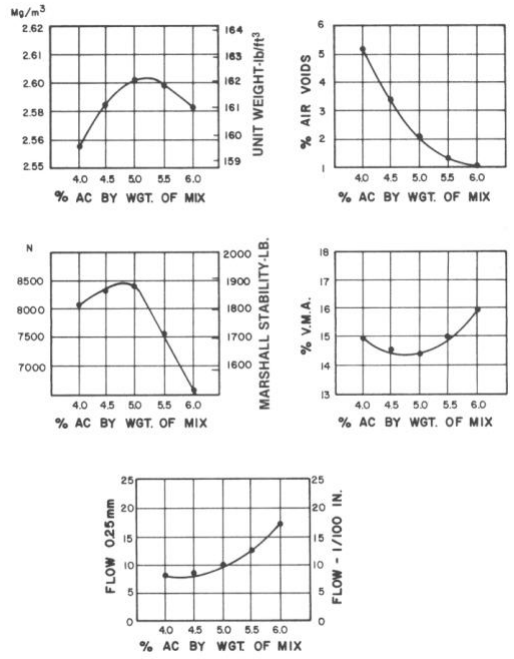


Figure III-4—Test property curves for hot-mix design data by the Marshall method (See also Figure III-3)

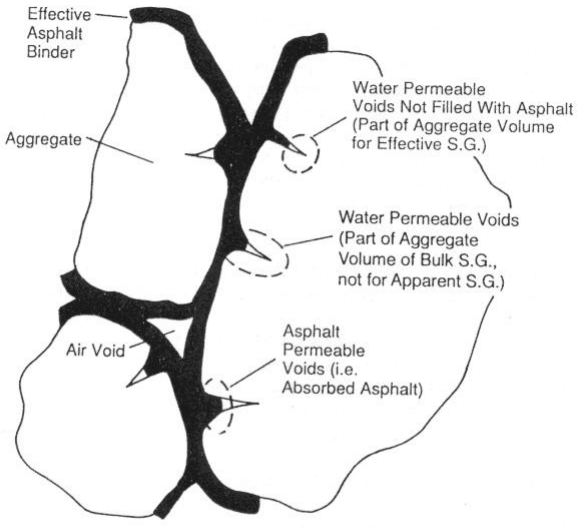


Figure 4.1 -- **Illustrating bulk, effective, and apparent specific gravities; air voids; and effective asphalt content in compacted asphalt paving mixture**

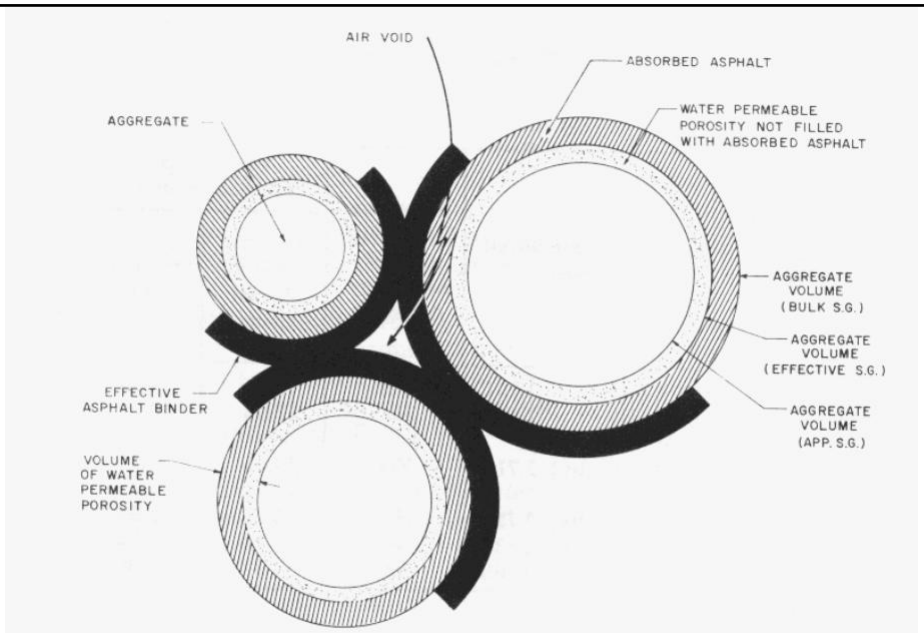
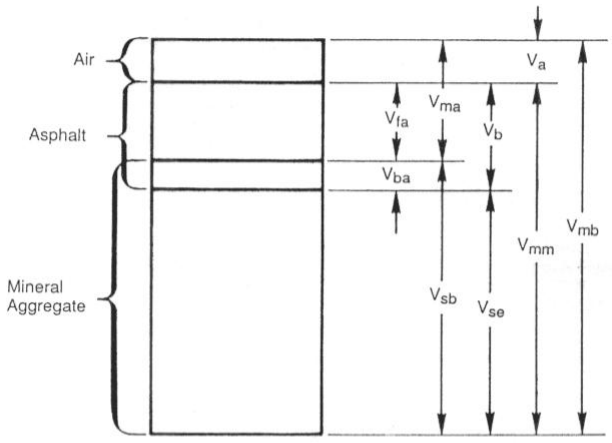


