ROAD BUILDING FUNDAMENTALS: VOLUMETRIC PROPERTIES OF ASPHALT MIXES

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START WITH THE BASICS

- 1. Vocabulary
- 2. History
- 3. Science
- 4. Math
- 5. Real World

VOCABULARY

- Volumetric – Of or relating to measurement by volume.
- Empirical – Based on observation or experience rather than theory or pure logic.
- Specific Gravity – The ratio of the mass of a solid or liquid to the mass of an equal volume of distilled water.
- Density – The mass per unit volume of a substance under specified conditions.
- Mass – A dimensionless quantity representing the amount of matter in an object.
- Weight – A measure of the heaviness of an object. The force with which a body is attracted to Earth, equal to the product of the object's mass and the acceleration of gravity.
- Volume – The amount of 3-dimensional space an object occupies. Capacity.

VOCABULARY

- Asphalt – A dark brown to black cementitious material in which the predominating constituents are bitumens which occur in nature or are obtained in petroleum processing.
- Aggregate – Construction aggregate, or simply "aggregate", is a broad category of coarse particulate material used in construction, including sand, gravel, crushed stone, slag, recycled concrete and geosynthetic aggregates. Aggregates are the most mined materials in the world.
- Mineral Admixture – Fine material added to asphalt mixtures to improve moisture resistance and/or volumetric properties; e.g. hydrated lime and Portland cement.

VOCABULARY

- Air Voids (Va) – The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as percent of the total volume of the sample.
- Effective Asphalt Content (Pbe) –The total asphalt content of a paving mixture minus the portion that is absorbed into the aggregate particles.
- Voids in Mineral Aggregate (VMA) – The volume of intergranular 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.
- 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.

VOLUMETRIC EXAMPLE - AGGREGATE

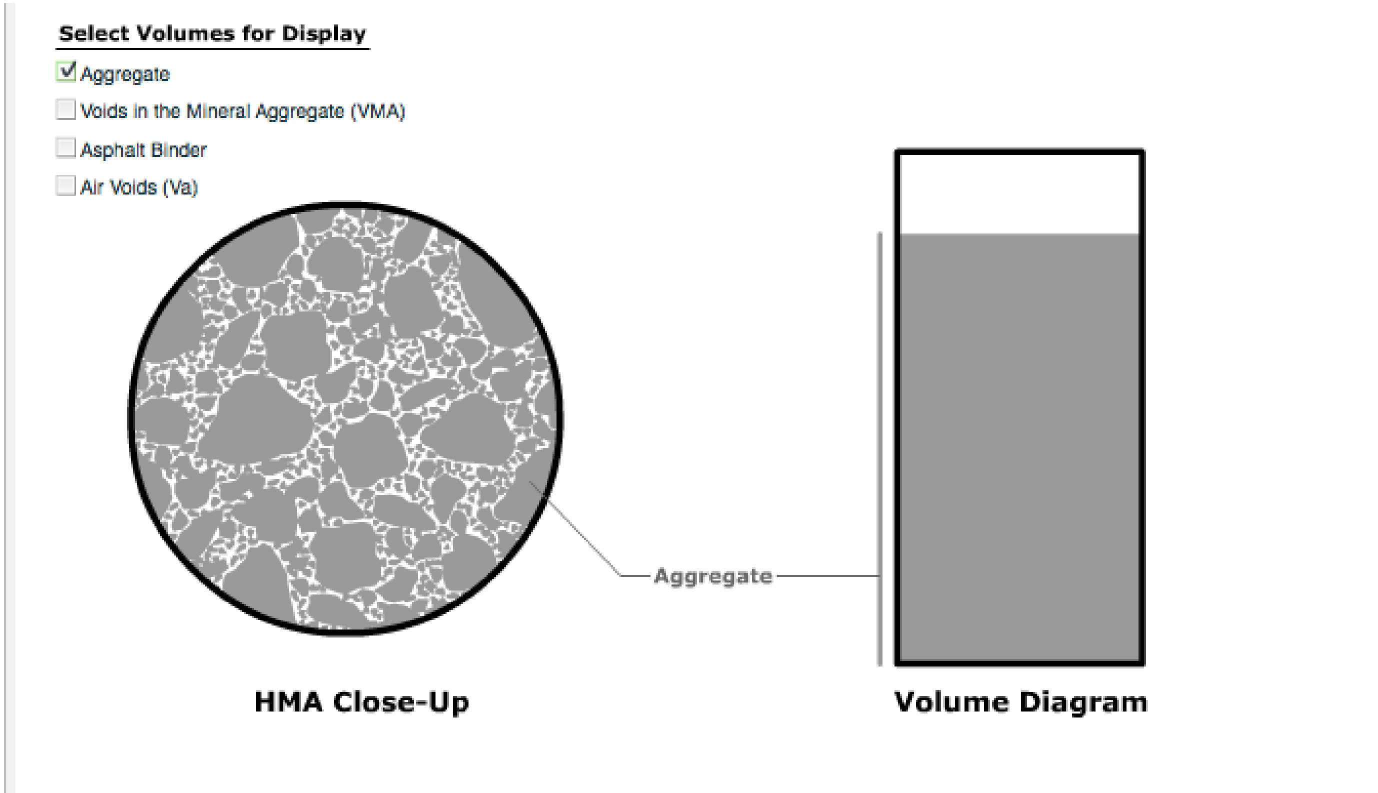
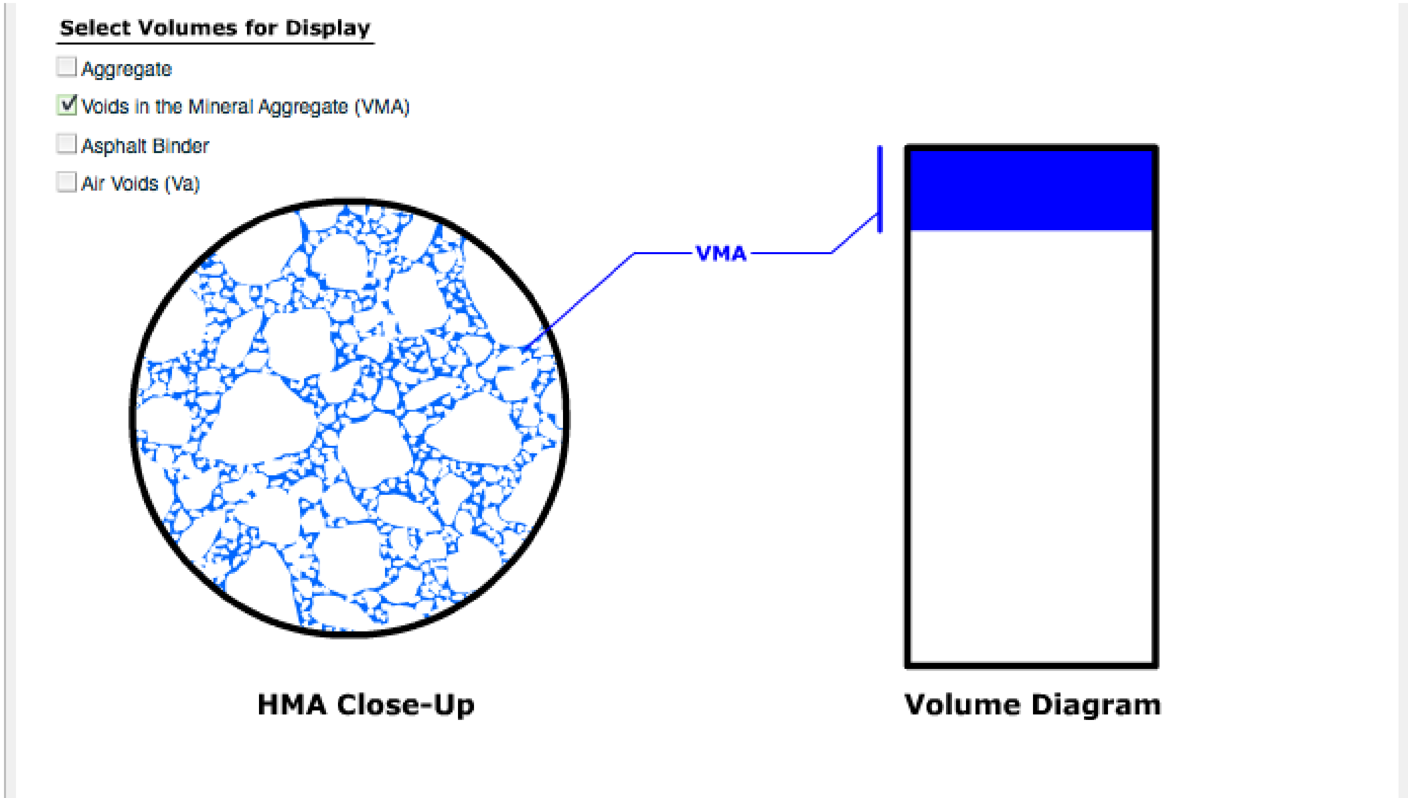


Figure 1. The volumetric relationship of key HMA constituents.

