A New Concept of Aggregate Gradation and Mix Design for Asphalt Mixture

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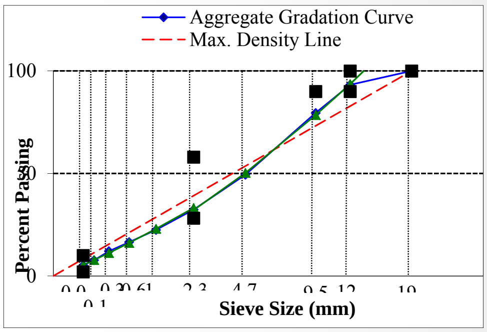
Contents

- **Introduction**
- **Concept of New Design Method**
  - Material selection
  - Volumetric design (Gradation and binder content design)
  - Evaluation of moisture susceptibility
- **Design Examples**
- **Summary Remarks**

Superpave Gradation & Mix Design

- "Trial-and-error" method for gradation design based only on control points
- Achieving volumetric criteria are not always easy especially for new mix types and material sources
- No ways to adjust optimum asphalt content
- Designer may have little knowledge about the expected performance of the design
- No mechanical properties investigated in the Superpave mix design approach (except moisture susceptibility)



Other Gradation Design Methods

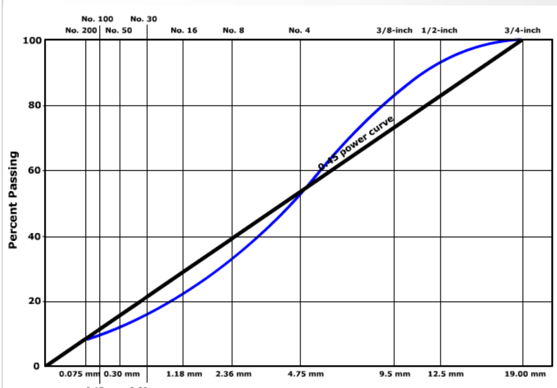
- Power Law method
- Bailey method
- NCHRP 9-33 recommendations

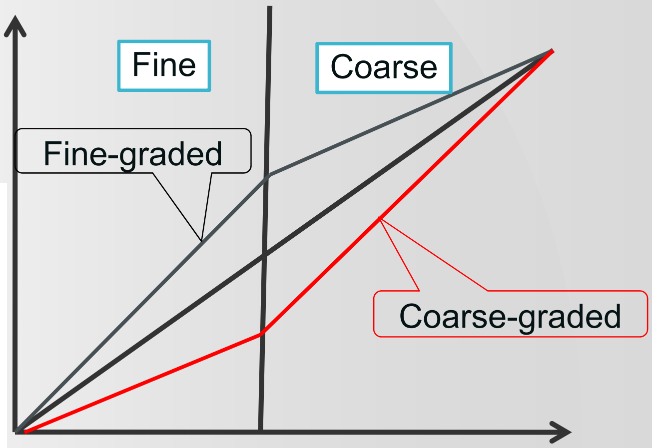
Power Law Methods

Coarse-graded: n_{FA}<0.45, and n_{CA}>0.45

Fine-graded: n_{FA}>0.45, n_{CA}<0.45

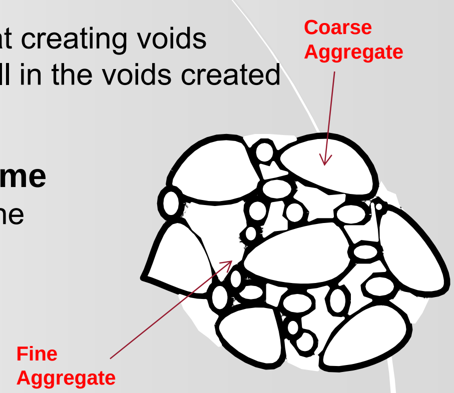
$$P_{FA} = a_{FA} d^{n_{FA}} \quad P_{CA} = a_{CA} d^{n_{CA}}$$





Bailey Method

- New definitions of coarse and fine aggregates
  - Use Primary control sieve (PCS), secondary control sieve (SCS), etc. to define aggregates
    - Coarse aggregates --- aggregates that creating voids
    - Fine aggregates --- aggregates that fill in the voids created by coarse aggregates
- Evaluate aggregate interlock by volume
  - Chosen Unit Weight ≈ 95% to 105% of the Loose Unit Weight
- Analysis of design blend
  - CA ratio, FAc ratio, FAf ratio



