20 to 23 kg

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MIX SEAL SURFACING

- Close-graded premix surfacing of 20 mm thickness using VG bitumen

Property	Test	Specification
Cleanliness	Grain size analysis	Max. 5% passing 75 μm sieve
Particle shape	Flakiness index	Max. 25%
Strength	Aggregate impact value	Max. 30%
Durability	Soundness using Sodium Sulphate	Max. 12%
	Soundness using Magnesium Sulphate	Max. 18%
Water absorption	Water absorption	**Max. 1%**
Stripping	Stripping	Min. retained coating 95%

MIX SEAL SURFACING

- Aggregate gradation:

IS Sieve, mm	Percent passing	
-	Type A	Type B
13.2	-	100
11.2	100	88 to 100
5.6	52 to 88	31 to 52
2.8	14 to 38	5 to 25
0.09	0 to 5	0 to 5

- Total quantity of aggregates (Type A or Type B): 0.27 m^3/10 m^2
- Total quantity of bitumen is 22 kg/10 m^2 for Type A and 19 kg/10 m^2 for Type B

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SEAL COAT

- Seals the voids in a bituminous surface
- VG bitumen or bitumen emulsion
- Three types:
  - Type A: liquid seal coat (layer of bituminous binder + cover of stone chips)
  - Type B: premixed seal coat
  - Type C: premixed seal coat with 6.7 mm NMAS aggregates

SEAL COAT

- Quantities of binder:

Seal coat type	Bitumen, kg/10 m^2	Bitumen emulsion, kg/10 m^2
A	9.8	12 to 14
B	6.8	10 to 12
C	4.5	9 to 11

TYPE A SEAL COAT

- Stone chips of 6.7 mm (11.2 mm to 2.36 mm) @ 0.09 $m^3/10\ m^2$

Property	Test	Specification
Cleanliness	Grain size analysis	Max. 5% passing 75 μm sieve
Particle shape	Flakiness index	Max. 25%
Strength	Aggregate impact value	Max. 30%
Durability	Soundness using Sodium Sulphate	Max. 12%
	Soundness using Magnesium Sulphate	Max. 18%
Water absorption	Water absorption	**Max. 1%**
Stripping	Stripping	Min. retained coating 95%

TYPE B SEAL COAT

- Aggregates passing 2.36 mm and retained over 180 μm sieve

- Aggregates @ 0.06 m^3/10 m^2

TYPE C SEAL COAT

- Aggregates of 6.7 mm size (passing 9.5 mm and retained over 2.36 mm sieve)
- Aggregates @ 0.09 m^3/10 m^2

Property	Test	Specification
Cleanliness	Grain size analysis	Max. 5% passing 75 μm sieve
Particle shape	Flakiness index	Max. 25%
Strength	Aggregate impact value	Max. 30%
Durability	Soundness using Sodium Sulphate	Max. 12%
	Soundness using Magnesium Sulphate	Max. 18%
Water absorption	Water absorption	**Max. 1%**
Stripping	Stripping	Min. retained coating 95%

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MARSHALL MIX DESIGN

- Basic steps in Marshall method of mix design:

  1) Aggregate selection

  2) Bitumen selection

  3) Sample preparation (including compaction)

  4) Density and voids calculations

  5) Stability determination using Marshall stability and flow test

  6) Optimum bitumen content selection

MARSHALL MIX DESIGN

1) Aggregate selection:

1) Determination of aggregate physical properties : consists of running various tests to determine properties such as:
   - toughness and abrasion
   - durability and soundness
   - cleanliness and deleterious materials
   - particle shape and surface texture
2) Determination of other aggregate descriptive physical properties:
   - Gradation and size
   - Specific gravity and absorption
3) Blending calculations to achieve mix design aggregate gradation

MARSHALL MIX DESIGN

1) Aggregate selection:

Property	Test	Specification		
		SDBC	DBM	BC
Cleanliness	Grain size analysis	Max. 5% passing 75 µm sieve		
Particle shape	FI+EI	Max. 35%		
Strength	Los Angeles abrasion value (or)	Max. 35%		Max. 30%
	Aggregate impact value	Max. 27%		Max. 24%
Polishing	Polished stone value	Min. 55	-	Min. 55
Durability (5 cycles)	Soundness using Sodium Sulphate	Max. 12%		
	Soundness using Magnesium Sulphate	Max. 18%		
Water absorption	Water absorption	Max. 2%		
Stripping	Stripping	Min. retained coating 95%		
Water sensibility	Retained tensile strength	Min. 80%		

MARSHALL MIX DESIGN

1) Aggregate selection:

- When crushed gravel is used, not less than 90% by weight retained on 4.75 mm sieve shall have at least two fractured faces
- If TSR< 80%, use anti-stripping agents (use 2% hydrated lime as filler)
- Sand equivalent value for fine aggregates > 50
- Plasticity index of material passing 425 μm sieve < 4
- Filler: rock dust, hydrated lime, cement
- Hydrated lime is preferred because of good anti-stripping and antioxidant properties
- Filler (PI < 4, not applicable for hydrated lime or cement) gradation:

IS Sieve, mm	Percent passing
0.6	100
0.3	95 to 100
0.075	85 to 100

MARSHALL MIX DESIGN

1) Aggregate selection:

- For aggregates with specific gravity > 2.7, bitumen content can be reduced proportionately
- Increase bitumen content by 0.5% when highest daily mean air temperature is ≤ 30 °C and lowest daily mean air temperature is ≤ -10 °C

MARSHALL MIX DESIGN

1) Aggregate selection:

- Combined gradation for coarse aggregate, fine aggregate and fillers:

Semi-Dense Bituminous Concrete

NMAS	9.5 mm
Layer thickness	25 mm
Sieve size, mm	Percent passing
13.2	100
9.5	90 to 100
4.75	35 to 51
2.36	24 to 39
1.18	15 to 30
0.3	9 to 19
0.075	3 to 8
Bitumen content by weight of total mix	Min. 5.0%

MARSHALL MIX DESIGN

1) Aggregate gradation for Dense Bituminous Macadam:

Mix Designation	Grading 1	Grading 2
NMAS	37.5 mm	26.5 mm
Layer thickness	75 to 100 mm	50 to 75 mm
Sieve size, mm	Percent passing	
45	100	100
37.5	95-100	100
26.5	63-93	90-100
19	-	71-95
13.2	55-75	56-80
4.75	38-54	38-54
2.36	28-42	28-42
0.3	7-21	7-21
0.075	2-8	2-8
Bitumen content by weight of total mix	Min. 4.0	Min. 4.5

1) AGGREGATE GRADATION FOR BITUMINOUS CONCRETE:

Mix Designation	Grading 1	Grading 2
NMAS	19 mm	13.2 mm
Layer thickness	50 mm	30 mm/40 mm
Sieve size, mm	Percent passing	
26.5	100	100
19	90-100	100
13.2	59-79	90-100
9.5	52-72	70-88
4.75	35-55	53-71
2.36	28-44	42-58
1.18	20-34	34-48
0.6	15-27	26-38
0.3	10-20	18-28
0.15	5-13	12-20
0.075	2-8	4-10
Bitumen content by weight of total mix	Min. 5.2%	Min. 5.4%

MARSHALL MIX DESIGN

2) Bitumen selection:

- Marshall test does not have a common generic bitumen selection and evaluation procedure
- IRC specifies appropriate binder depending on climatic conditions:

Lowest daily mean air temperature, °C	Highest daily mean air temperature, °C		
	< 20 °C	20 to 30 °C	> 30 °C
> -10 °C	VG 10	VG 20	VG 30
≤ -10 °C	VG 10	VG 10	VG 20

- Once the binder is selected, several preliminary tests are run to determine the bitumen temperature-viscosity relationship - necessary to arrive at mixing and compaction temperatures

2) Bitumen selection:

Grade (1)	*Suitable for 7 day Average Maximum Air Temperature* °C (2)
VG10	< 30
VG20	30-38
VG30	38-45
VG40	> 45

NOTE — This is the 7 day average maximum air temperature for a period not less than 5 years from the start of the design period.