Figure V-1 – Illustrating VMA, air voids and effective asphalt content in compacted asphalt paving mixture



V_{ma} = Volume of voids in mineral aggregate
V_{mb} = Bulk volume of compacted mix
V_{mm} = Voidless 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 4.2 – **Representation of volumes in a compacted asphalt specimen**

Table 4.2 – **Basic data for sample of paving mixture**

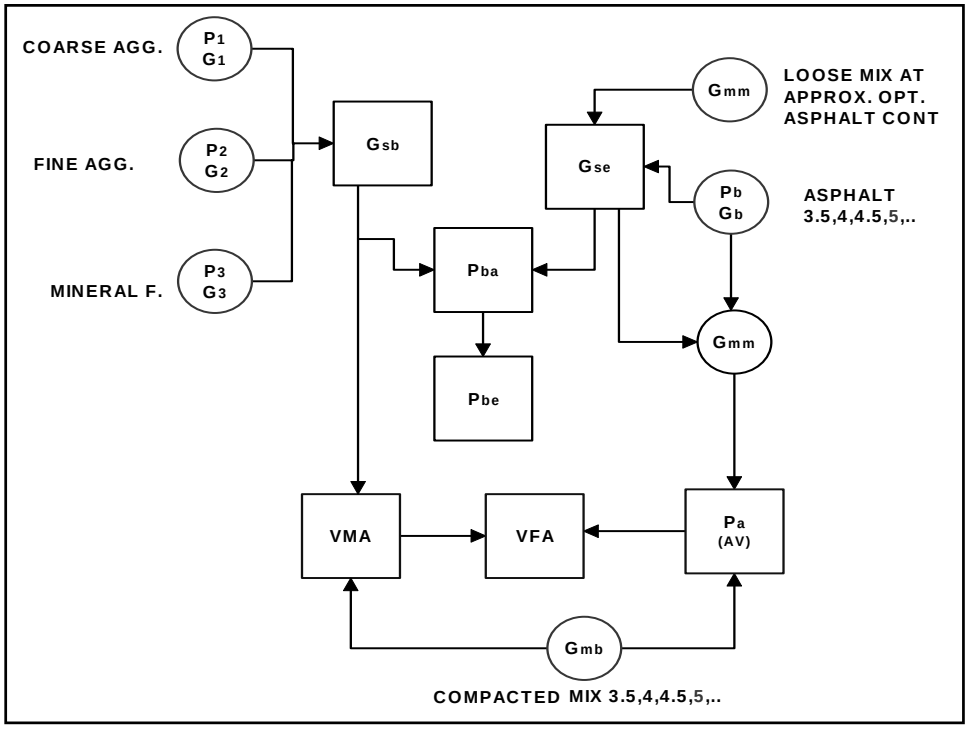
(a) Constituents

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



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

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

$$G_{sb} = \frac{50.0 + 50.0}{\frac{50.0}{2.716} + \frac{50.0}{2.689}} = \frac{100}{18.41 + 18.59} = 2.703$$

$$G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}} \qquad (2)$$

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

$$G_{se} = \frac{100 - 5.3}{\frac{100}{2.535} - \frac{5.3}{1.030}} = \frac{94.7}{39.45 - 5.15} = 2.761$$