Gradation ? Performance

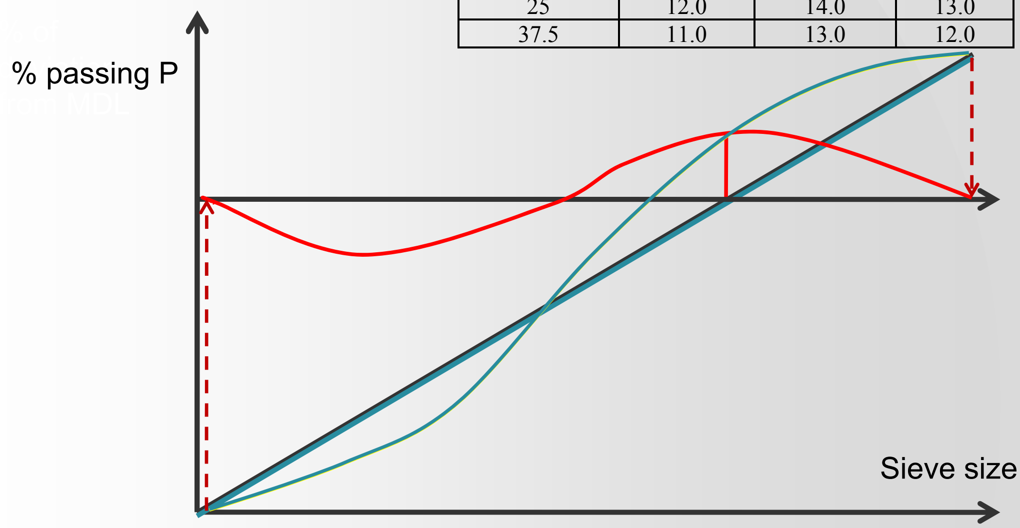
NCHRP 9-33 Recommendations for VMA

Continuous Maximum Density (CMD) plot

$P_d(d)=P(d)- P_{Dens.}$

VMA Requirements of NCHRP 9-33

Aggregate NMAS (mm)	Minimum VMA (%)	Maximum VMA (%)	Target VMA (%)
4.75	16.0	18.0	17.0
9.5	15.0	17.0	16.0
12.5	14.0	16.0	15.0
19	13.0	15.0	14.0
25	12.0	14.0	13.0
37.5	11.0	13.0	12.0



Objectives

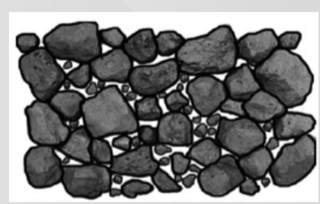
- **Objectives for this study**
  - Propose a new gradation and mix design concept based on packing to
    - Achieve volumetric properties easily
    - Estimate binder content and mechanical properties (E*) at the early stage of mix design
- **Ultimate goal**
  - Develop functional asphalt mixtures for optimized particle interlocking, cost, and performance

Contents

- Introduction
- **Concept of New Design Method**
- Design Examples
- Conclusion and Future Work

Concept of New Design Method

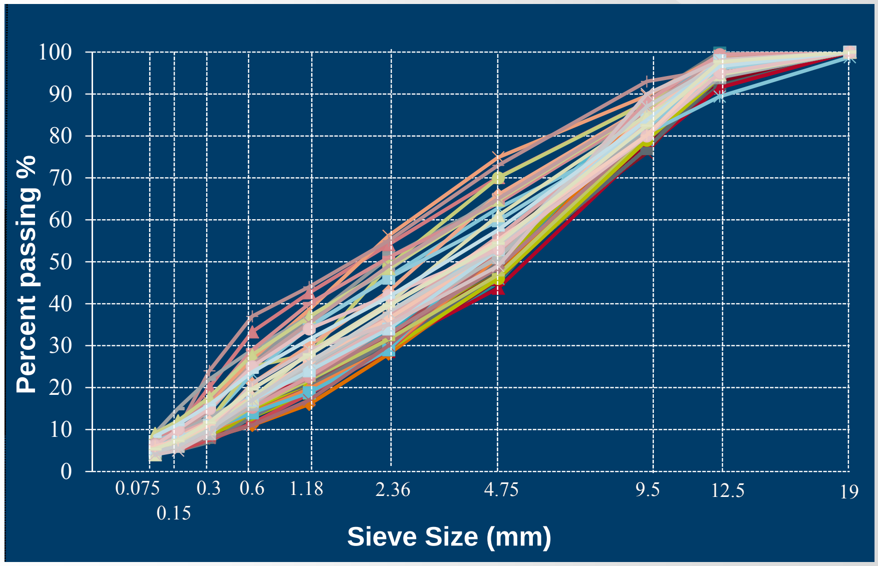
- **Selecting gradation based on VMA and Packing**
  - Gradation type classification
  - VMA prediction