2) Bitumen selection: [IS: 73 (2018)]

Sl No.	Characteristics	Paving Grades				Method of Test, Ref to
		VG10	VG20	VG30	VG40	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
i)	Penetration at 25°C, 100 g, 5 s, 0.1 mm, *Min*	80	60	45	35	IS 1203
ii)	Absolute viscosity at 60°C, Poises	800-1 200	1 600-2400	2 400-3 600	3 200-4 800	IS 1206 (Part 2)
iii)	Kinematic viscosity at 135°C, cSt, *Min*	250	300	350	400	IS 1206 (Part 3)
iv)	Flash point (Cleveland open cup), °C, *Min*	220	220	220	220	IS 1448 [P : 69]
v)	Solubility in trichloroethylene, percent, *Min*	99.0	99.0	99.0	99.0	IS 1216
vi)	Softening point (R&B), °C, *Min*	40	45	47	50	IS 1205
vii)	Tests on residue from rolling thin film oven test:					
	a) Viscosity ratio at 60°C, *Max*	4.0	4.0	4.0	4.0	IS 1206 (Part 2)
	b) Ductility at 25°C, cm, *Min*	75	50	40	25	IS 1208

2) Bitumen selection: [IS: 15462 (2019)]

Service Condition	Pavement Temp Range (*Max* and *Min*), °C				
	64 to (-10)	70 to (-10)	76 to (-10)	82 to (-10)	76 to (-22)
Standard S $J_{nr3200} < 4.5\ kPa^{-1}$	PMB 64-10	PMB 70-10	PMB 76-10	PMB 82-10	PMB 76-22
Heavy H $J_{nr3200} < 2\ kPa^{-1}$	PMB 64-10	PMB 70-10	PMB 76-10	PMB 82-10	PMB 76-22
Very Heavy V $J_{nr3200} < 1\ kPa^{-1}$	PMB 64-10	PMB 70-10	PMB 76-10	PMB 82-10	PMB 76-22
Extremely Heavy E $J_{nr3200} < 0.5\ kPa^{-1}$	PMB 64-10	PMB 70-10	PMB 76-10	PMB 82-10	PMB 76-22

1) **Standard Service Condition** — Traffic levels fewer than 10 million Equivalent Single Axle Loads (ESALs) and more than the standard traffic speed (>70 km/h).
2) **Heavy Service Condition** — Traffic levels 10-30 million ESALs or slow-moving traffic (20 to 70 km/h).
3) **Very Heavy Service Condition** — Traffic levels of greater than 30 million ESALs or very slow moving/ standing traffic («20 km/h)
4) **Extremely Heavy Service Condition** — Traffic levels of greater than 30 million ESALs and very slow moving/ standing traffic («20 km/h)

MARSHALL MIX DESIGN

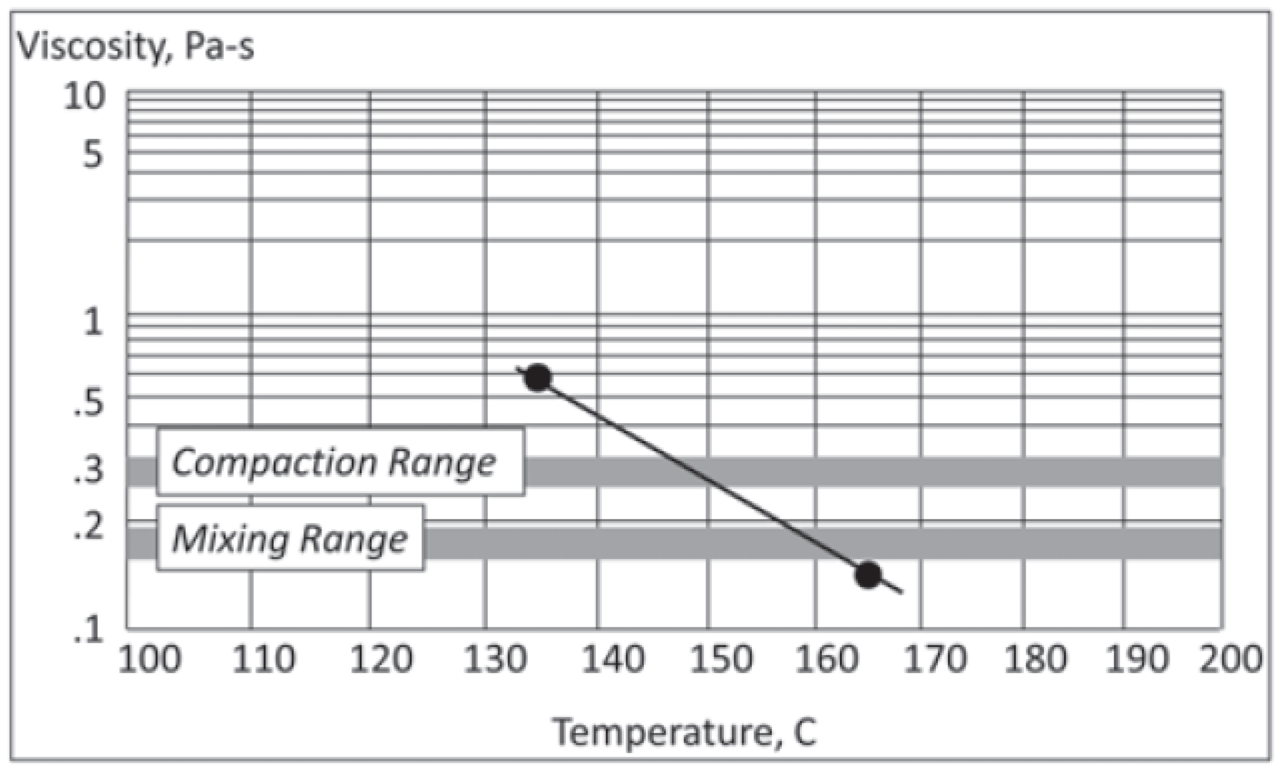
3) Sample preparation:

- 6 blends with 3 samples each for a total of 18 specimens
- Trial blends must contain a range of bitumen contents both above and below the optimum bitumen content
- Compaction of a 102 mm diameter, 64 mm height cylindrical sample by a 4536 g hammer falling freely for 457.2 mm
- 75 blows on either side based on anticipated traffic levels

MARSHALL MIX DESIGN

3) Sample preparation:

- Mixing temperature: corresponding to viscosity range of 0.17 ± 0.02 Pa-s
- Compaction temperature: corresponding to viscosity range of 0.28 ± 0.03 Pa-s



MARSHALL MIX DESIGN

3) Sample preparation:

Bitumen grade	Bitumen Temperature (^{0}C)	Aggregate Temperature (^{0}C)	Mixed Material Temperature (^{0}C)	Laying Temperature (^{0}C)	Rolling Temperature (^{0}C)
VG 40	160 to 170	160 to 175	160 to 170	150 (Min.)	100 (Min.)
VG 30	150 to 165	150 to 170	150 to 165	140 (Min.)	90 (Min.)
VG 20	145 to 165	145 to 170	145 to 165	135 (Min.)	85 (Min.)
VG 10	140 to 160	140 to 165	140 to 160	130 (Min.)	80 (Min.)

- Difference in temperature between binder and aggregate shall at no time exceed 14 °C

MARSHALL MIX DESIGN

4) Density and voids analysis:

- Necessary to calculate the following parameters:
  - Bulk specific gravity (G_{mb})
  - Theoretical maximum specific gravity (TMD, G_{mm})
  - Air voids (V_a), also expressed as voids in the total mix (VTM)
  - Voids in the mineral aggregate (VMA)
  - Voids filled with bitumen (VFB)

MARSHALL MIX DESIGN

4) Density and voids analysis:

- Weight and volume terms are abbreviated as Gxy, where,

x: b = binder;

s = stone;

m = mixture

y: b = bulk;