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

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

$$G_{mm} = \frac{100}{\frac{96}{2.761} + \frac{4.0}{1.030}} = \frac{100}{34.77 + 3.88} = 2.587$$

$$G_{mm} = W_{mm} / V_{mm}$$

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

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

$$P_{ba} = 100 \left(\frac{2.761 - 2.703}{2.703 \times 2.761}\right) 1.030 = 100 \left(\frac{0.058}{7.463}\right) 1.030 = 0.8$$

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

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

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

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

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 T166; ASTM D 1188 or D 2726)
P_s = aggregate content, percent by total weight of mixture

$$VMA = 100 - \frac{2.442 \times 94.7}{2.703} = 100 - 85.6 = 14.4$$

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

where, P_b = asphalt content, percent by weight of aggregate.

$$VMA = 100 - \frac{2.442}{2.703} \times \frac{100}{100 + 5.6} \times 100 = 100 - 85.6 = 14.4$$

$$VMA = P_a + P_{be}$$

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

where, V_a = air voids in compacted mixture, percent of total volume
G_{mm} = maximum specific gravity of paving mixture (as determined in Article 4.07 or as measured directly for a paving mixture by ASTM D 2041)
G_{mb} = bulk specific gravity of compacted mixture

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

$$AV = 100 - (V_{sb} + P_{be})$$

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

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

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

Figure 4.3 – **Worksheet: Analysis by weight of total mixture**

Worksheet for Volumetric Analysis of Compacted Paving Mixture
(Analysis by weight of total mixture)

Sample: _____ Date: _____

Identification: _____

Composition of Paving Mixture

	Specific Gravity, G			Mix Composition, % by wt. of Total Mix, P					
					Mix or Trial Number				
			Bulk		1	2	3	4	5
1. Coarse Aggregate	G_1		2.716	P_1			47.4		
2. Fine Aggregate	G_2		2.689	P_2			47.3		
3. Mineral Filler	G_3		--	P_3			--		
4. Total Aggregate	G_s	--	--	P_s			94.7		
5. Asphalt Cement	G_b	1.030	--	P_b			5.3		
6. Bulk Sp. Gr. (G_{sb}), total aggregate				(1)			2.703		
7. Max. Sp. Gr. (G_{mm}), paving mix ASTM D2041				—			2.535		
8. Bulk Sp. Gr. (G_{mb}), compacted mix ASTM D2726				—			2.442		
9. Effective Sp. Gr. (G_{se}), total aggregate				(2)			2.761		
10. Absorbed Asphalt (P_{ba}), % by wgt. total agg.				(4)			0.8		
CALCULATIONS									
11. Effective Asphalt Content (P_{be}) = Line 5 P_b – $\frac{(\text{Line 10} \times \text{Line 4 } P_s)}{100}$				(5)			4.5		
12. VMA = $100 - \frac{\text{Line 8} \times \text{Line 4 } P_s}{\text{Line 6}}$				(6)			14.4		
13. Air Voids (V_a) = $100 \frac{\text{Line 7} - \text{Line 8}}{\text{Line 7}}$				(8)			3.7		
14. VFA = $100 \frac{\text{Line 12} - \text{Line 13}}{\text{Line 12}}$				(9)			74.3		

*Equations from Chapter 4, MS-2

Figure 4.4 – **Worksheet: Analysis by weight of aggregate**

Worksheet for Volumetric Analysis of Compacted Paving Mixture
(Analysis by weight of aggregate)