- **Estimating design asphalt content**
- **Evaluating the mechanical properties (E*) of the mixture**

Gradation → AC Content → Mixture

Aggregate Gradation Classification

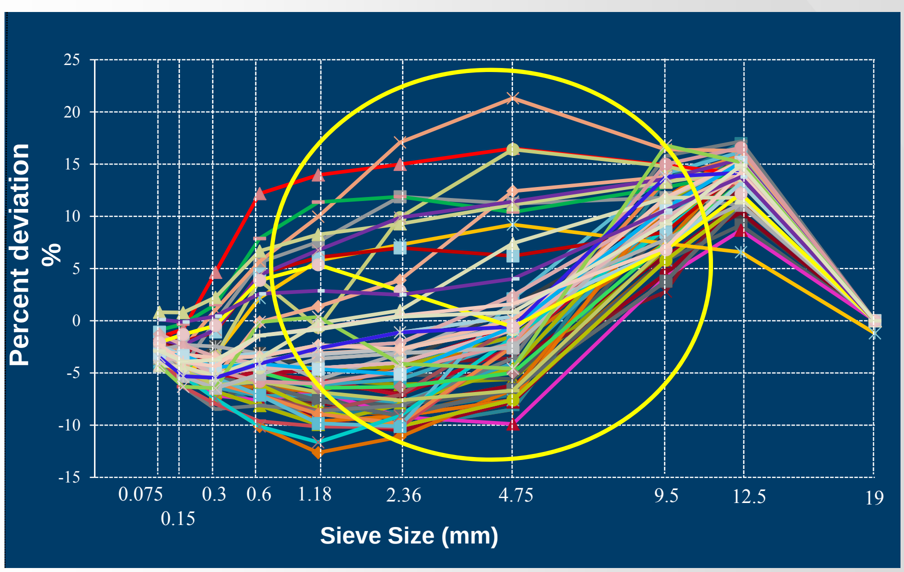


107 aggregate gradations including mix designs from Washington, Illinois, Alabama, Wisconsin, and Michigan State

Aggregate Gradation Classification

Continuous Maximum Density (CMD) plot from NCHRP 9-33 (2009)

$P_d(d)=P(d)- P_{Dens.}$



Aggregate Gradation Classification

Separate aggregates into coarse-graded, medium-graded, and fine-graded for similar volumetric properties and performance

$P_d(d)=P(d)- P_{Dens.}$

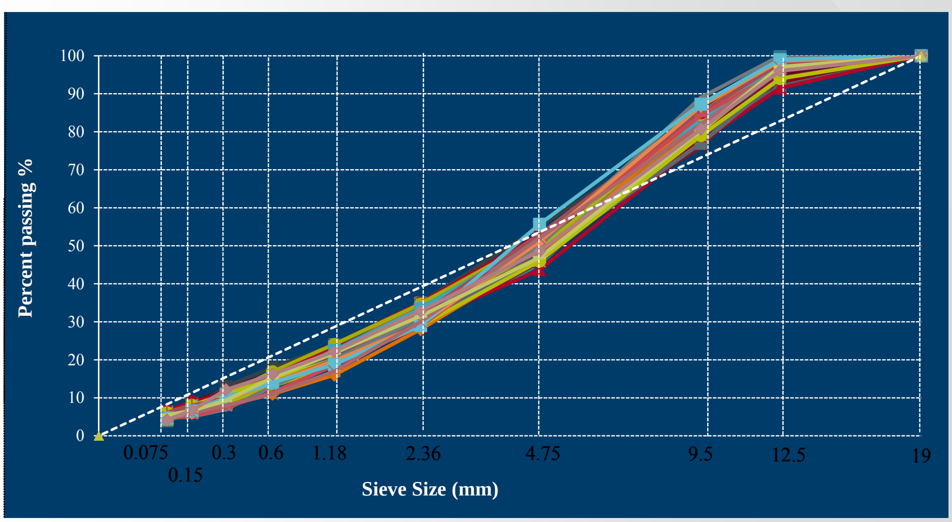
$$P_{dc} = \sum_{i=1}^{n} P_d(d_i)$$

$$P_{dc} = P_d(9.5) + P_d(4.75) + P_d(2.36) + P_d(1.18)$$

P_{dc}	Gradation type
$P_{dc} \leq 0$	coarse-graded
$0 < P_{dc} \leq 20$	medium-graded
$P_{dc} > 20$	fine-graded