e = effective; a

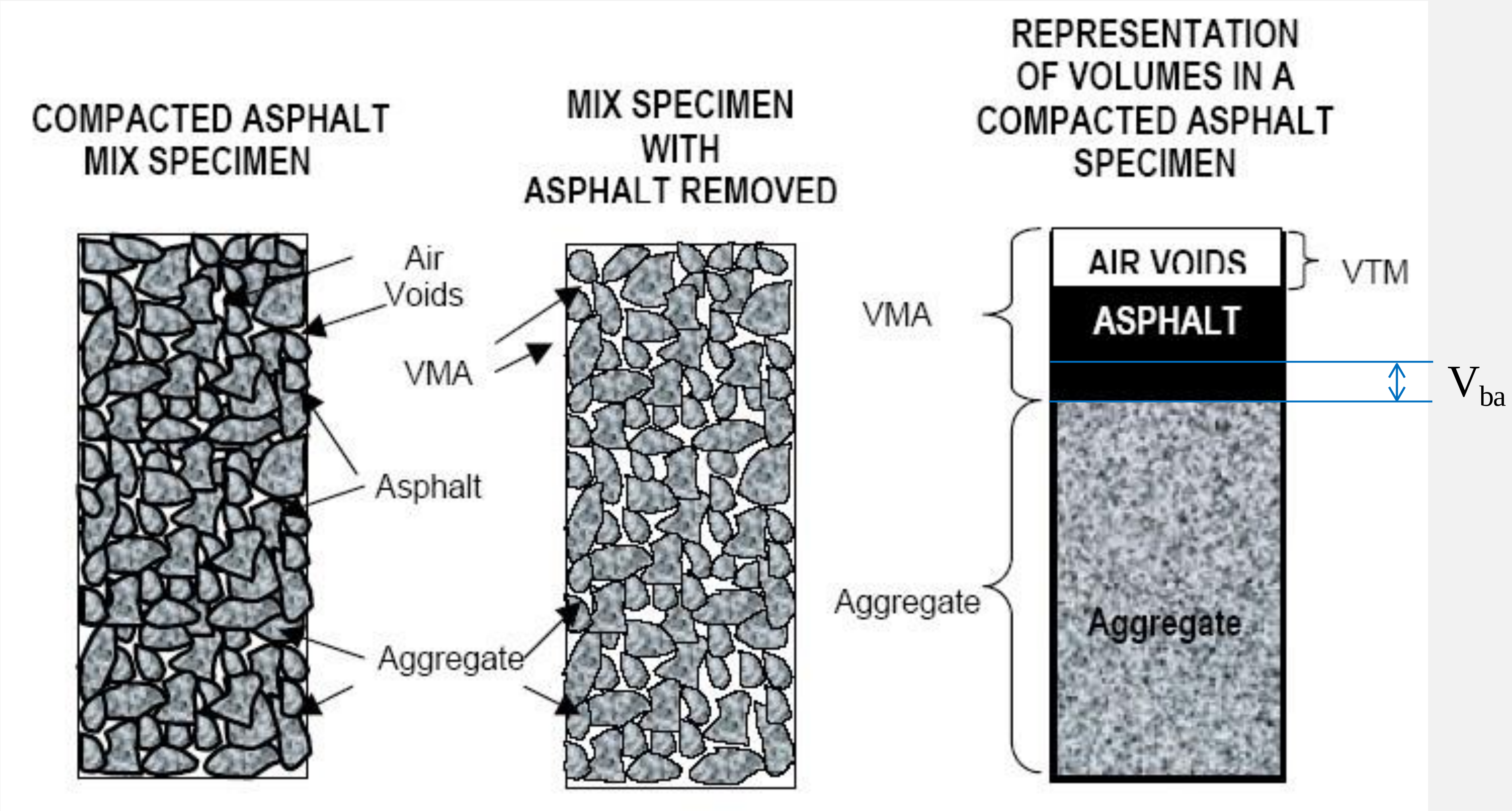
= apparent; m

= maximum

- G_{mb} = bulk specific gravity of mix
- G_{mm} = maximum specific gravity of mix
- G_{se} = effective specific gravity of stone

MARSHALL MIX DESIGN

4) Density and voids analysis:



MARSHALL MIX DESIGN

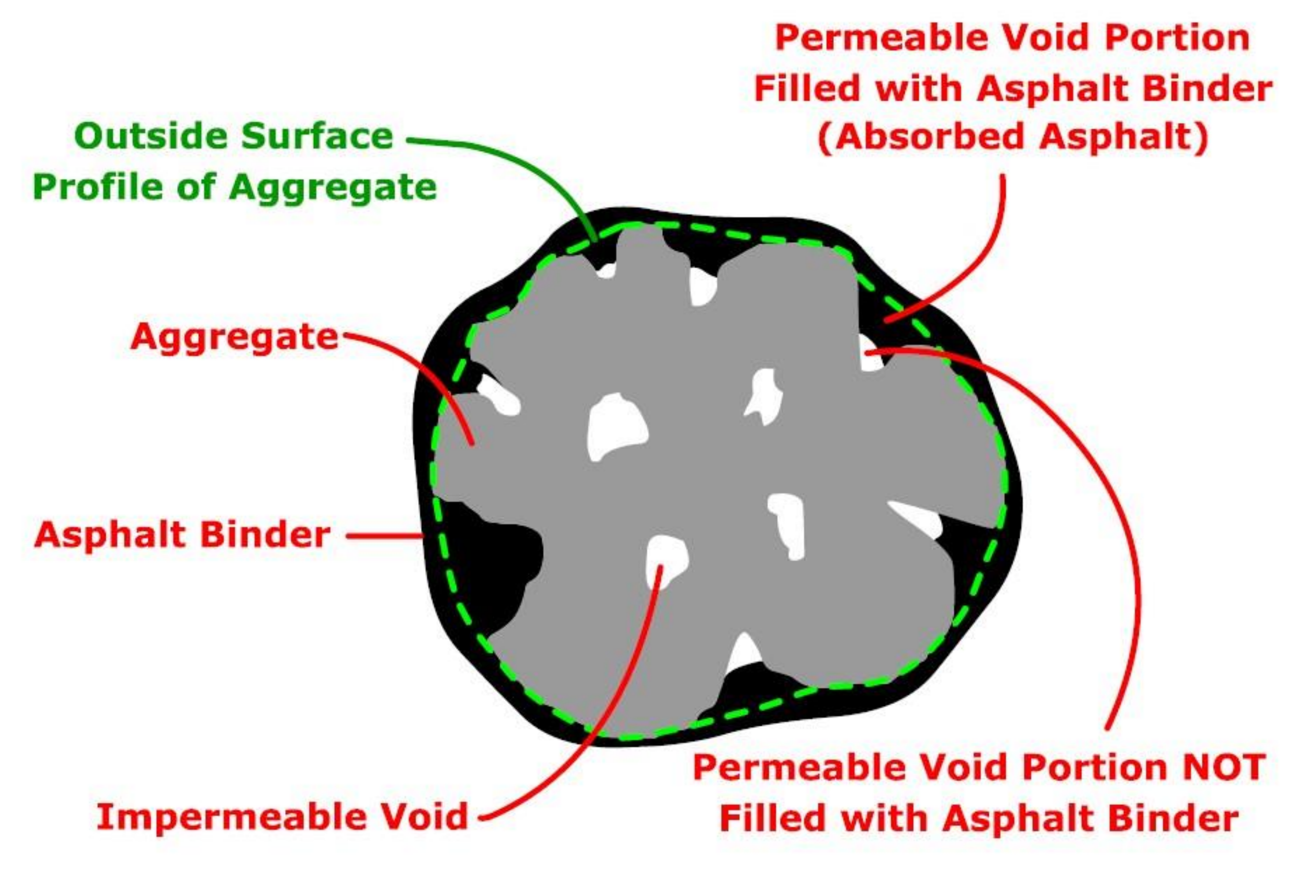
4) Density and voids analysis:

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}}$$

$$G_{mm} = \frac{1}{\left[\frac{1-P_b}{G_{se}} + \frac{P_b}{G_b}\right]}$$

$$V_a = \frac{V_V}{V_T} x100$$

$$V_a = \left[1 - \frac{G_{mb}}{G_{mm}}\right] x100$$



MARSHALL MIX DESIGN

4) Density and voids analysis:

$$VMA = \frac{V_V + V_{be}}{V_T} x100$$

$$VMA = \left[1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right] x100$$