VOLUMETRIC EXAMPLE - VMA



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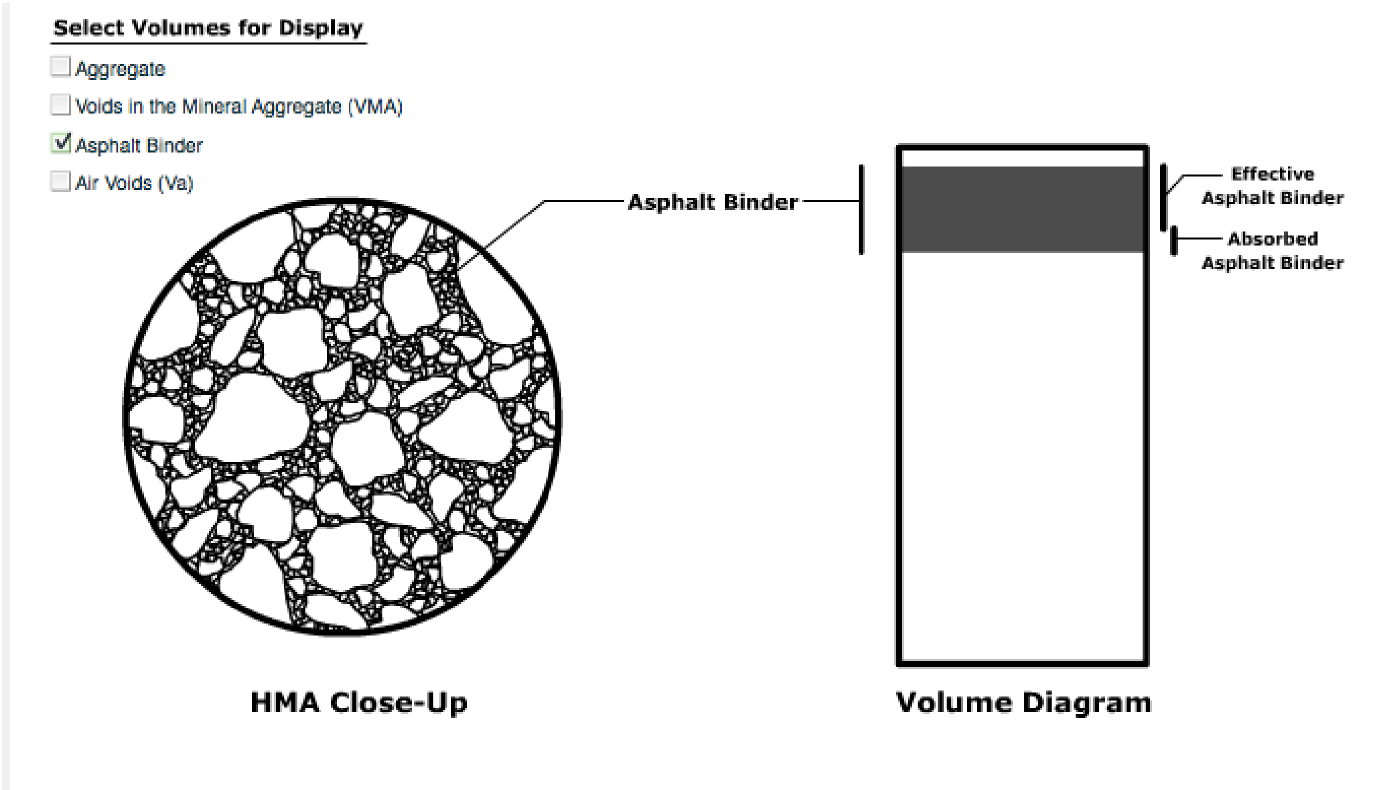
VOLUMETRIC EXAMPLE-ASPHALT BINDER



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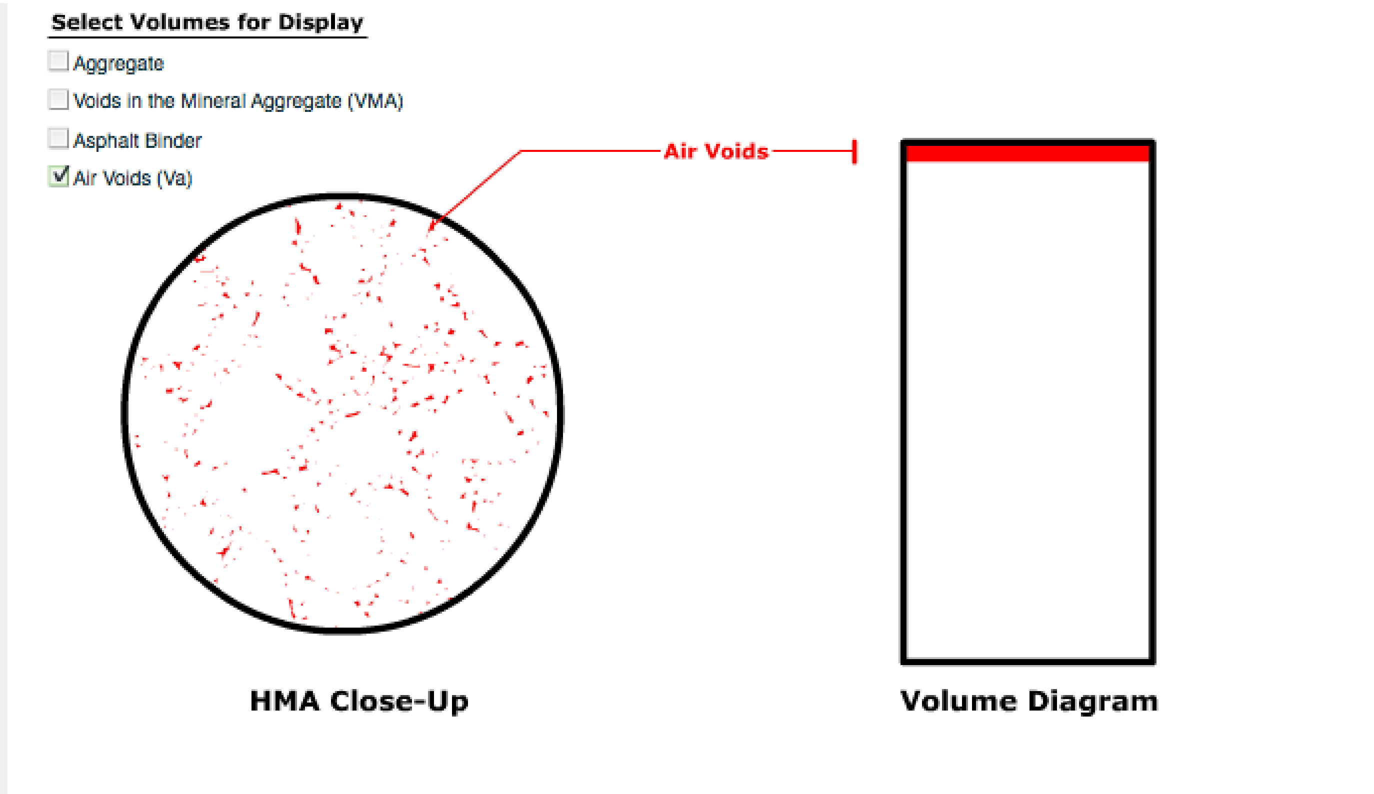
VOLUMETRIC EXAMPLE – AIR VOIDS



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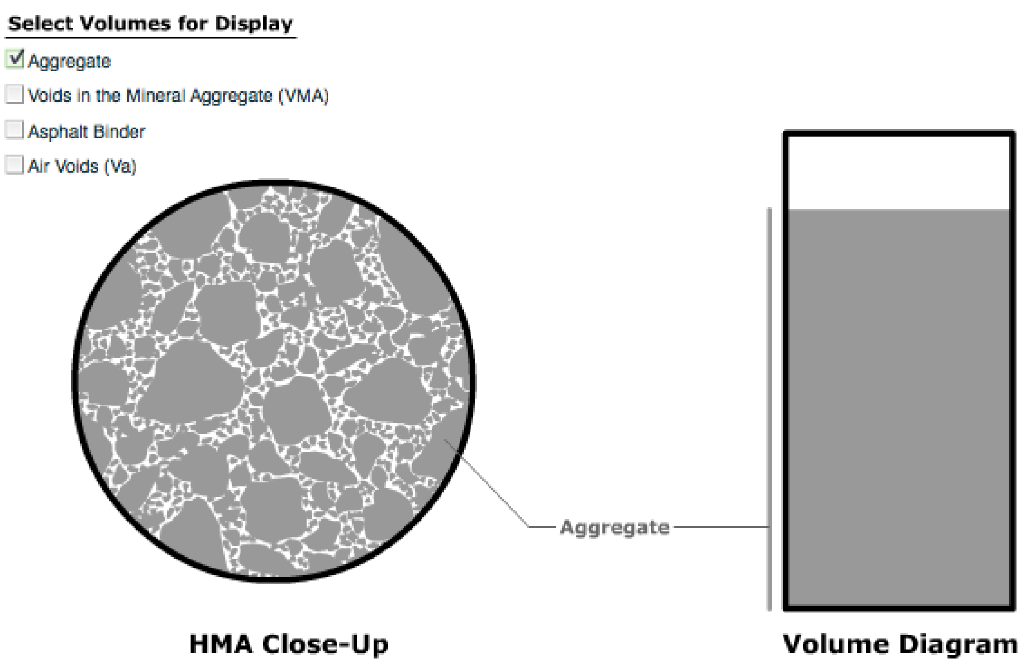