Aggregate Gradation Classification

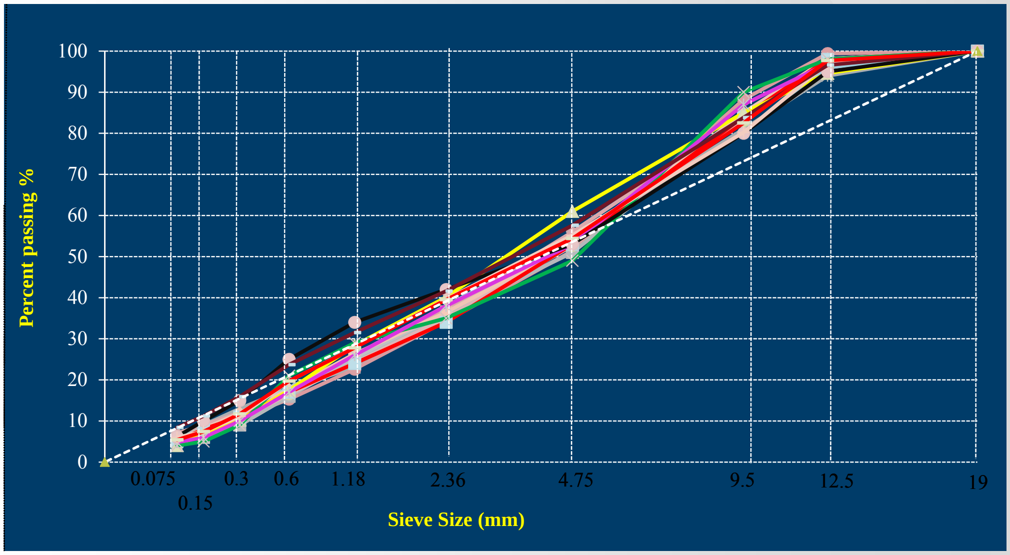
Plot of coarse-graded gradations



Part 1. Gradation design based on VMA

Aggregate Gradation Classification

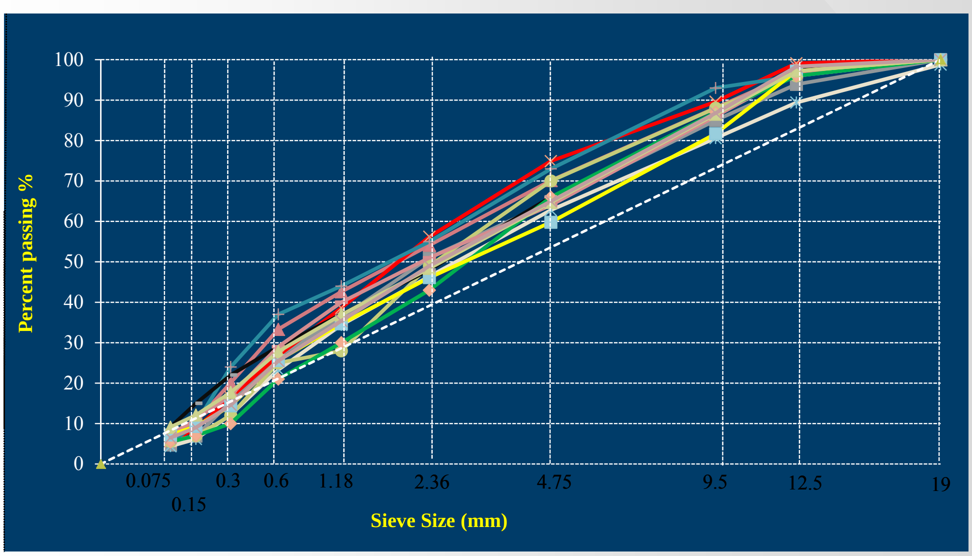
Plot of medium-graded gradations



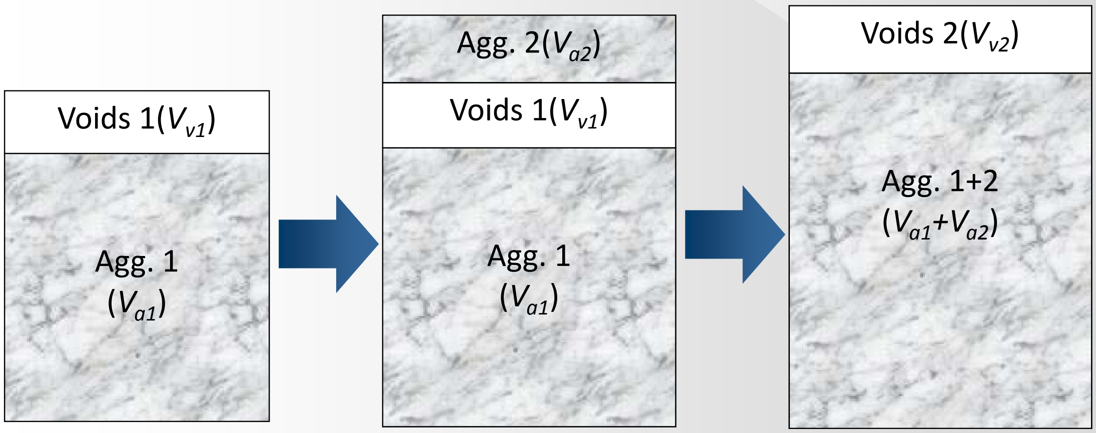
Part 1. Gradation design based on VMA

Aggregate Gradation Classification

Plot of fine-graded gradations



Analysis of Packing and VMA Prediction



$V_1 = V_{a1} + V_{v1}$
$p_1 = V_{v1}/V_1 = (V_1 - V_{a1})/V_1$
$V_1 = V_{a1}/(1-p_1)$

$$f_v = \frac{V_{v2} - V_{v1}}{V_{a2}} \qquad V_{v1} = V_1 p_1 \qquad V_{v2} = V_2 p_2$$

fv: **percent of voids change by volume due to the addition of unit aggregate**

Analysis of Packing and VMA Prediction

Derivation of VMA prediction equations

- Determine mixture's porosity when new aggregates are added in

$$p_2 = \frac{V_{v2}}{V_2} = \frac{f_v V_{a2} + V_{v1}}{V_1 + (1 + f_v) V_{a2}}$$

- Predict the VMA (or porosity) of the HMA mixtures