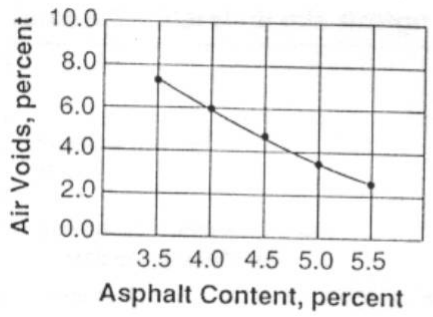
Sample: _____ Date: _____

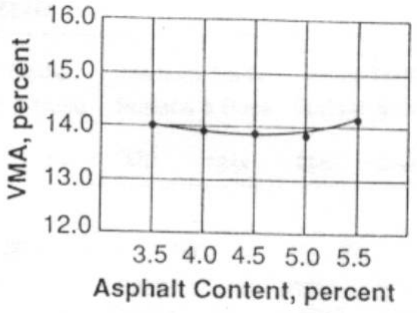
Identification: _____

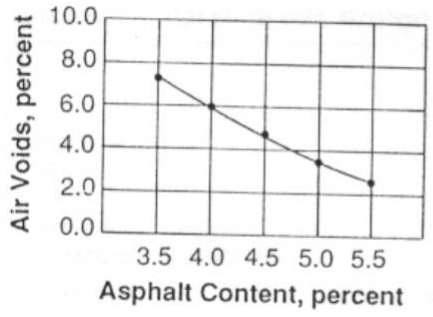
Composition of Paving Mixture

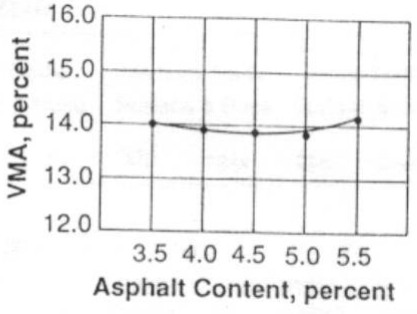
	Specific Gravity, G			Mix Composition, % by wt. of Aggregate, P					
					Mix or Trial Number				
			Bulk		1	2	3	4	5
1. Coarse Aggregate	G_1		2.716	P_1			50.0		
2. Fine Aggregate	G_2		2.689	P_2			50.0		
3. Mineral Filler	G_3		--	P_3			--		
4. Total Aggregate	G_s	--	--	P_s			100.0		
5. Asphalt Cement	G_b	1.030	--	P_b			5.6		
6. Bulk Sp. Gr. (G_{sb}), total aggregate				(1)			2.703		
7. Max. Sp. Gr. (G_{mm}), paving mix ASTM D2041				—			2.535		
8. Bulk Sp. Gr. (G_{mb}), compacted mix ASTM D2726				—			2.442		
9. Effective Sp. Gr. (G_{se}), total aggregate				(2)			2.761		
10. Absorbed Asphalt (P_{ba}), % by wgt. total agg.				(4)			0.8		
CALCULATIONS									
11. Effective Asphalt Content (P_{be}) = Line 5 P_b – Line 10				(5)			4.5		
12. VMA = $100 - \frac{\text{Line 8}}{\text{Line 6}} \times \frac{100}{100 + \text{Line 5 } P_b} \times 100$				(7)			14.4		
13. Air Voids (V_a) = $100 \frac{\text{Line 7} - \text{Line 8}}{\text{Line 7}}$				(8)			3.7		
14. VFA = $100 \frac{\text{Line 12} - \text{Line 13}}{\text{Line 12}}$				(9)			74.3		

*Equations from Chapter 4, MS-2


Air Voids, percent
10.0
8.0
6.0
4.0
2.0
0.0
3.5 4.0 4.5 5.0 5.5
Asphalt Content, percent


VMA, percent
16.0
15.0
14.0
13.0
12.0
3.5 4.0 4.5 5.0 5.5
Asphalt Content, percent


Air Voids, percent
10.0
8.0
6.0
4.0
2.0
0.0
3.5 4.0 4.5 5.0 5.5
Asphalt Content, percent


VMA, percent
16.0
15.0
14.0
13.0
12.0
3.5 4.0 4.5 5.0 5.5
Asphalt Content, percent