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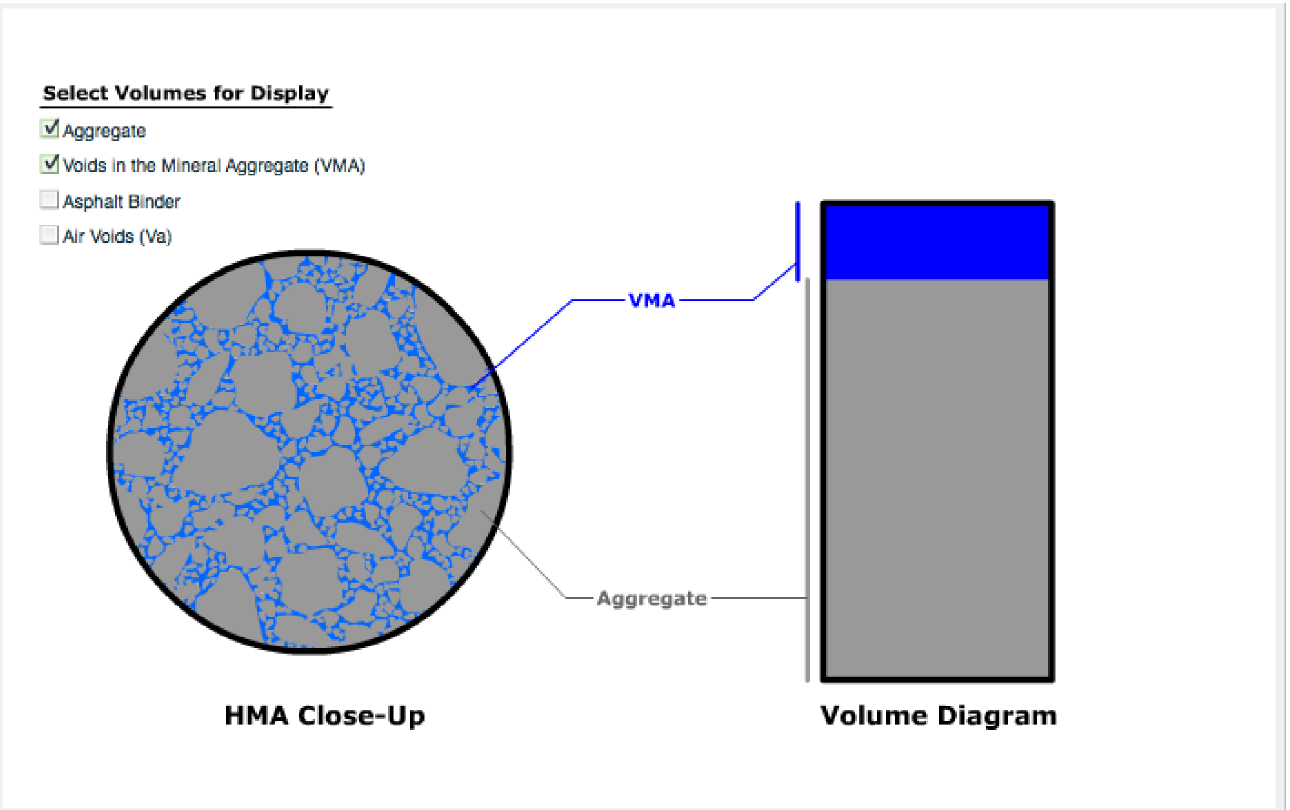

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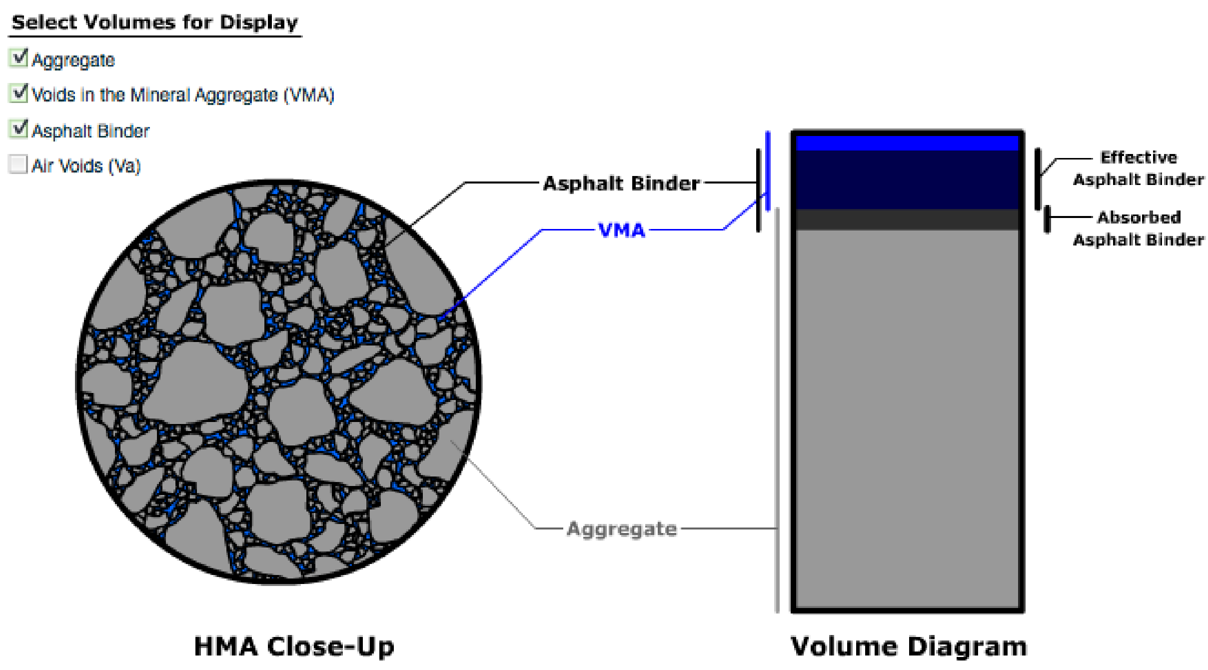

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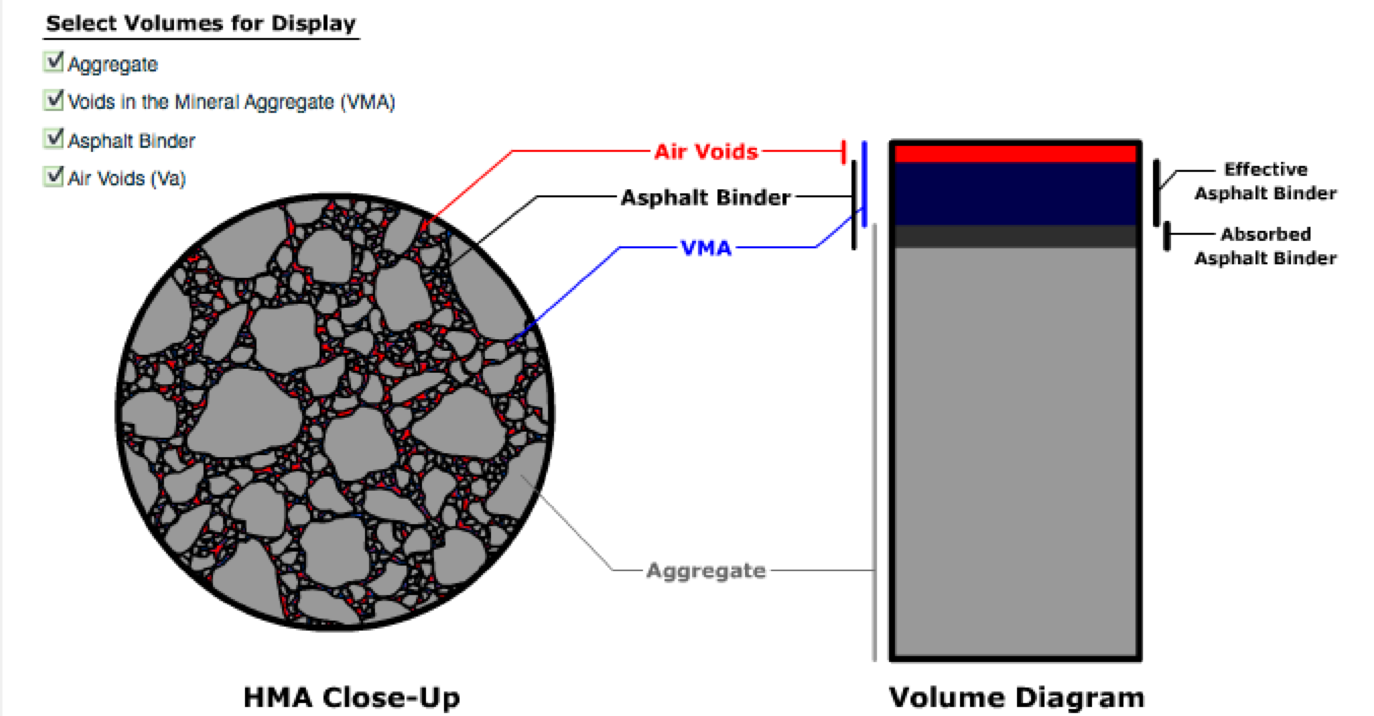


Figure 1. The volumetric relationship of key HMA constituents.