$$p = \frac{\sum_{i=1}^{n} f_{vi} V_{ai}}{\sum_{i=1}^{n} (1 + f_{vi}) V_{ai}}$$

Where f_{vi} is the f_v value for *i*th sieve size of the gradation, V_{ai} is the percentage by volume of aggregate retained in the *i*th sieve size, and p is the porosity or VMA of the aggregate structure.

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Analysis of Packing and VMA Prediction

❑ Relation between Aggregate Gradation and VMA

➢ Two methods to determinate fv values

- Data regression

$$p = \frac{\sum_{i=1}^{n} f_{vi} V_{ai}}{\sum_{i=1}^{n} (1 + f_{vi}) V_{ai}}$$

- Discrete Element Modeling (DEM) simulation

$$f_v = \frac{V_{v2} - V_{v1}}{V_{a2}}$$

Sieve size	Data Regression	DEM Simulation result
	f_v	f_v
19	0.411	0.429
12.5	0.411	0.429
9.5	0.411	0.429
4.75	0.410	0.429
2.36	0.169	0.196
1.18	-0.366	-0.400
0.6	-0.366	-0.400
0.3	-0.366	-0.420
0.15	-0.536	-0.600
0.075	-0.952	-1.000

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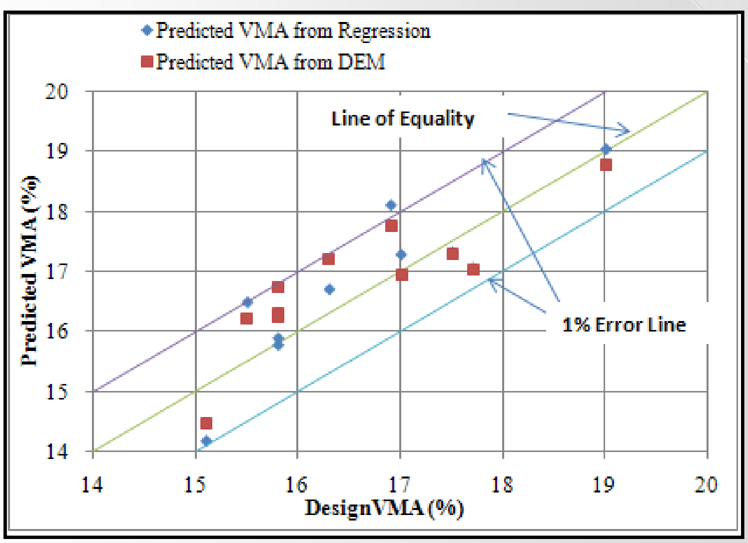
Analysis of Packing and VMA Prediction