$$VFA = \frac{V_{be}}{V_{be} + V_V} x100$$

$$VFA = \frac{VMA - V_a}{VMA}$$

$$VFA = VMA - P_a$$

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

$$P_{ba} = 100\left[\frac{G_{se} - G_{sb}}{G_{sb}G_{se}}\right]G_b$$

$$P_{be} = P_b - \left(\frac{P_{ba}}{100}\right)P_s$$

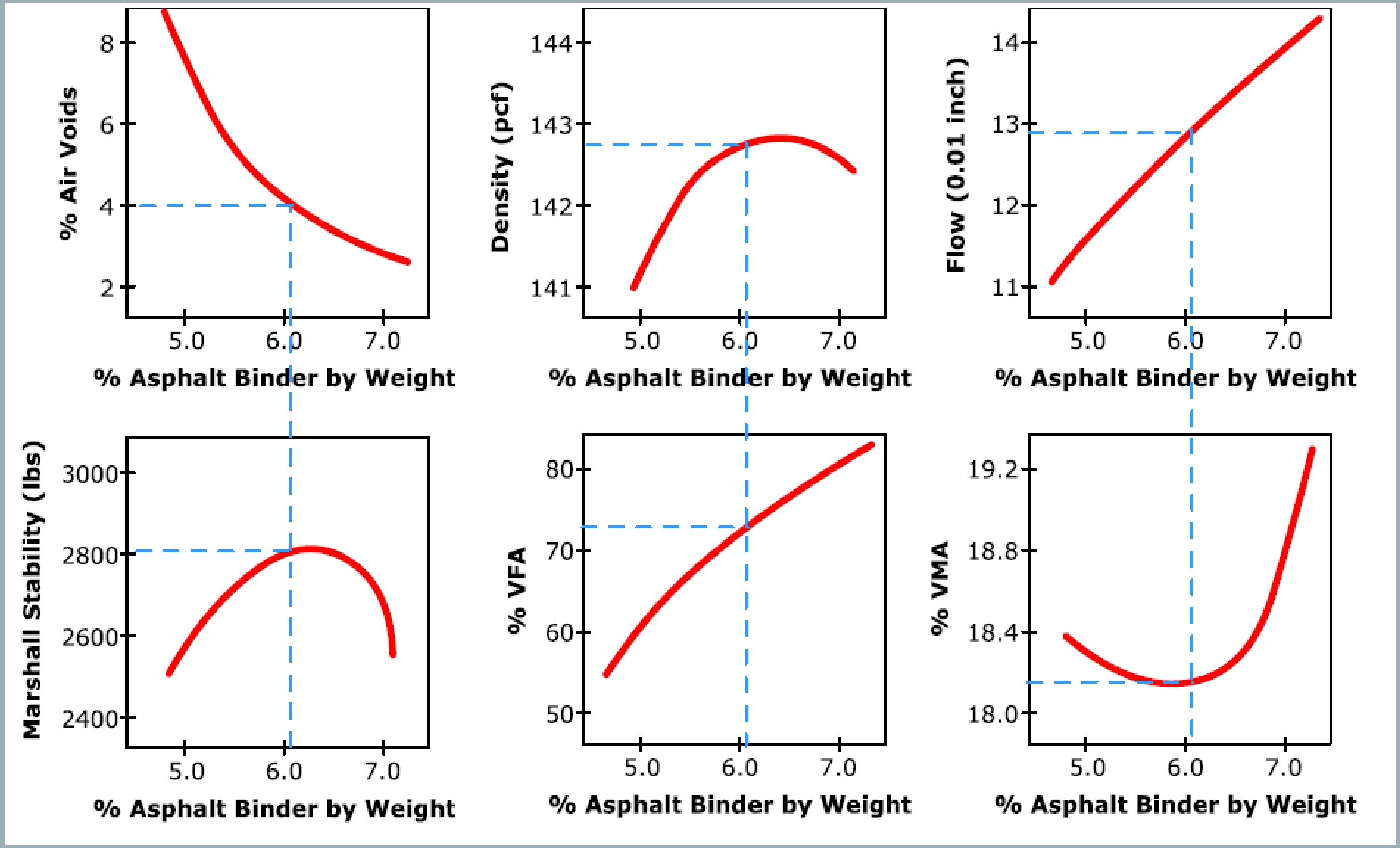
MARSHALL MIX DESIGN

5) Stability and flow test:

- Stability portion of the test measures the maximum load supported by the test specimen at a loading rate of 50.8 mm/min. at 60 °C

- Load is increased until it reaches a maximum then when the load just begins to decrease, the loading is stopped and the maximum load is recorded
- During loading, an attached dial gauge measures the specimen's plastic flow as a result of the loading
- Stability and flow are recorded

6) Optimum bitumen content:



MARSHALL MIX DESIGN

<table>
<tr><th rowspan="2">Properties</th><th colspan="2" rowspan="2">Viscosity grade paving bitumen</th><th colspan="2">Modified bitumen</th></tr>
<tr><th>Hot climate</th><th>Cold climate</th></tr>
<tr><td>Compaction level</td><td colspan="4">75 blows on each face of the specimen</td></tr>
<tr><td>Min. stability at 60 °C, kN</td><td colspan="2">9.0</td><td>12.0</td><td>10.0</td></tr>
<tr><td>Marshall flow, mm</td><td colspan="2">2 to 4</td><td>2.5 to 4</td><td>3.5 to 5</td></tr>
<tr><td>Marshall quotient (stability/flow)</td><td colspan="2">2 to 5</td><td colspan="2">2.5 to 5</td></tr>
<tr><td>Air voids, %</td><td colspan="4">3 to 5</td></tr>
<tr><td>Voids filled with bitumen (VFB), %</td><td colspan="4">65 to 75</td></tr>
<tr><td>Coating of aggregate particle</td><td colspan="4">95% minimum</td></tr>
<tr><td>Tensile strength ratio (TSR)</td><td colspan="4">80% minimum</td></tr>
<tr><td rowspan="5">Voids in mineral aggregate (VMA), %</td><td rowspan="2">NMAS</td><td colspan="3">Min. % VMA related to design % air voids</td></tr>
<tr><td>3.0</td><td>4.0</td><td>5.0</td></tr>
<tr><td>9.5 mm</td><td>14</td><td>15</td><td>16</td></tr>
<tr><td>26.5 mm</td><td>11</td><td>12</td><td>13</td></tr>
<tr><td>37.5 mm</td><td>10</td><td>11</td><td>12</td></tr>
</table>

MARSHALL MIX DESIGN

- Replace aggregates retained on 26.5 mm sieve by the aggregates passing 26.5 mm sieve and retained on 22.4 mm sieve
- Where maximum size of aggregate is more than 26.5 mm, modified Marshall method using 150 mm diameter specimen shall be used
- Modified Marshall method requires modified equipment and procedures
- When modified Marshall test is used, the minimum stability values shall be multiplied by 2.25, and the minimum flow shall be 3 mm

MARSHALL MIX DESIGN

Maximum Theoretical Specific Gravity: $\dfrac{100}{\dfrac{\%Asp.}{Sp.Gr.Asp.}+\dfrac{\%Agg.}{Sp.Gr.Agg.}}$

S. No.	% Asphalt	% Aggregate	Maximum Theoretical Specific Gravity
1	4.0	96.0	
2	4.5	95.5	
3	5.0	95.0	
4	5.5	94.5	
5	6.0	94.0	

MARSHALL MIX DESIGN

Correction Factors for Stability:

Volume of specimen in cm^3	Approx. 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

MARSHALL MIX DESIGN

No.	% ac by wt of mix	Weight - g		Bulk vol. cm^3	Specific gravity		Volume - % Total			Voids - %			Unit wt kN/m^3	Stability - kN		Flow mm
		Air	Water		Bulk	Max. Theor.	AC	AGG	Voids	AGG	Filled AGG	Total mix		Meas.	Adj.	
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q
a	b	c	d	c-d	$\frac{c}{e}$	g	$\frac{b*f}{G_{ac}}$	$\frac{(100-b)*f}{G_{agg}}$	100-h-i	100-i	$\frac{h}{k}$	$100*(1-\frac{f}{g})$	9.81 *f	o	p	q

BITUMINOUS MIX DESIGN CONCEPTS

Objective:

- Balance of engineering properties and economics ensuring durable pavements

- To determine combination of bitumen and aggregate (proportions of materials used in bituminous mix) that result in long-lasting pavement performance
  - To determine appropriate blend of aggregate sources to produce proper gradation
  - To select type and quantity of bitumen for the specific gradation

- Apart from construction practices, poor performance of pavements can be due to:
  - Poor mix design
  - Production of mixture different from designed laboratory mix

BITUMINOUS MIX DESIGN CONCEPTS

Requirements of Bituminous Mix:

- Sufficient "bitumen" to ensure a durable pavement
- Sufficient "mix stability" to satisfy demands of traffic without displacement
- Sufficient "air voids" in the total compacted mix to allow for slight additional compaction under traffic loading and slight binder expansion without flushing, bleeding, and loss of stability
- Maximum "air voids" to limit permeability of harmful air and moisture into the mix
- Sufficient "workability" to permit efficient placement of the mix without segregation and without sacrificing stability and performance
- "Aggregate texture and hardness" to provide sufficient skid resistance in unfavourable weather conditions