HISTORY – HVEEM

- Francis Hveem - In 1927, Francis Hveem became a resident engineer in California.
- He recognized that asphalt demand was related to aggregate surface area and developed a method to determine asphalt content based on this information.
- Hveem recognized that mechanical strength of the mix was important and developed the Hveem stabilometer.
- Hveem's mix design philosophy was that sufficient asphalt binder is needed to satisfy aggregate absorption and to have a minimum film thickness on the surface of the aggregates. In order to carry load, the aggregates had to have a minimum sliding resistance and a minimum tensile strength.
- Air voids were not part of Hveem's mix design system. He believed that film thickness and mechanical properties as described by stability were most important.
- In the 1980s and '90s, air voids were added as a consideration.

HISTORY – MARSHALL

- Bruce G. Marshall of the Mississippi Department of Highways developed Marshall mix design in the late 1930s to early 1940s.
- The Corps of Engineers adopted Marshall's system in World War II for use on airfields. Post WW II, it was "civilianized" for use by state highway departments.
- The Marshall method uses a sliding hammer and matches the compactor diameter to the mold diameter and standardized the compaction energy applied by using a drop hammer.
- Marshall included calculation of air voids but not VMA. Instead, he used voids filled with asphalt as a criterion. There are also strength and flexibility components – Marshall stability and flow.
- In the 1950s and 1960s, the Asphalt Institute was the de facto keeper of the Marshall standard and published it in "MS-2, A Manual of Mix Design Methods for Asphalt Concrete." ASTM and AASHTO both mirrored MS-2.
- In 1962, after much debate, the Asphalt Institute changed MS-2 to include VMA as a mix design criteria. AASHTO and ASTM changed their standards to reflect the Asphalt Institute revision.
- The Marshall and Hveem mix design procedures served as the primary means of designing dense mixtures until the mid-90s.

HISTORY – RICE

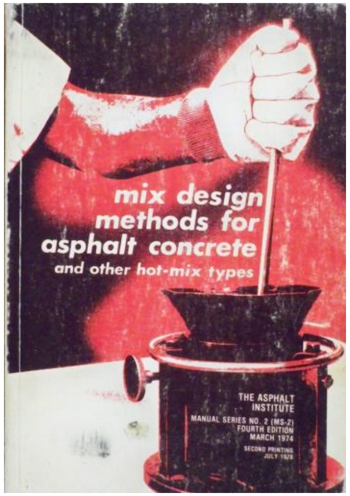
- James M. Rice – Developed the Maximum Theoretical Specific Gravity (Rice) test method – "Maximum Specific Gravity of Bituminous Mixtures by Vacuum Saturation Procedure," ASTM Special Technical Publication No. 191, June 1956. Rice test was standardized as ASTM D-2041 in 1964.
- Allowed for indirect determination of mixture air voids when compared to bulk specific gravity of compacted specimen.
- Allowed for accounting of asphalt absorption into aggregate.

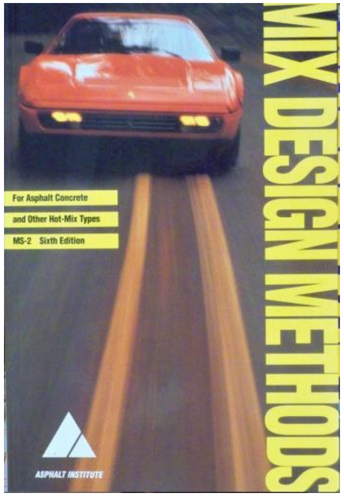
HISTORY – SHRP PROGRAM

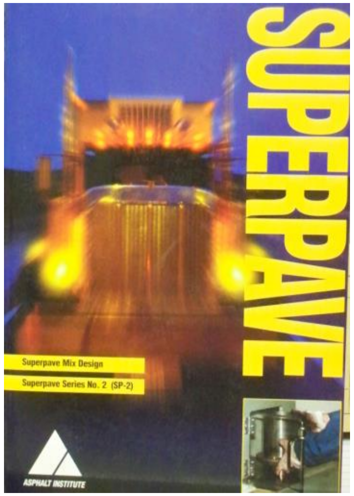
- Superpave mix design was developed as part of the Strategic Highway Research Program (SHRP) from 1987 to 1993. The objective of the Asphalt Research Program was to develop a performance-based asphalt binder specification, a performance-based asphalt mixture specification and a mix design system.
- The Performance-Graded (PG) asphalt binder specification was the initial result of the research. The performance-based mix specification was less successful. Although performance tests for asphalt mixture were developed and models were designed to predict mixture response (stress, strain, etc.) and to predict mixture performance (rutting, fatigue cracking, thermal cracking), the system ended up being too difficult to implement and was never used by state DOTs.
- As the SHRP research progressed, it became apparent that using a simple, empirical design method as the base or entry level mix design would be feasible. So, it was decided that Level 1 mix design would be based on mixture properties, including air voids, VMA, and VFA.
- A new method of compaction (gyratory compactor) and new aggregate quality requirements were also implemented.

HISTORY – ASPHALT INSTITUTE

- Asphalt Institute – Founded in 1919. The Asphalt Institute has been and continues to be a leader in education and promotion of asphalt and its related materials. It has been a leading proponent of rational and standardized asphalt mix design procedures through the years with its publication MS-2, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types" and more recently with SP-2, "Superpave Mix Design".

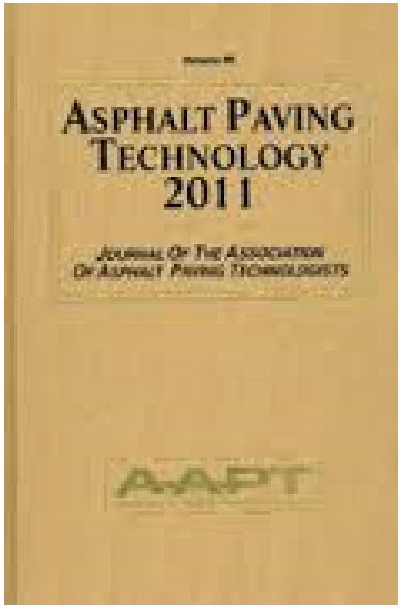






HISTORY – AAPT

- The Association of Asphalt Paving Technologists (AAPT) was founded in 1924 and has served as a dedicated avenue for research and development of asphalt technology, including volumetric mix design procedures. Today AAPT continues as a leader in the advancement of asphalt paving technology.



SCIENCE

- Weight vs. Volume – The volume relationships of the constituent materials in asphalt mixes are what we need to know. So, why are most measurements made using weights?
- Basic HMA weight-volume relationships are important to understand for both mix design and construction purposes. Fundamentally, mix design is meant to determine the volume of asphalt binder and aggregates necessary to produce a mixture with the desired properties (Roberts et al., 1996). However, since weight measurements are typically much easier to perform, they are typically taken then converted to volume by using specific gravities.

SCIENCE

- Direct vs. Indirect Measurement – Often, we cannot directly measure specific properties of an item. Therefore, we need to take an indirect approach to determine those properties. This is especially true with asphalt mixes.
- An example includes taking physical measurements of a specimen and calculating the volume using L x W x D. This type of measurement assumes perfectly smooth surfaces and doesn't allow for voids or protrusions. The amount of error can be significant. Therefore, we determine the volume of these types of samples by measuring how much water they displace. Since 1 gram of water = 1 cm^3, we can determine the volume of the desired object.

SCIENCE

- Lab Methods vs. Real World – How close do results obtained from lab testing come to the real world properties of constructed pavements?
- Lab testing provides an approximation of real-world properties and performance. Much of the anticipated ultimate performance is extrapolated from lab tests to field conditions and is based on empirical or comparative evaluations; i.e past experience or trial-and-error.