❑ Verification of the VMA prediction method

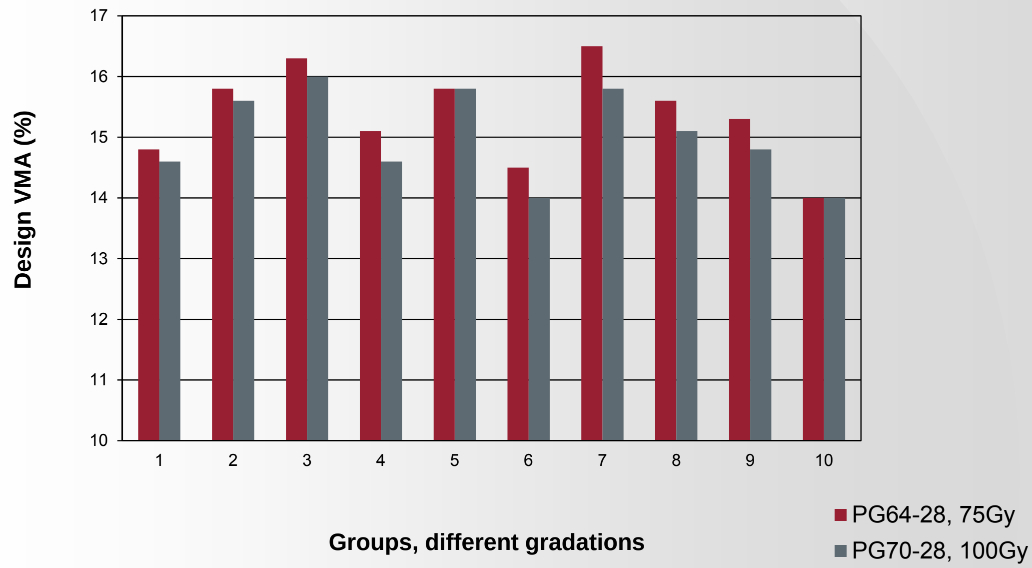


- Mix designs from Washington, Michigan, and Alabama’s NCAT Test Track

Part 1. Gradation design based on VMA

Analysis of Packing and VMA Prediction

Effect of Gradation, binder type, and compaction level on VMA



Part 2. AC content determination

Asphalt Content Estimation

Total volume (100%) – VMA = design air voids (4%) + Effective AC

Effective AC + Absorbed AC = Design AC

VFA=100*(1-Va/VMA)

$$P_{be} = \frac{(VMA - Va) \times G_b \times 100}{(100 - VMA)G_{sb} + (VMA - Va)G_b}$$

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

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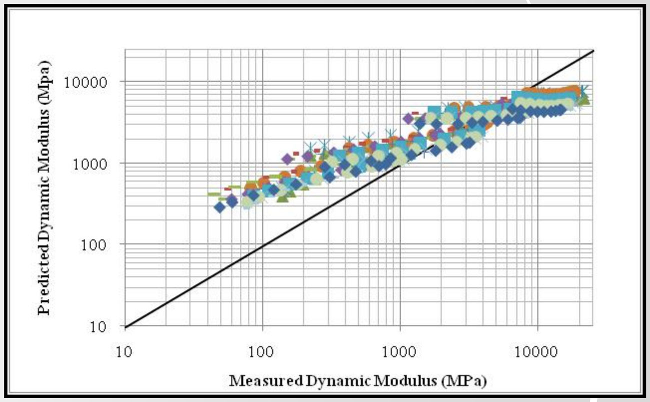
Mechanical Property Estimation

Dynamic Modulus

Witczak Model (old)

$$\log|E^*| = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a$$
$$-0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}}$$

IE*I = viscosity, 1dynamic modulus, psi
η= bitumen 06 Poise
f = loading frequency, Hz
Va = air void content, %
Vbeff = effective bitumen content, % by volume
ρ34 = cumulative % retained on the 19-mm (3/4) sieve
ρ38 = cumulative % retained on the 9.5-mm (3/8) sieve
ρ4 = cumulative % retained on the 4.76-mm (No. 4) sieve
ρ200 = % passing the 0.075-mm (No. 200) sieve