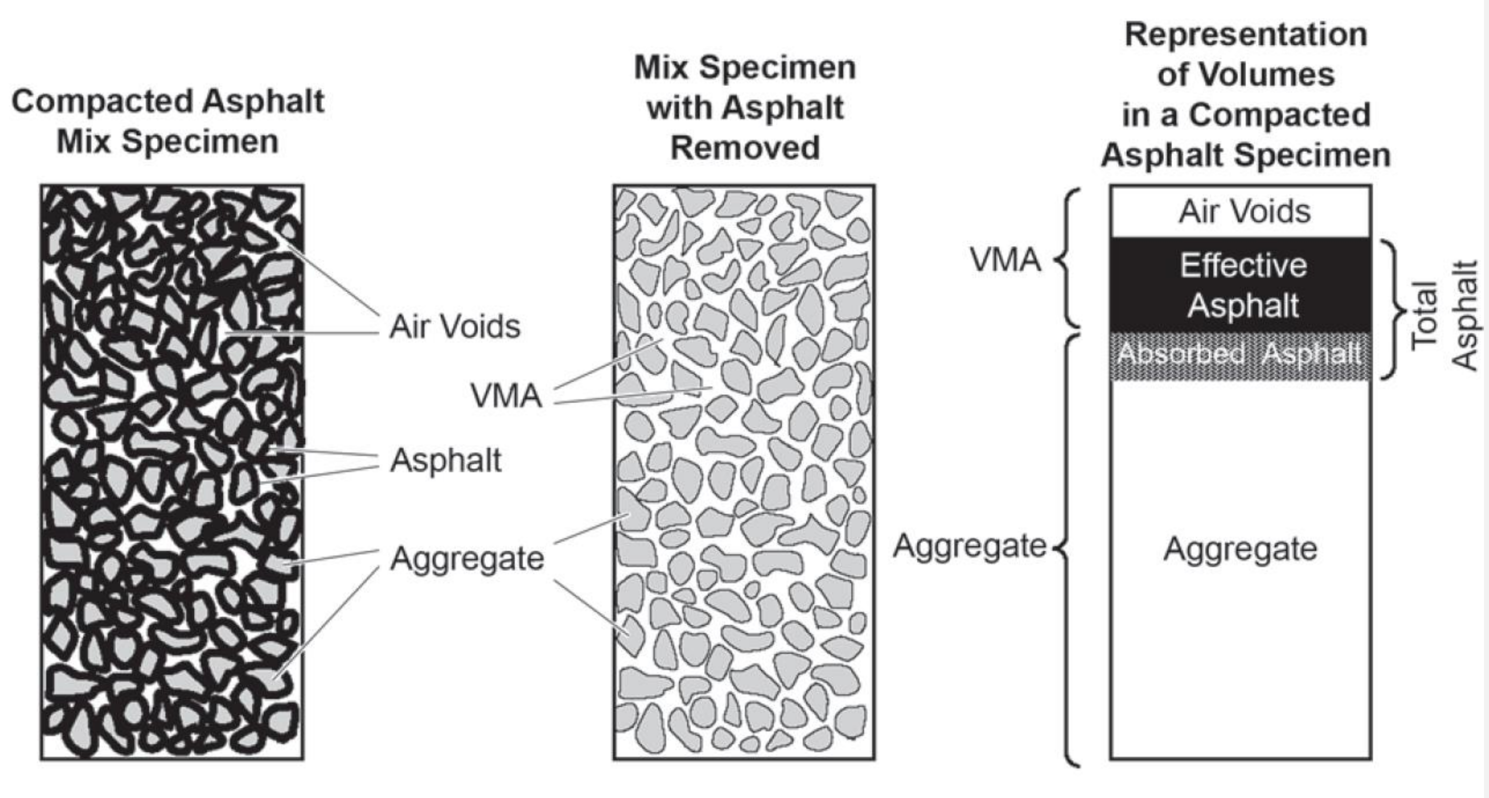
BITUMINOUS MIX DESIGN CONCEPTS

Desirable Characteristics of Bituminous Mix:

- ✓ Stability: resistance to permanent deformation {depends on: (i) internal friction = f(aggregate shape, surface texture, gradation), (ii) cohesion = f(bitumen bonding ability, stiffness}
- ✓ Fatigue Resistance: resistance to repeated bending {depends on: (i) bitumen layer thickness, (ii) air voids, (iii) bitumen binder properties, (iv) subgrade support
- ✓ Impermeability: moisture resistance {depends on: (i) aggregates, (ii) bitumen, (iii) bituminous mix}
- ✓ Durability: disintegration of aggregates {depends on soundness, toughness} and resistance to aging {depends on: (i) air voids, (ii) bitumen film thickness}
- ✓ Skid Resistance: {depends on: (i) texture, (ii) surface condition, (iii) aggregates}
- ✓ Workability: ease of placement and compaction {depends on: (i) aggregate gradation, shape, texture, (ii) bitumen viscosity and content}

BITUMINOUS MIX DESIGN CONCEPTS

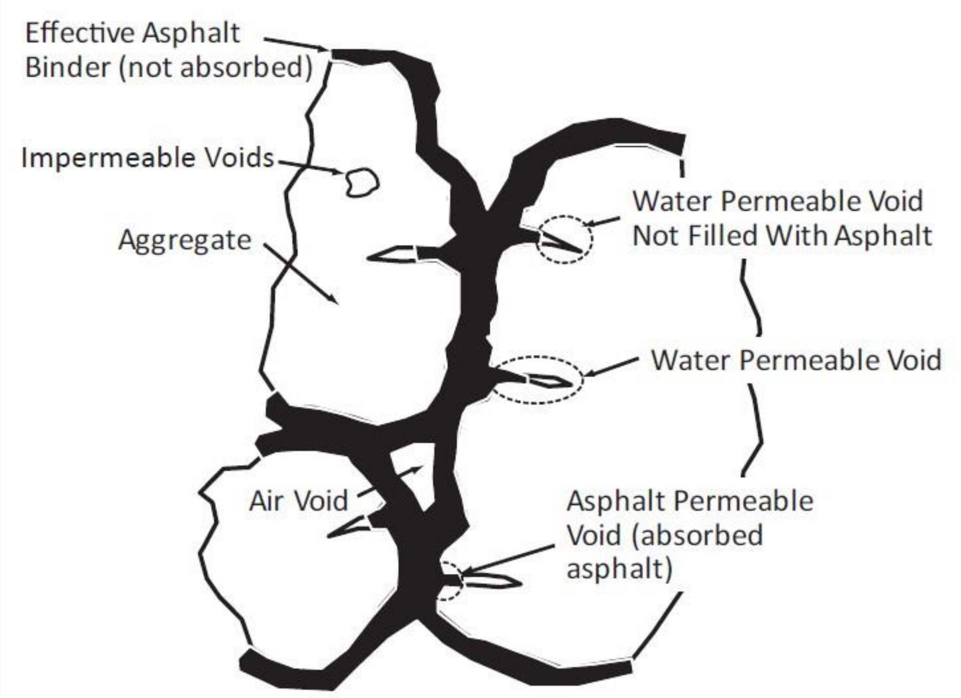
Bituminous Mix Volumetric Characteristics:



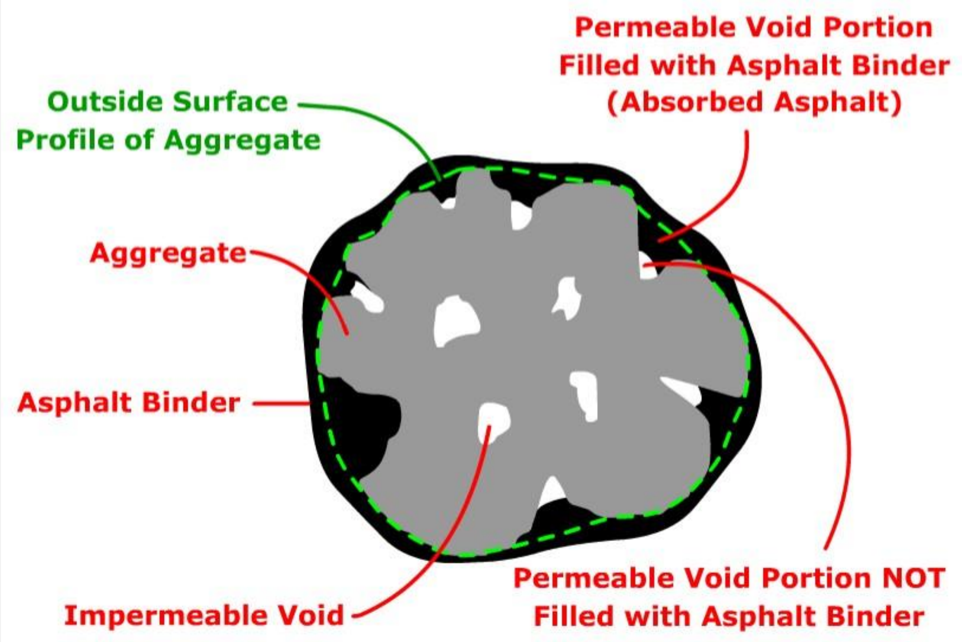
Source: MS-2, 2014

BITUMINOUS MIX DESIGN CONCEPTS

Microscopic View of Bituminous Mix:

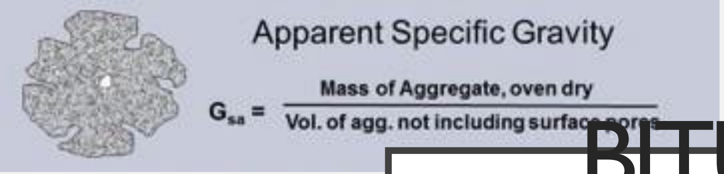


Source: MS-2, 2014

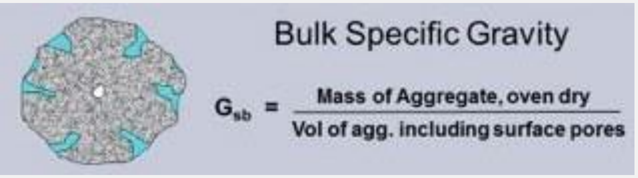


Source: https://pavementinteractive.org/reference-desk/testing/aggregate-tests/coarse-aggregate-specific-gravity/