MATH – PRIMARY FORMULAS

- $VFA = (VMA - V_a)/VMA \times 100$
- $VMA = 100 - (G_{mb} \times P_s)/G_{sb}$
- $V_a = (G_{mm} - G_{mb})/G_{mm} \times 100$
- $P_{ba} = 100 \times ((G_{se} - G_{sb})/(G_{sb} \times G_{se})) \times G_b$
- $G_{se} = (100 - P_b)/((100/G_{mm}) - (P_b/G_b))$
- $P_{be} = P_b - (P_{ba}/100) \times P_s$

VOLUMETRIC PROPERTIES

- What goes into determining the volumetric properties of a mix?
  - Aggregate Properties
  - Admixture Type and Properties
  - Asphalt Binder Properties

VOLUMETRIC PROPERTIES – AGGREGATES

- Aggregate Properties
  - Composite Gradation
    - Fuller-Thompson Curves – 1907
    - FHWA 0.45 Power Chart – Early 1960's
    - Optimization vs. Production Considerations
  - Particle Shape
  - Particle Texture
  - Absorption Characteristics
  - Durability
  - Toughness
  - Asphalt mix sensitivity to deviations in gradation

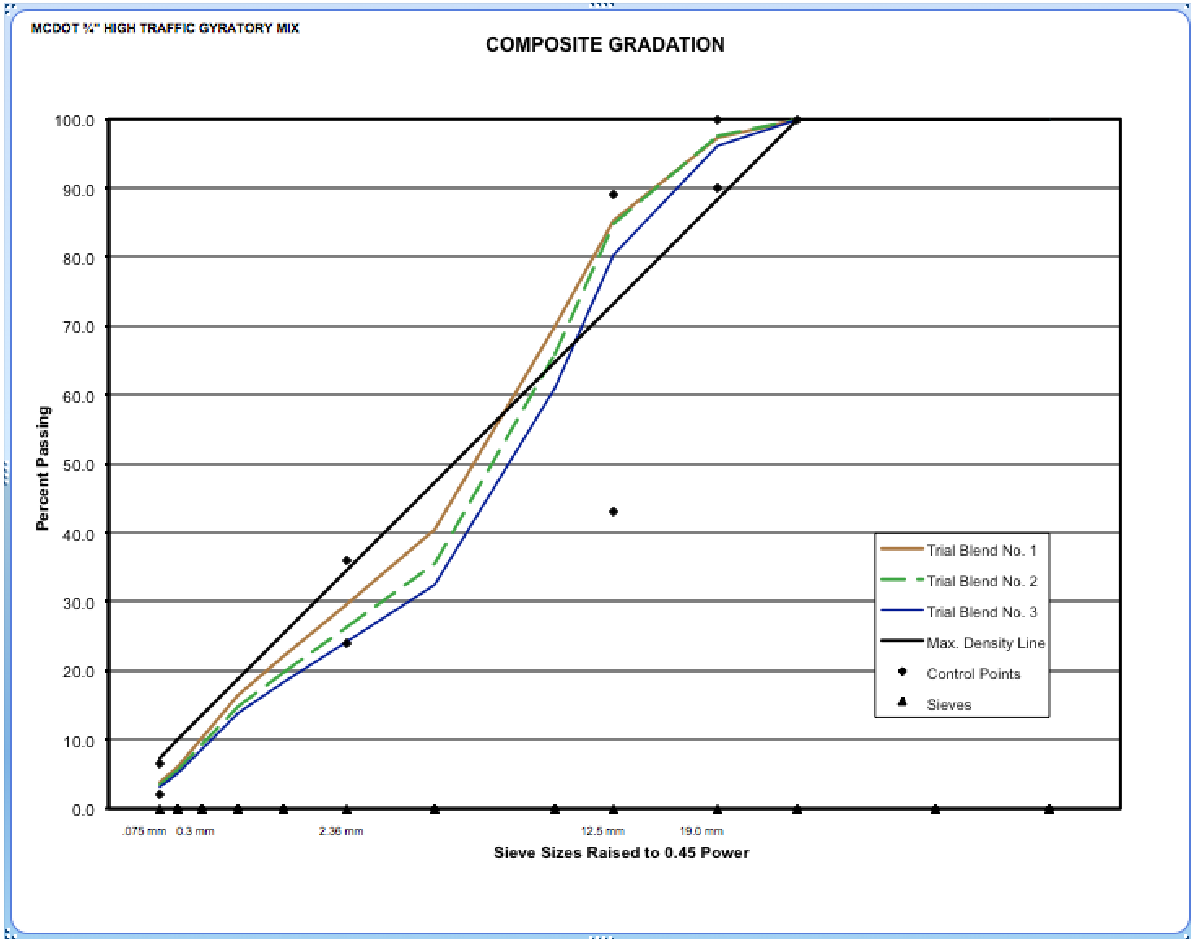
VOLUMETRIC PROPERTIES – AGGREGATES

MIX TYPE:	**MCDOT ¾" HIGH TRAFFIC GYRATORY MIX**	SOURCE OF MAT'L:	**WHY, ARIZONA**
SOURCE:	**STOCKPILES**	SAMPLED BY:	**CLIENT**
LAB NO:	**370449**	ADMIX TYPE:	**HYDRATED LIME**

	ORIGINAL GRADATION-% PASSING											
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	BLEND	BLEND	BLEND		
MAT'L	HYDRATED	WASHED	MA	3/8-INCH	1/2-INCH	3/4-INCH		NO. 1	NO. 2	NO. 3		
NAME	LIME	SAND	SAND	AGGR.	AGGR.	AGGR.		----------COMPOSITE----------			CONTROL	
LAB NO.	N/A	368138	368137	368136	368135	368134		% PASS	% PASS	% PASS	POINTS	SIEVE
	% USED											
BLEND # 1	1	15	23	29	21	11						
BLEND # 2	1	15	18	29	27	10					with	
BLEND # 3	1	15	15	27	27	15					admix	
SIEVE												SIEVE
US/mm												US/mm
1½" / 37.5	100.0	100.0	100.0	100.0	100.0	100.0		100.0	100.0	100		1½" / 37.5
1" / 25	100.0	100.0	100.0	100.0	100.0	100.0		100.0	100.0	100	100	1" / 25
3/4" / 19	100.0	100.0	100.0	100.0	100.0	75.0		97.3	98	96	90-100	3/4" / 19
1/2" / 12.5	100.0	100.0	100.0	100.0	79.0	6.0		85.3	85	80	43-89	1/2" / 12.5
3/8" / 9.5	100.0	100.0	100.0	95.8	15.0	1.3		70.1	66	61		3/8" / 9.5
1/4" / 6.3	100.0	100.0	100.0	36.2	0.8	0.5		49.7	45	41		1/4" / 6.3
#4 / 4.75	100.0	99.5	99.2	5.0	0.8	0.4		40.4	35	32		#4 / 4.75
#8 / 2.36	100.0	85.0	67.0	0.9	0.7	0.3		29.6	26	24	24-36	#8 / 2.36
#10 / 2.00	100.0	83.1	63.3	0.9	0.7	0.3		28.5	25	23		#10 / 2.00
#16 / 1.18	100.0	67.3	45.6	0.9	0.7	0.3		22.0	20	18.4		#16 / 1.18
#30 / .600	100.0	48.8	33.5	0.8	0.7	0.3		16.4	15	14		#30 / .600
#40 / .425	100.0	37.7	28.1	0.8	0.7	0.2		13.5	12	11	3-18	#40 / .425
#50 / .300	100.0	25.4	22.4	0.8	0.7	0.2		10.4	9	9		#50 / .300
#100 / .150	100.0	9.6	14.4	0.8	0.7	0.1		6.1	5	5		#100 / .150
#200 / .075	100.0	2.4	9.2	0.7	0.6	0.1		3.8	3.4	3.1	2.0-6.5	#200 / .075

MAT'L 1 =	HYDRATED	LIME	LHOIST
MAT'L 2 =	WASHED	SAND	WHY, ARIZONA
MAT'L 3 =	MA	SAND	WHY, ARIZONA
MAT'L 4 =	3/8-INCH	AGGR.	WHY, ARIZONA
MAT'L 5 =	1/2-INCH	AGGR.	WHY, ARIZONA
MAT'L 6 =	3/4-INCH	AGGR.	WHY, ARIZONA
MAT'L 7 =			

VOLUMETRIC PROPERTIES – AGGREGATES



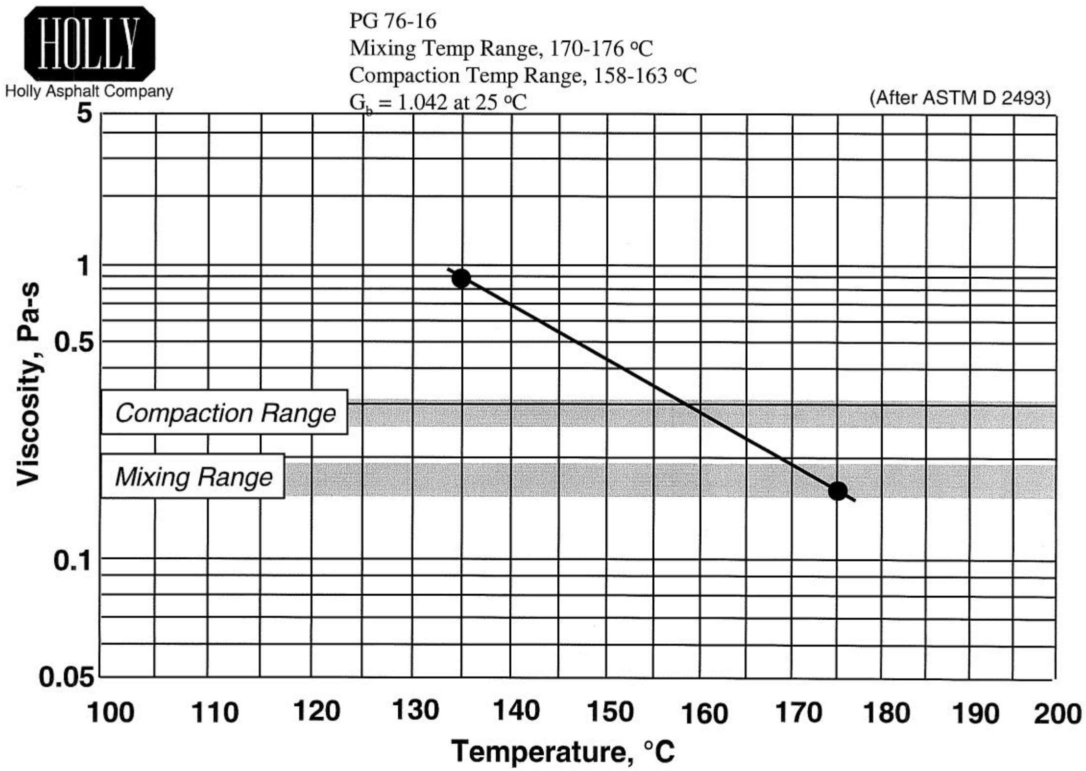
VOLUMETRIC PROPERTIES – ADMIXTURES

- Admixture – Typically for Moisture Resistance
  - Hydrated Lime
  - Portland Cement
  - Liquid Anti-strips