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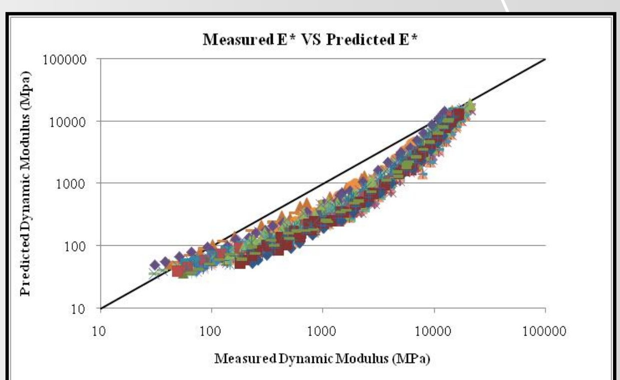
Mechanical Property Estimation

Dynamic Modulus

Witczak Model (New)

$$\log_{10} E^* = -0.349 + 0.754\left(|G_b^*|^{-0.0052}\right)$$
$$\times\begin{pmatrix} 6.65 - 0.032\rho_{200} + 0.0027\rho_{200}^2 + 0.011\rho_4 - 0.0001\rho_4^2 \\ + 0.006\rho_{38} - 0.00014\rho_{38}^2 - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_a+V_{beff}}\right)\end{pmatrix}$$
$$+\frac{2.56 + 0.03V_a + 0.71\left(\frac{V_{beff}}{V_a+V_{beff}}\right) + 0.012\rho_{38} - 0.0001\rho_{38}^2 - 0.01\rho_{34}}{1+e^{(-0.7814-0.5785\log|G_b^*|+0.8834\log\delta_b)}}$$

IE*I = dynamic modulus, psi
|Gb*| = dynamic shear modulus of binder, psi
Va = air void content, %
Vbeff = effective bitumen content, % by volume
ρ34 = cumulative % retained on the 19.5-mm (3/4") sieve
ρ38 = cumulative % retained on the 9.5-mm (3/8") sieve
ρ4 = cumulative % retained on the 4.76-mm (No. 4) sieve
ρ200 = % passing the 0.075-mm (No. 200) sieve
δb = phase angle of binder associated with |Gb*|, degree



Mechanical Property Estimation

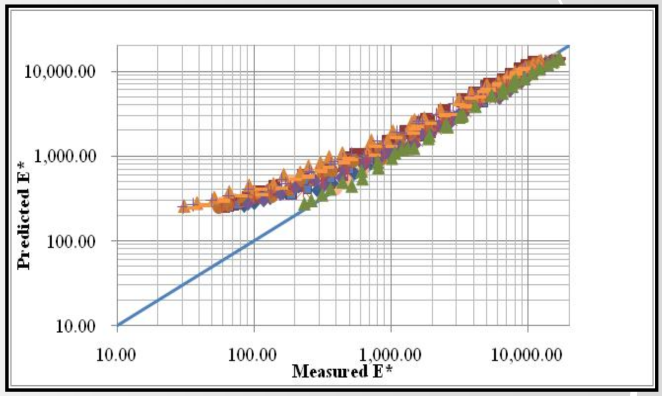
Dynamic Modulus

- Hirsch model

$$|E^*| = Pc\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G^*|_{binder}\left(\frac{VFA\cdot VMA}{10{,}000}\right)\right]+(1-Pc)\left[\frac{1-\frac{VMA}{100}}{4{,}200{,}000}+\frac{VMA}{VFA\cdot 3|G^*|_{binder}}\right]^{-1}$$

$$Pc = \frac{\left(20+\frac{VFA\cdot 3|G^*|_{binder}}{VMA}\right)^{0.58}}{650+\left(\frac{VFA\cdot 3|G^*|_{binder}}{VMA}\right)^{0.58}}$$

IE*I = dynamic modulus, psi
IG*Ibinder = binder dynamic modulus, psi
VMA= voids in the mineral aggregate, %
VFA = voids filled with asphalt, %
Pc = aggregate contact factor



Mechanical Property Estimation

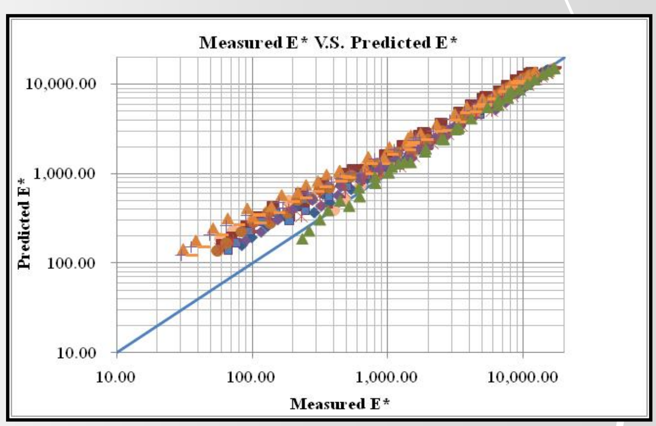
Dynamic Modulus

- Hirsch model (Calibrated by Asphalt Binder)