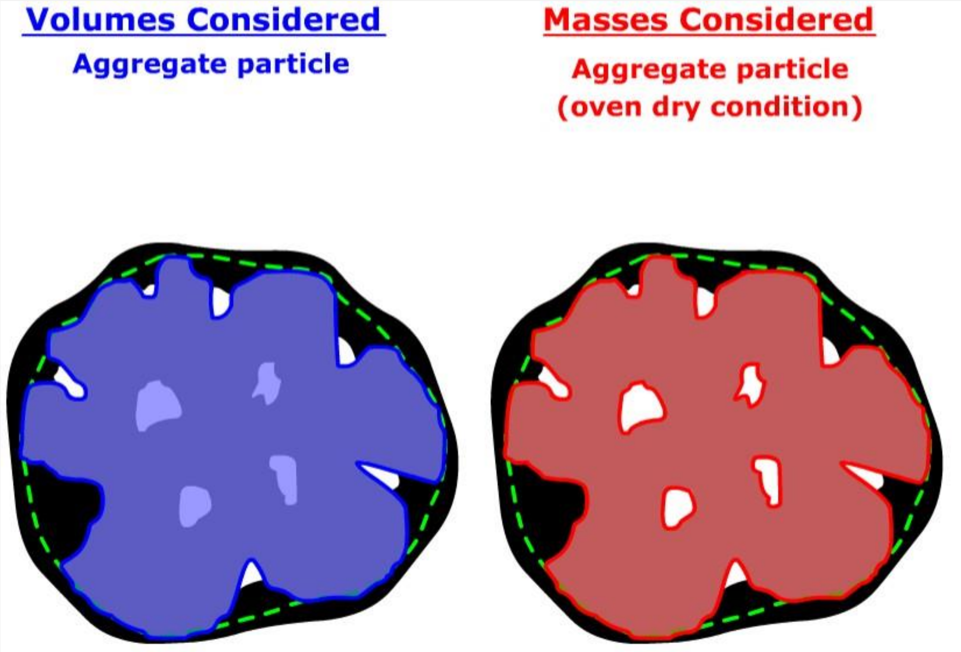
BITUMINOUS MIX DESIGN CONCEPTS



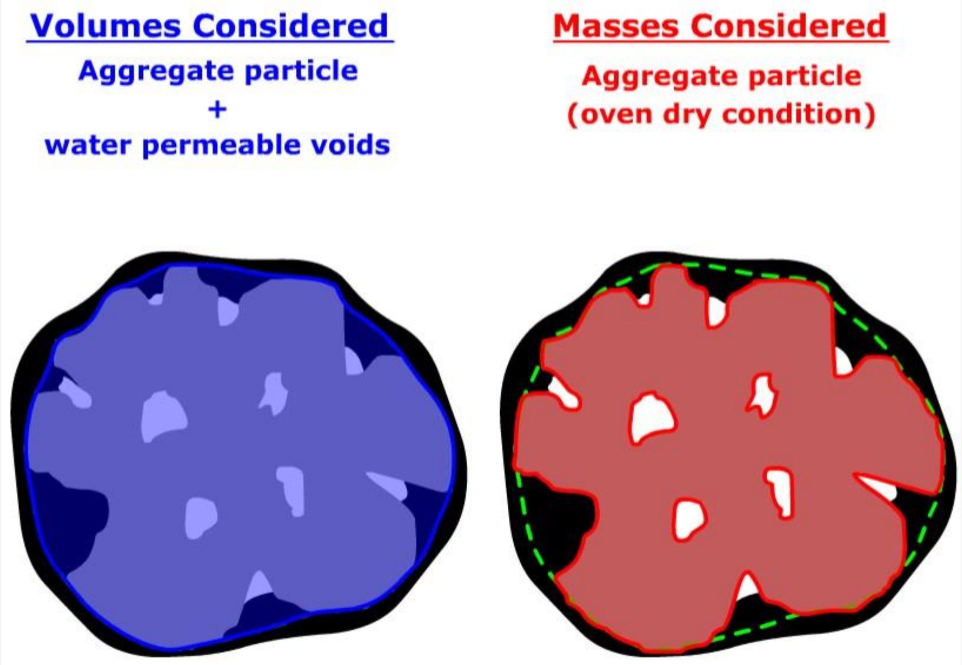
Source: http://www.eng.auburn.edu/research/centers/ncat/newsroom/2017-spring/gsb.html



Specific Gravity of Aggregate:



Apparent Specific Gravity (G_{sa})



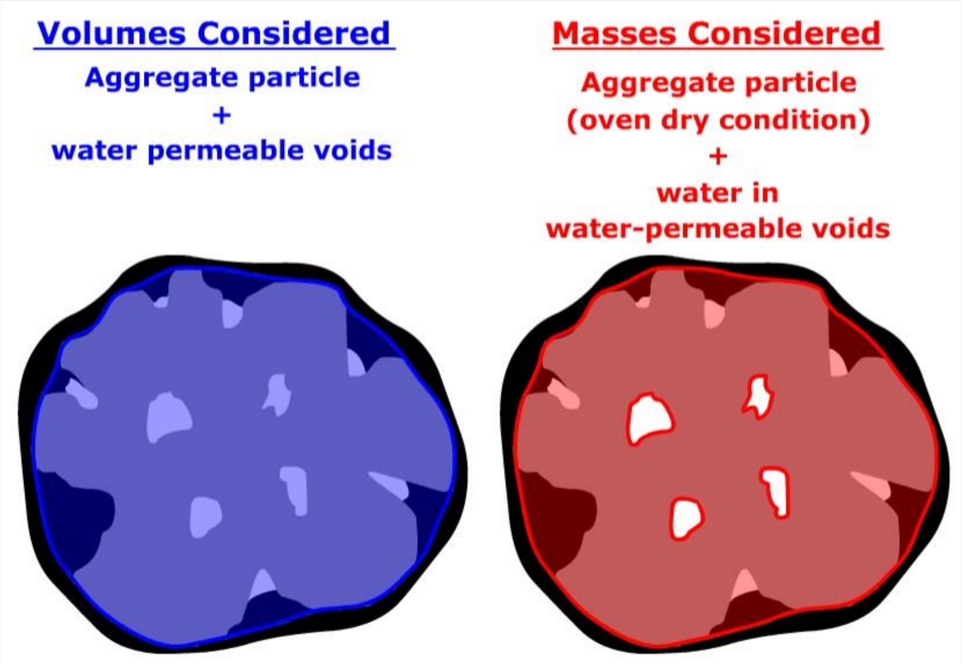
Bulk Dry Specific Gravity (G_{sb})

- $G_{sa} \geq G_{sb}$, *equality holds good when aggregate absorption is zero*

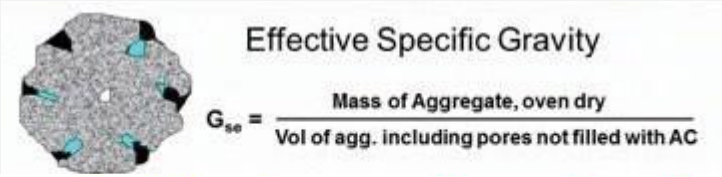
Source: https://pavementinteractive.org/reference-desk/testing/aggregate-tests/coarse-aggregate-specific-gravity/

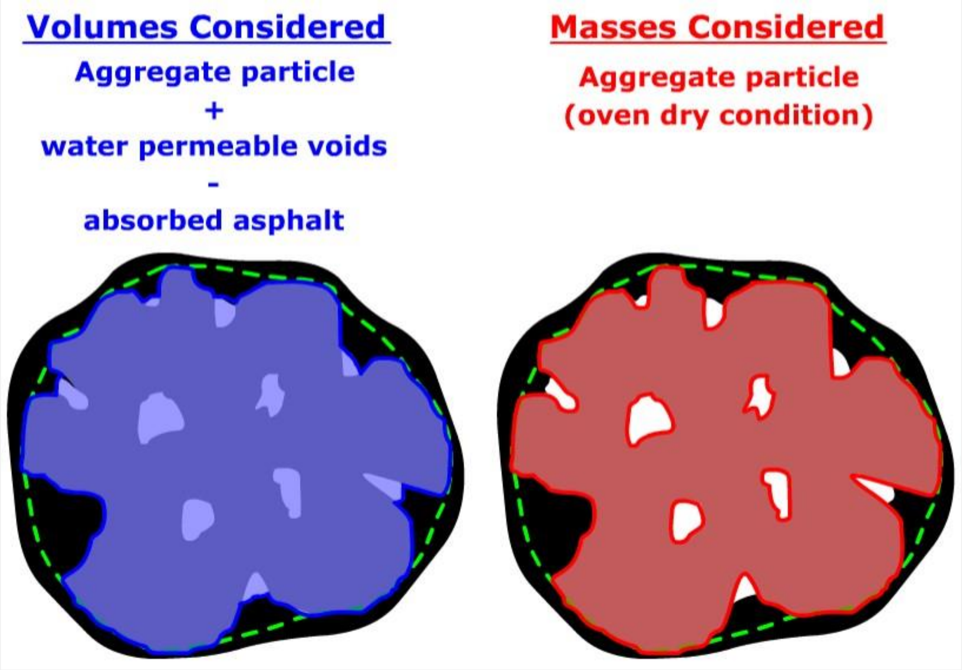
BITUMINOUS MIX DESIGN CONCEPTS

Specific Gravity of Aggregate:



Bulk SSD Specific Gravity (G_{SSD})





Effective Specific Gravity (G_{se})

- $G_{sa} \geq G_{se} \geq G_{sb}$, *equality holds good when aggregate absorption is zero*

Source: https://pavementinteractive.org/reference-desk/testing/aggregate-tests/coarse-aggregate-specific-gravity/

BITUMINOUS MIX DESIGN CONCEPTS

Specific Gravity of Aggregate:

- $G_{sa} = \frac{A}{A-C}$, $Gs_b = \frac{A}{B-C}$, $G_{SSD} = \frac{B}{B-C}$, water absorption = $\frac{B-A}{A} \times 100$

Where, A is mass of oven-dry sample in air (g) B is mass of SSD sample in air (g)

C is mass of SSD sample in water (g)

- $G_{sb} = \frac{P_1+P_2+\cdots+P_n}{\frac{P_1}{G_1}+\frac{P_2}{G_2}+\cdots+\frac{P_n}{G_n}}$