VOLUMETRIC PROPERTIES – BINDER

- Asphalt Binder
  - Grading Systems – PG vs. AC vs. AR vs. Pen
  - Physical Properties
  - Temperature – Viscosity Relationship
  - Adhesion
  - Asphalt mix sensitivity to deviations in binder content

VOLUMETRIC PROPERTIES – BINDER



VOLUMETRIC PROPERTIES – MATERIALS

- Specific Gravities
  - Aggregates – Specific gravity and absorption vary greatly by source and material type; e.g. 2.300 to 3.000 in Arizona. Testing is operator dependent and can be variable.
  - Admixture – Consistent. Therefore, constants typically used rather than individual tests. Type II Cement = 3.14, Type IP Cement = 3.00, Lime = 2.20
  - Asphalt Binder – Typically is within narrow range depending on source and process; i.e. 0.990 to 1.050. Considerably more consistent for single source and grade. Testing is relatively precise and repeatable.

LABORATORY MIX TEST METHODS

- Maximum Theoretical Specific Gravity (Rice)
- Marshall
- Hveem
- Gyratory
  - Height vs. Gyrations
  - Densification Curves

MIX TEST DATA – GYRATORY

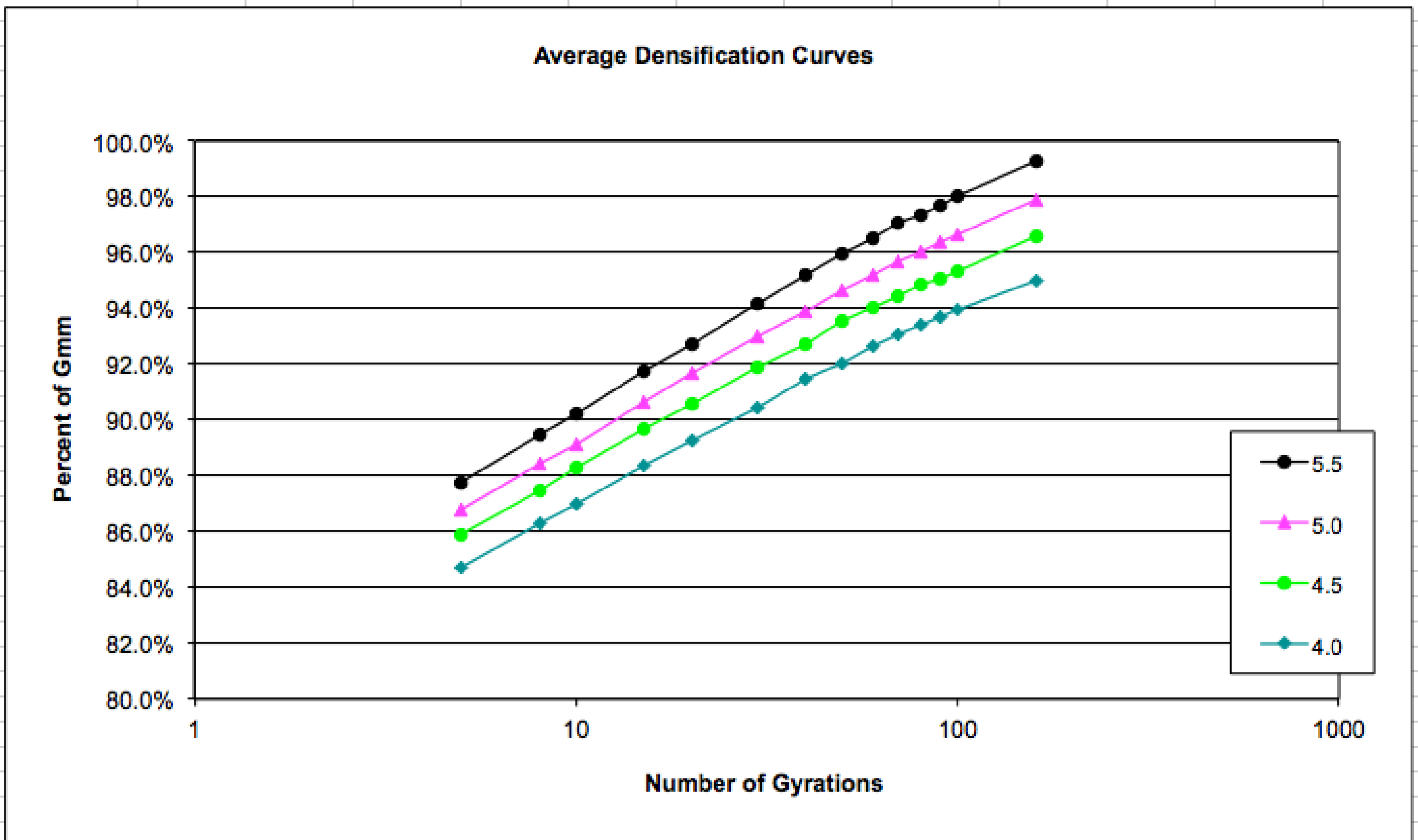
INTERLAKEN TECHNOLOGY CORPORATION PAGE 1

GYRATORY COMPACTION TEST

TEST ID : 037D6.3B ANGLE : 1.25
FILE : BAE01893.gyr PRESSURE : 600.0
START DATE : 4/14/2002
START TIME : 11:28:47
MODE : CYCLE

	0	1	2	3	4	5	6	7	8	9
0	142.9	139.2	135.6	133.4	131.7	130.4	129.2	128.3	127.6	126.8
10	126.2	125.6	125.1	124.7	124.2	123.8	123.5	123.1	122.8	122.5
20	122.3	122.0	121.8	121.6	121.3	121.1	120.9	120.7	120.6	120.4
30	120.2	120.0	119.9	119.7	119.6	119.4	119.3	119.2	119.0	118.9
40	118.8	118.7	118.5	118.4	118.3	118.2	118.1	118.0	117.9	117.8
50	117.7	117.7	117.6	117.5	117.4	117.3	117.3	117.2	117.1	117.0
60	116.9	116.9	116.8	116.7	116.7	116.6	116.5	116.5	116.4	116.3
70	116.3	116.2	116.2	116.1	116.0	116.0	115.9	115.9	115.8	115.7
80	115.7	115.7	115.6	115.6	115.5	115.5	115.4	115.4	115.3	115.3
90	115.2	115.2	115.2	115.1	115.1	115.0	115.0	115.0	114.9	114.9
100	114.9	114.8	114.7	114.7	114.7	114.6	114.6	114.6	114.5	114.5
110	114.5	114.4	114.4	114.4	114.4	114.3	114.3	114.2	114.2	114.2
120	114.2	114.1	114.1	114.1	114.1	114.0	114.0	114.0	113.9	113.9
130	113.9	113.8	113.8	113.8	113.8	113.7	113.7	113.7	113.7	113.6
140	113.6	113.6	113.6	113.5	113.5	113.5	113.5	113.5	113.4	113.4
150	113.4	113.4	113.3	113.3	113.3	113.3	113.2	113.2	113.2	113.2
160	113.2									

MIX TEST DATA – GYRATORY



MIX DESIGN DATA REVIEW

- Recap Page
- Volumetric Property Table
- Property Curves
- Strength – Stability
- Flexibility – Flow

MIX DESIGN DATA – RECAP PAGE

COMPOSITE GRADATION

MATERIAL I.D.		% USED WITHOUT ADMIX	% USED WITH ADMIX
WASHED	CR. FINES	32.0	31.7
CRUSHED	SAND	25.0	24.8
3/8-INCH	CRUSHED	8.0	7.9
1/2-INCH	CRUSHED	15.0	14.9
3/4-INCH	CRUSHED	20.0	19.8
		0.0	0.0
ADMIX			0.99