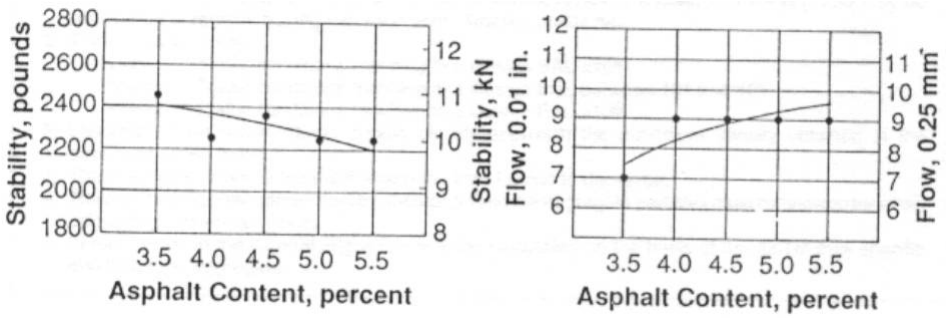
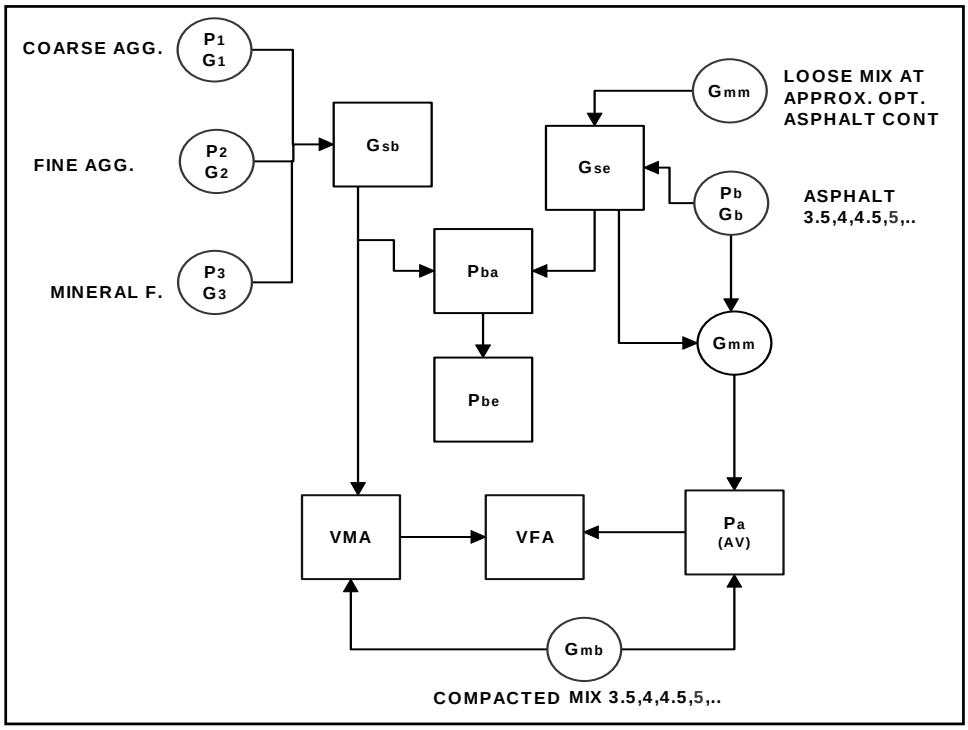


Table 5.3 – **Minimum percent voids in mineral aggregate (VMA)**

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	19.0	20.0	21.0
4.75	No. 4	16.0	17.0	18.0
9.5	3/8	14.0	15.0	16.0
12.5	1/2	13.0	14.0	15.0
19.0	3/4	12.0	13.0	14.0
25.0	1.0	11.0	12.0	13.0
37.5	1.5	10.0	11.0	12.0
50	2.0	9.5	10.5	11.5
63	2.5	9.0	10.0	11.0

1 - Standard Specification for Wire Cloth Sieves for Testing Purposes, ASTM E11 (AASHTO M92)
2 - The nominal maximum particle size is one size larger than the first sieve to retain more than 10 percent.
3 - Interpolate minimum voids in the mineral aggregate (VMA) for design air void values between those listed.


COARSE AGG.
P1
G1
FINE AGG.
P2
G2
MINERAL F.
P3
G3
Gsb
Gmm
LOOSE MIX AT
APPROX. OPT.
ASPHALT CONT
Gse
Pb
Gb
ASPHALT
3.5,4,4.5,5,..
Pba
Gmm
Pbe
VMA
VFA
Pa
(AV)
Gmb
COMPACTED MIX 3.5,4,4.5,5,..