Where, P_1, P_2, P_n are individual percentage of aggregate fractions by weight of total aggregate G_1, G_2, G_n are individual bulk specific gravity of each aggregate fraction

- $G_{se} = \frac{100-Pb}{\left(\frac{100}{G_{mm}}\right)-\left(\frac{P_b}{G_b}\right)}$, $P_{ba} = 100 \times \left(\frac{G_{se}-Gs_b}{G_{sb}G_{se}}\right) \times G_b$, $P_{be} = Pb - \left(\frac{P_{ba}}{100}\right) \times P_s$
- **Aggregates can absorb 40 to 80% of water permeable voids**

Binder Absorption and Efective Binder Content:

- P_{ba} is percentage by mass of binder absorbed into aggregate
- P_{ba} is assumed constant and is calculated based on mass of aggregate
- $P_{ba} = 100 \times \left(\frac{M_{ba}}{M_s}\right) = 100 \times \left(\frac{G_{se} - Gs_b}{G_{sb} G_{se}}\right) \times G_b$
- If P_{ba} is calculated based on total mass of mix, P_{ba} changes with amount of binder added to the mix
- Effective binder content (P_{be}) is expressed as percentage of total mass of the mix
- $P_{be} = 100 \times \left(\frac{M_{be}}{M_{mb}}\right) = Pb - \left(\frac{P_{ba}}{100}\right) \times P_s$
- Theoretically, $P_{ba} + P_{be} \neq P_b$
- Practically, as mass of total aggregate and total mix are very close in magnitude, assumption of $P_{ba} + P_{be} = P_b$ holds good!

Dust to Binder Ratio:

- Also called dust proportion (DP), ($P_{0.075}$/P_{be})
- Allowable range is 0.6 to 1.2 with few exceptions (ref. MS-2, 2014 for addl. Info.)
- Addresses workability of asphalt mixes
- Low ($P_{0.075}$/P_{be}) results in tender mix (unstable mix; lacks cohesion and is difficult to compact in the field as tender mixes move laterally under the roller; mix shoves instead of getting compacted under rollers)
- As $P_{0.075}\uparrow$, mixes tend to stiffen
- High ($P_{0.075}$/P_{be}) also results in tender mix, results in check cracking

BITUMINOUS MIX DESIGN CONCEPTS

Bulk Specific Gravity of Asphalt Mix (G_{mb}):

- $G_{mb} = \dfrac{\text{Mass of aggregate} + \text{mass of asphalt}}{\text{Effective volume of aggregate} + \text{volume of asphalt} + \text{volume of voids}} = \dfrac{A}{B - C}$
- SSD method (ASTM D2726) with water absorption by volume ≤ 2%

[A is dry mass of specimen in air, B is SSD mass of specimen in air, C is mass of specimen in water]

- For water absorption > 2%, use either vacuum sealing method (ASTM D6752) or parafilm coated method (ASTM D1188)

- $G_{mb} = \dfrac{A}{(B - C) - \left(\frac{B - A}{D}\right)}$

[A is dry mass of specimen in air, B is sealed (or parafilm coated) specimen mass in air, C is mass of sealed (or parafilm coated) specimen in water, D is specific gravity of bag (or parafilm)]

BITUMINOUS MIX DESIGN CONCEPTS

Maximum Specific Gravity of Asphalt Mix (G_{mm}):

- Corresponds to zero air voids asphalt mix

Source: MS-2, 2014

- $G_{mm} = \frac{\text{Mass of aggregate + mass of asphalt}}{\text{Effective volume of aggregate + volume of asphalt}} = \frac{A}{A-C}$

[A is mass of sample in air, C is mass of water displaced by the sample]

- ASTM D2041 is used
- Used to calculate air voids in specimens as well as in-place air voids in construction of asphalt layer
- Used to calculate G_{se} [$G_{se} = \frac{100-Pb}{\left(\frac{100}{G_{mm}}\right)-\left(\frac{P_b}{G_b}\right)}$]
- If G_{mm} is not measured at other trial binder contents, G_{se} can be used to calculate G_{mm} at other binder contents [$G_{mm} = \frac{100}{\left(\frac{P_s}{G_s}\right)+\left(\frac{P_b}{G_b}\right)}$]

BITUMINOUS MIX DESIGN CONCEPTS

Air Voids in Total Mix (VTM):

- $P_a = 100 \times \frac{V_a}{V_{mb}} = 100 \times \left[\frac{G_{mm} - Gm_b}{G_{mm}}\right]$

Voids in Mineral Aggregate (VMA):

- Includes air voids and effective asphalt content (excludes surface voids)
- $VMA = 100 \times \left(\frac{V_a + Vb_e}{V_{mb}}\right) = 100 - \left[\frac{G_{mb} \times P_s}{G_{sb}}\right]$

Voids Filled with Asphalt (VFA):

- Percentage by volume of VMA filled with effective asphalt
- $VFA = 100 \times \left(\frac{V_{be}}{V_{be} + V_a}\right) = 100 \times \left[\frac{VMA - P_a}{VMA}\right]$
- As NMAS↓, surface area of total aggregate structure↑, P_b↑
- VMA and VFA should↑ to allow sufficient room for additional asphalt to maintain the target air voids

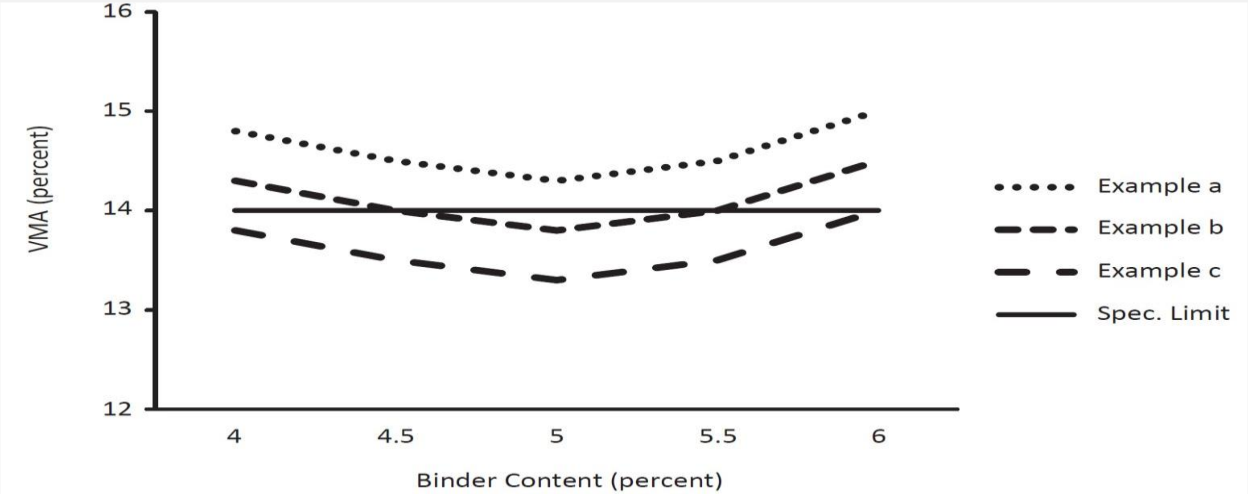
BITUMINOUS MIX DESIGN CONCEPTS

Analysis of VMA Curve:

- Most difficult mix design is to achieve a minimum VMA such that enough space is available for asphalt to provide adequate adhesion to bind aggregate particles without any bleeding during higher temperatures when asphalt expands
- VMA varies with binder content as opposed to a constant value where it is assumed that asphalt displaces air voids
- Assumption of a constant unit volume is not correct as total volume changes across the range of asphalt contents, i.e., mix becomes more workable with increase in asphalt content
- With increase in asphalt content the bulk density increases and VMA decreases up to a particular asphalt content due to densification of the mix beyond which further increase in asphalt content starts displacing the aggerate structure there by decreasing the bulk density and increasing the VMA

BITUMINOUS MIX DESIGN CONCEPTS

Source: MS-2, 2014



Analysis of VMA Curve:

- Asphalt contents on wet-side should be avoided even if air voids and minimum VMA criteria is satisfied
- Design asphalt contents on wet-side will have a tendency to bleed and/or exhibit plastic flow due to additional compaction caused by traffic (secondary compaction) as there will not be enough room for asphalt to expand and also there will be loss of aggregate-to-aggregate contact resulting in mix rutting and shoving in heavily trafficked areas; **design asphalt content should be to the dry-side (left-side)!**

BITUMINOUS MIX DESIGN CONCEPTS

Analysis of VMA Curve:

- Very flat bottom of U-shaped VMA curve represent asphalt mix insensitive to asphalt content within that range where compactability is influenced by aggregate properties; beyond a particular point, asphalt content becomes critical to mix behavior resulting in drastic increase of VMA!
- If bottom of U-shaped VMA curve falls below the minimum VMA criteria of specific NMAS of the mix, required to change job mix formula to provide additional VMA and not to adopt the extremes of the acceptable range even if minimum criteria are satisfied (dry-side results in segregation and high air voids whereas wet-side results in rutting susceptible mix)
- If U-shaped VMA curve is completely below the minimum VMA criteria over complete range of asphalt content, significant redesign and/or change of aggregate source is recommended