SIEVE US/mm	W/O ADMIX % PASSING	W/ADMIX % PASSING	SPEC. LIMITS w/o Admix	SPEC. LIMITS w/ Admix	PRODUCTION LIMITS
1¼"	100	100			
1"	100	100	100	100	100
3/4"	98	98	90-100	90-100	
1/2"	80	81			
3/8"	68	68	62-77	62-77	62 - 74
1/4"	61	61			
#4	57	58			
#8	40	41	37-46	38-47	35 - 47
#10	38	38			
#16	28	29			
#30	19	20			
#40	15	16	10-18	11-19	11 - 21
#50	12	12			
#100	7	8			
#200	3.9	4.9	1.5-4.5	2.5-6.0	2.9 - 6.9

DESIGN DATA

SPECIMEN ID	1	2	7	3	MIX DESIGN CRITERIA
BLENDED BINDER EQUIV. GRADE/SP GR	PG 76-1(	1.0330			
% OF BITUMEN	4.0	4.5	**4.6**	5.0	
MARSHALL BULK DENSITY (lb/ft^3)	141.1	142.8	**143.1**	144.4	
MARSHALL STABILITY (lb.)	5110	5270	**5174**	4790	2000 min.
MARSHALL FLOW (.01 in.)	12	11	**11**	12	8 - 16
% AIR VOIDS	7.7	5.9	**5.6**	4.2	5.3 - 5.7
% VMA	15.6	15.1	**15.0**	14.6	15.0 - 18.0
% AIR VOIDS FILLED	50.8	60.8	**62.8**	71.2	
% EFF ASP TOTAL MIX	3.63	4.13	**4.23**	4.63	
DUST/BITUMEN RATIO	1.35	1.19	**1.16**	1.06	0.6 - 1.2

IMMERSION COMPRESSION - Ariz 802

SET I.D.	AIR PSI	H2O PSI	RETAINED STRENGTH	PERCENT ASPHALT	PERCENT ADMIX
NO.1	582.7	489.3	84%	4.6	1.00
NO.2					
Specification		150 min.	60 min.		

RECOMMENDED TOTAL BINDER CONTENT (%) = 4.60 *

(* by weight of total mix)

MIX DESIGN DATA-VOLUMETRIC PROPERTIES

AGGREGATE SPECIFIC GRAVITY DATA

MATERIAL *% USED*	*CA* *42.7*	*FA* *57.3*	COMB. VIRGIN AGGR.	*RAP 1*	*RAP 2*	*ADMIX* *1.0*	*COMB* *SP GR*
BULK OD	2.587	2.578	2.582			2.200	2.578
SSD	2.622	2.615	2.618	N/A		2.200	2.613
APPARENT	2.683	2.676	2.679	N/A		2.200	2.673
ABSORPTION	1.382	1.420	1.404			N/A	1.387

MAXIMUM THEORETICAL SPECIFIC GRAVITY OF BITUMINOUS MIXTURES

SAMPLE I.D.	*SAMPLE WT. (DRY)*	*FLASK + H_2O*	*SAMPLE + FLASK + H_2O*	*SAMPLE WT. (S.S.D.)*	*SAMPLE VOLUME*	*MAXIMUM SP. GR.*	*MAXIMUM DENSITY*
1	1073.8	3497.8	4123.0	1075.1	449.9	2.387	148.7
2	1074.2	3473.3	4098.4	1076.0	450.9	2.382	148.4
3	1069.5	3608.7	4232.2	1071.6	448.1	2.387	148.7
AVERAGE	*1072.5*	*3217.5*				*2.385*	*148.6*

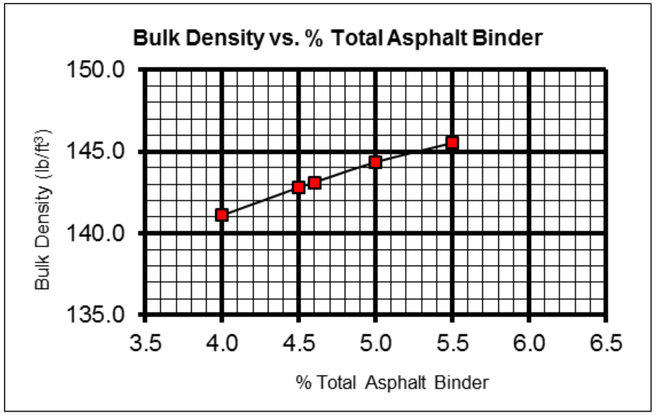
PHYSICAL PROPERTIES

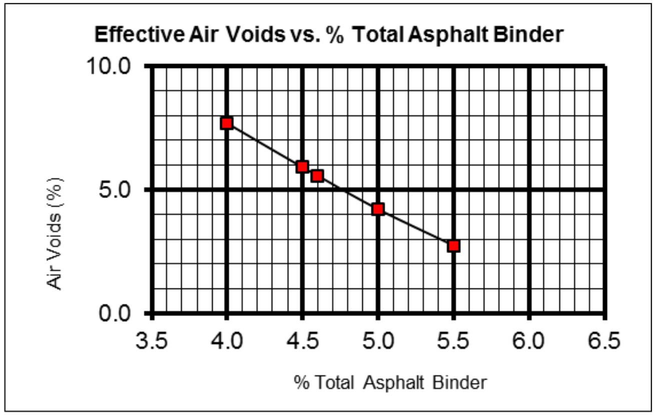
MAX SP GR	*MAX DENSITY*	*PERCENT ASPHALT*	*ASPHALT SP GR*	*EFFECTIVE SP GR*	*ASPHALT ABSORP.*	*ADMIX SP GR*
2.385	148.6	6.0	1.0330	2.603	0.389	2.20

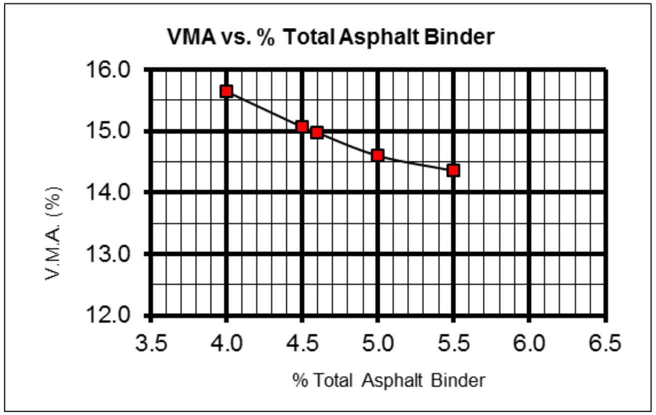
VOLUMETRIC CALCULATIONS

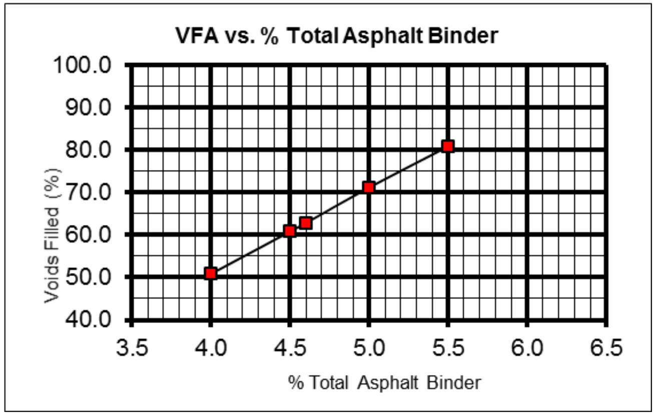
PERCENT ASPHALT	*SPECIFIC GRAVITY*	*BULK DENSITY*	*MAXIMUM SP GR*	*EFFECTIVE ASPHALT*	*VMA*	*AIR VOIDS*	*VOIDS FILLED*	*DUST/BIT RATIO*	*STABILITY*	*FLOW*
4.0	2.265	141.1	2.454	3.627	15.642	7.689	50.841	1.35	5110	12
4.5	2.292	142.8	2.436	4.129	15.068	5.905	60.808	1.19	5270	11
5.0	2.317	144.4	2.419	4.631	14.598	4.211	71.155	1.06	4790	11.7
5.5	2.336	145.5	2.402	5.133	14.354	2.747	80.864	0.96	4380	12.3
4.7	2.302	143.4	2.429	4.330	14.879	5.229	64.854	1.13	5078	11
4.6	**2.297**	**143.1**	**2.433**	**4.229**	**14.973**	**5.568**	**62.816**	**1.16**	**5174**	**11**