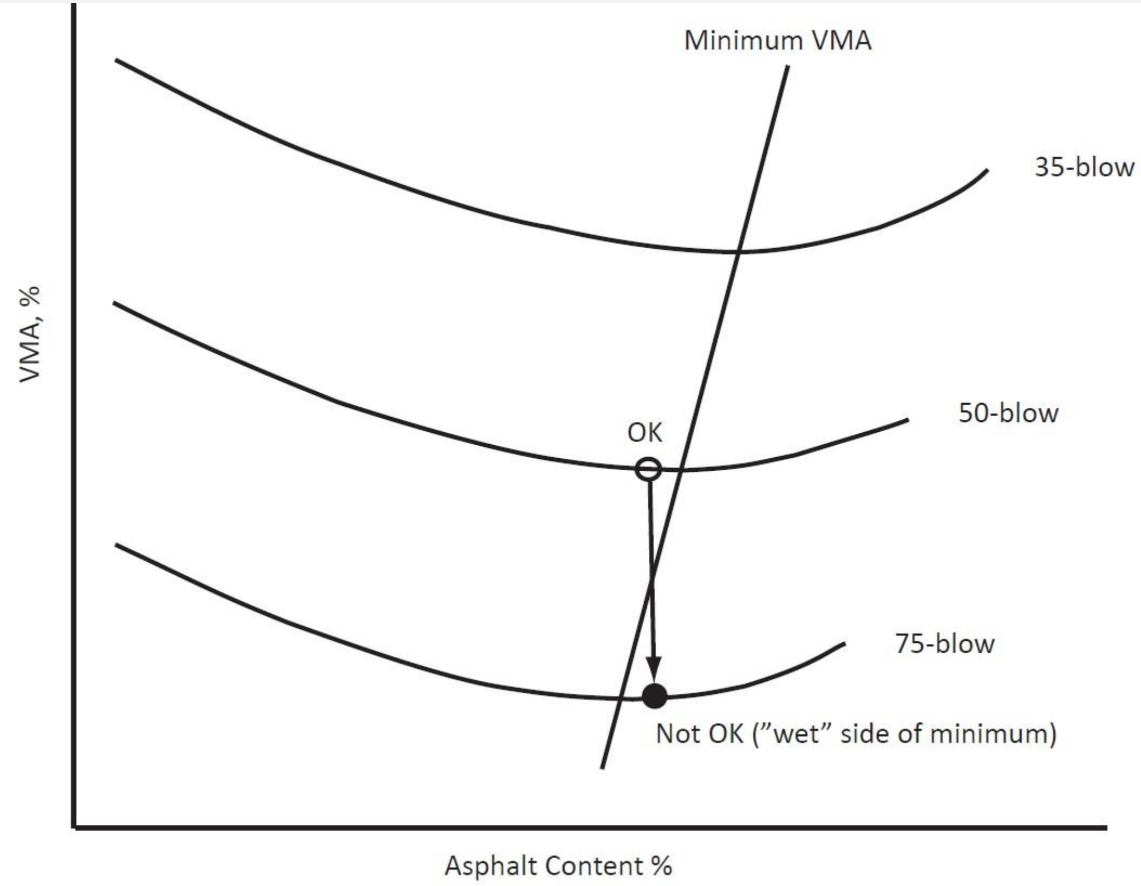
BITUMINOUS MIX DESIGN CONCEPTS

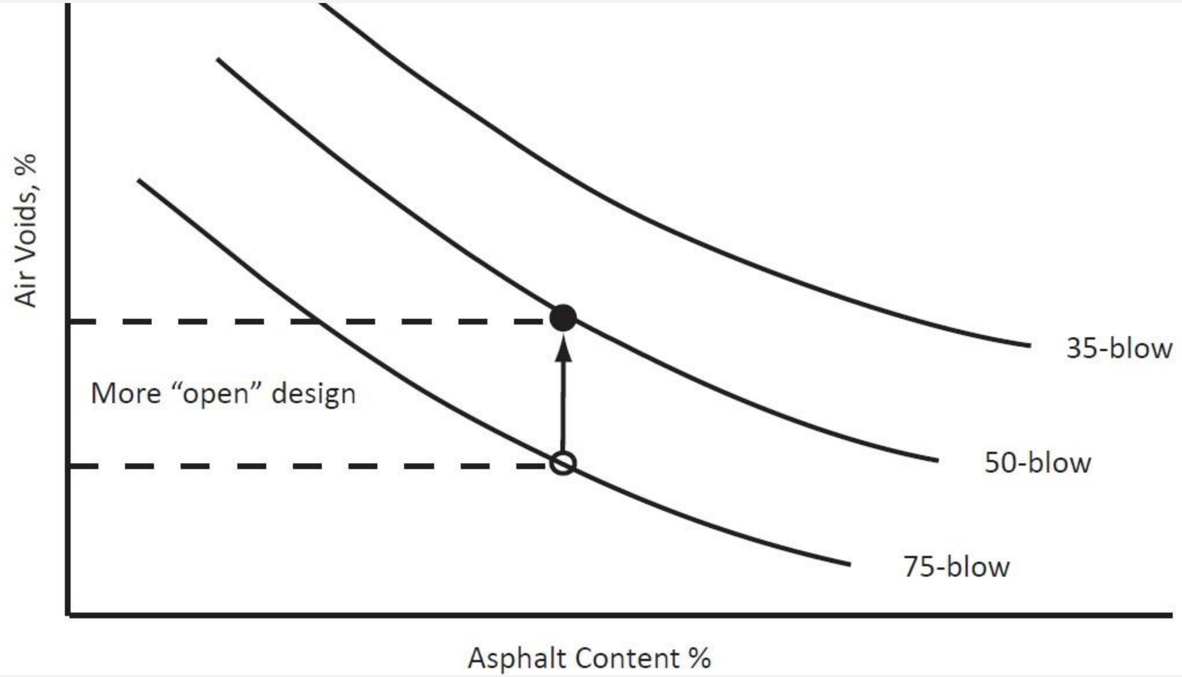
Effect of Compaction Level:

- At same asphalt content, higher compactive effort decreases air voids and VMA
- With change in compactive effort, magnitude of VMA changes, apart from a shift in asphalt content at which minimum VMA occurs
- If a mix designed at higher compactive effort is placed in a pavement with much lower volumes of traffic, then the final percentage air voids will be much higher than the planned percentage of air voids
- Higher air void mix harden prematurely due to entry of air → cracks
- Entry of water → aggregate can also ravel due to loss of adhesion
- Compactive effort should simulate the design traffic
- Adequate initial density should be ensured during the field compaction irrespective of climatic conditions through proper compactive effort
- Min. VMA criteria should not change based on compaction criteria (room for asphalt!)

BITUMINOUS MIX DESIGN CONCEPTS

Effect of Compaction Level:





Source: MS-2, 2014

BITUMINOUS MIX DESIGN CONCEPTS

Source: AASHTO, 201

Effect of Air Voids:

- Design air voids (4%) is the level desired after several years of traffic
- Laboratory compactive effort should be selected based on expected traffic
- Design air void range can be achieved even after secondary compaction caused by traffic if air voids after construction < 8% (density achieved > 92% of G_{mm})
- Mixtures that consolidate to < 2% air voids (due to accidental increase in asphalt content or increase in fines passing 75 μm sieve) can rut and shove
- If terminal air voids > 5% or if constructed with > 8% initial air voids, such mixes exhibit brittleness and cracking prematurely due to entry of air, ravel and strip due to entry of moisture
- Design asphalt content adjustments should be limited such that terminal air voids is within a tolerance of 4±0.5% (laboratory compaction should be changed to achieve dry or wet mixes desired for specific pavement type)

BITUMINOUS MIX DESIGN CONCEPTS

% air voids	3 – 5
% Voids Filled with Bitumen (VFB)	65 – 75

Nominal Maximum Particle Size[1] (mm)	Minimum VMA Percent Related to Design Percentage Air voids		
	3.0	4.0	5.0
26.5	11.0	12.0	13.0
37.5	10.0	11.0	12.0

Effect of Voids filled with Asphalt:

- VMA, VFA and P_a are interrelated
- Criteria for two parameters can take care of the third parameter
- Purpose of VFA criterion is to provide upper limits on VMA and asphalt content!!!
- VFA also restricts allowable air voids for mixes that are near minimum VMA
- Mixes designed for lower traffic will not pass VFA criteria with high percentage of air voids even if the air void criteria range is satisfied (to avoid less durable mixes which can crack due to higher air voids) [for 5% air voids with 13% VMA, VFA = 61.54% < 65%]
- Mixes designed for higher traffic will not pass VFA criteria with low percentage of air voids even if the air void criteria range is satisfied (to avoid rut susceptible mixes) [for 3% air voids with 13% VMA, VFA = 76.92% > 75%]
- VFA provides additional safety factor for pavement performance!