MIX DESIGN DATA – PROPERTY CURVES

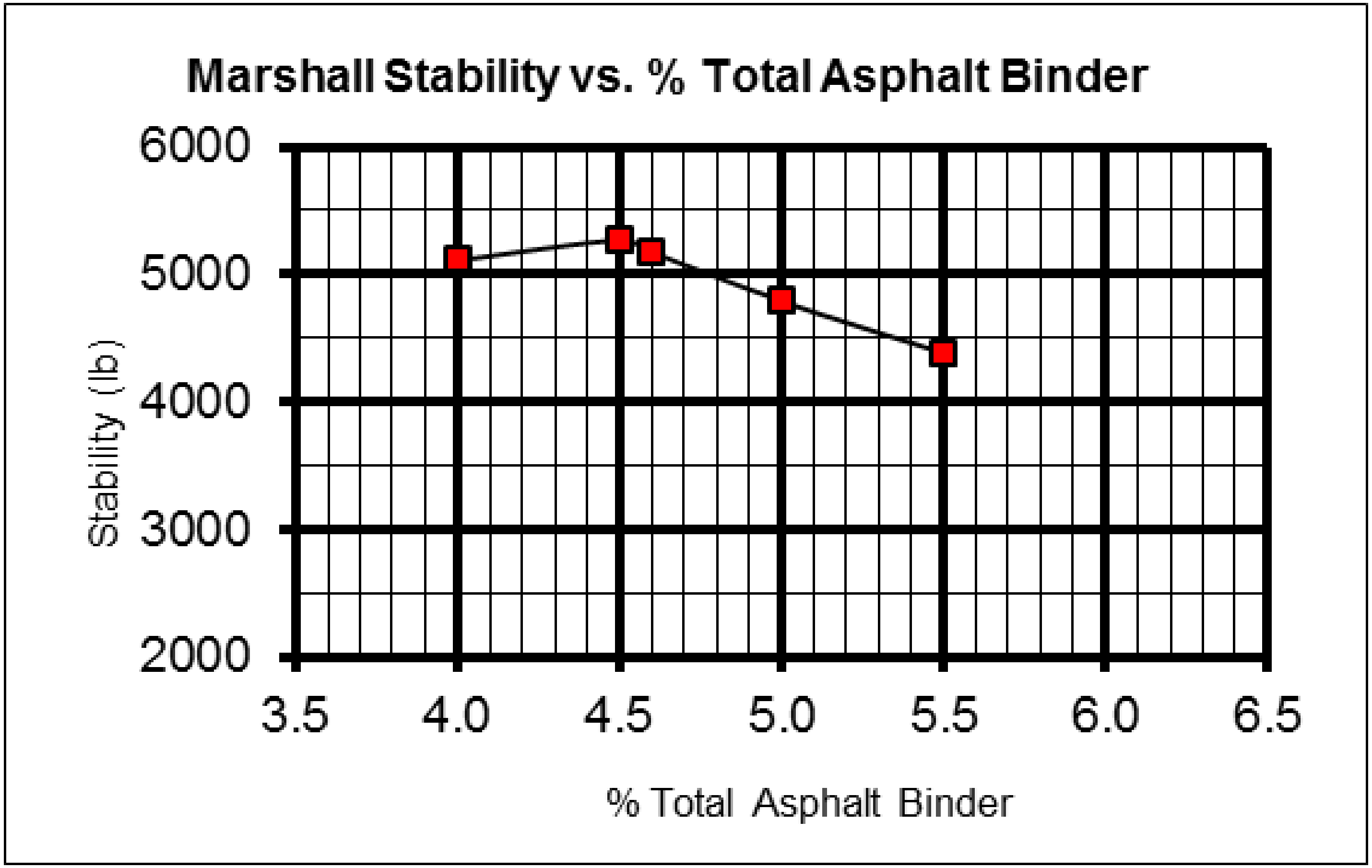




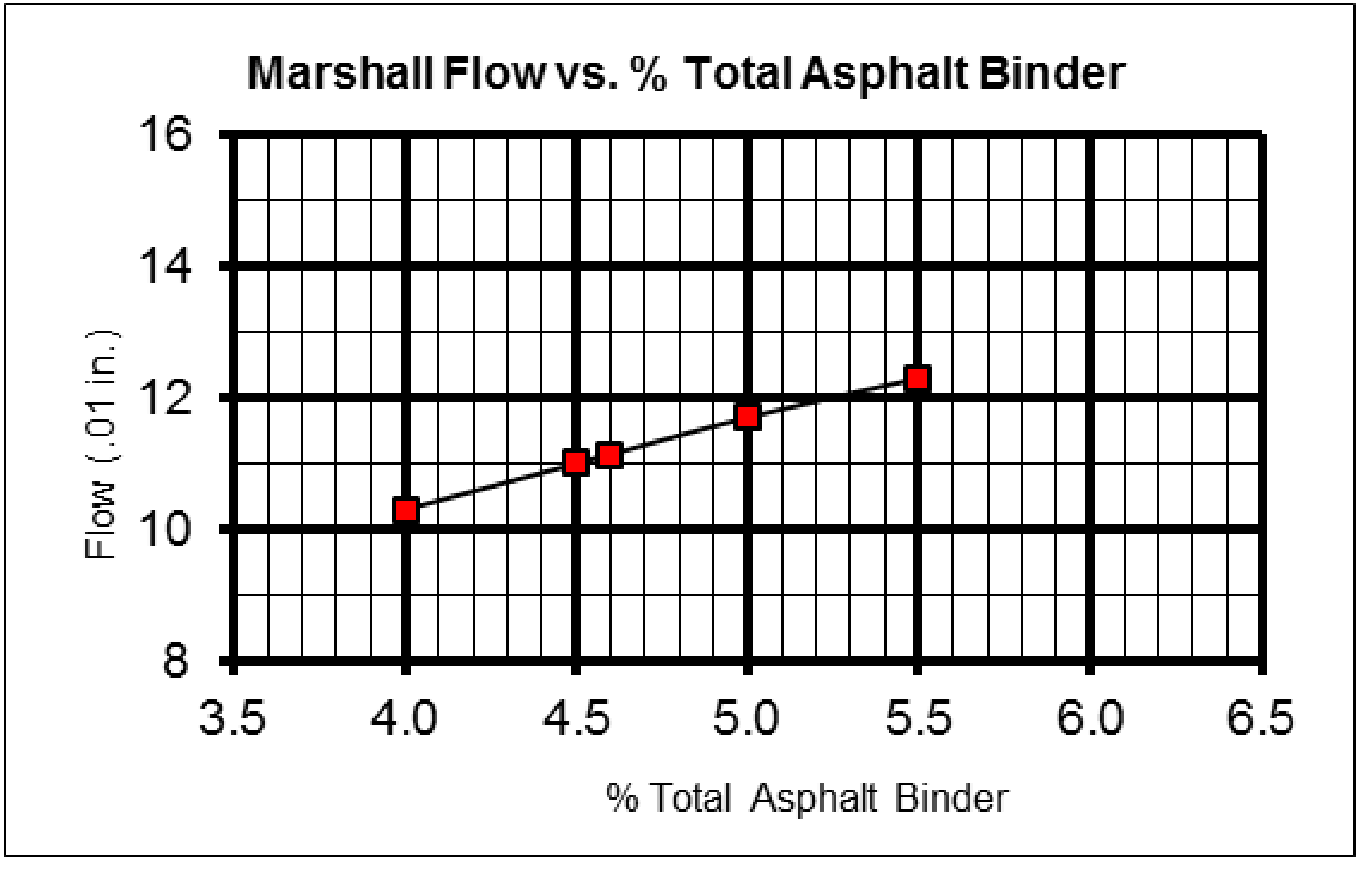




MIX DESIGN DATA-STRENGTH/STABILITY



MIX DESIGN DATA – FLEXIBILITY/FLOW



FIELD VOLUMETRIC PROPERTIES

- Nationally, it appears that the typical recommendation for in-place air voids is 8.0% maximum or 92.0% of Rice value.
- ADOT's acceptable range is 3.5% to 9.0% in-place air voids using a percent within limits (PWL) statistical acceptance method.
- The MAG Specifications allow a maximum of 8.0% in-place air voids for full payment (threshold specification); then penalties for up to 10.0% in-place air voids.
- In-place air voids in excess of 10% usually indicate an interconnected void system allowing moisture infiltration and premature oxidation throughout the pavement.
- An approximate rule of thumb, is that for every 1% that the in-place air voids exceed 7-8%, there will be a 10% or greater reduction in pavement life. Based on numerous studies of dense graded mixes, in-place air voids between 3 and 8 percent generally produce the best compromise of pavement strength, fatigue life, durability, raveling, rutting and moisture damage susceptibility.

FIELD VOLUMETRIC PROPERTIES

- Percent of Marshall – Indirect
  - If Marshall air voids = 4.0% and compaction is 95% of Marshall, then percent of Rice = 91.2% or 8.8% in-place air voids.
  - However, if Marshall air voids = 8.0% and compaction is 90.0% of Marshall, then percent of Rice is 82.8% or 17.2% in-place air voids.

FIELD VOLUMETRIC PROPERTIES

- Percent In-place Air Voids (Percent of Rice) – More Direct
  - The Rice test is a more precise, repeatable test than the Marshall test and uses larger, more representative sample.
  - Rice value can be used regardless of mix and final result is directly comparable between mixes or pavements.

SUMMARY AND CONCLUSIONS

- Mixture volumetric properties are important to the long-term performance and durability of a pavement.
- Minor deviations in gradation and/or asphalt binder content can usually be tolerated if the required volumetric properties are met.
- The number one contributing factor to pavement performance is the in-place volumetric properties. Reduction of the in-place air voids below 8.0% will result in significantly improved fatigue life, moisture resistance, and raveling resistance.
- Questions?