$$|E^*| = Pc\left[4800000\left(1-\frac{VMA}{100}\right)+3|G_b^*|\left(\frac{VFA\cdot VMA}{10{,}000}\right)\right]$$
$$+(1-Pc)\left[\frac{1-\frac{VMA}{100}}{4800000}+\frac{VMA}{VFA\cdot 3|G_b^*|}\right]^{-1}$$

$$Pc = \frac{\left(0.2+\frac{VFA\cdot 3|G_b^*|}{VMA}\right)^{0.56}}{600+\left(\frac{VFA\cdot 3|G_b^*|}{VMA}\right)^{0.56}}$$

IE*I = dynamic modulus, psi
IG*Ibinder = binder dynamic modulus, psi
VMA= voids in the mineral aggregate, %
VFA = voids filled with asphalt, %
Pc = aggregate contact factor



Part 3. Mechanical property evaluation

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Mechanical Property Estimation

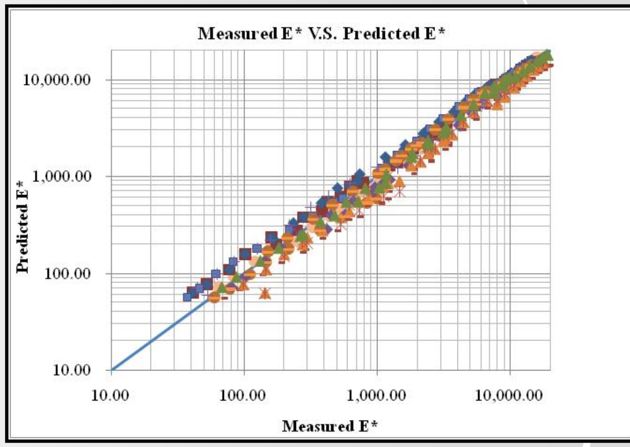
Dynamic Modulus

- **Hirsch model (Calibrated by Mastic)**

$$|E^*| = Pc\left[1.0E7\left(1-\frac{VMA}{100}\right)+3|G_m^*|\left(\frac{VFA\times VMA}{10{,}000}\right)\right]+(1-Pc)\left[\frac{1-\frac{VMA}{100}}{1.0E7}+\frac{VMA}{3VFA|G_m^*|}\right]^{-1}$$

$$Pc=\frac{\left(20+\frac{VFA\cdot 3|G_m^*|}{VMA}\right)^{0.67}}{10{,}000+\left(\frac{VFA\cdot 3|G_m^*|}{VMA}\right)^{0.67}}$$

IE*I = dynamic modulus, psi
IG*mI = mastic dynamic modulus, psi
VMA= voids in the mineral aggregate, %
VFA = voids filled with asphalt, %
Pc = aggregate contact factor



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- **Design Example**
- Conclusion and Future Work

Asphalt Mixture Design Example

- **Based on Volumetrics and Packing**
  - Step 1: Selection of a Trial Gradation
  - Step 2: Selection/Identification of a Design Gradation Type
  - Step 3: Gradation Adjustment Based on Estimated VMA
  - Step 4: Estimation of Design Binder Content
  - Step 5: Dynamic Modulus Prediction
  - Step 6: Mix Design Verification

Asphalt Mixture Design Example

- **Step 1: Selection of a Trial Gradation**
  - Should satisfy Superpave Control Points

Trial

	Stockpile X		Stockpile Y		Stockpile Z		Combined gradation
Sieve Size(mm)	% Passing	Proportion 30%	% Passing	Proportion 50%	% Passing	Proportion 20%	% Passing
19	100	30	100	50	100	20	100
12.5	99	29.7	100	50	98	19.6	96
9.5	60	18	98	49	90	18	85
4.75	2.8	0.8	62	31	66	13.2	45
2.36	1.8	0.5	38	19	48	9.6	29
1.18	1.6	0.5	24	12	33	6.6	19
0.6	1.5	0.5	17	8.5	23	4.6	14
0.3	1.4	0.4	12	6	16	3.2	10
0.15	1.3	0.4	9	4.5	12	2.4	7
0.075	1.1	0.3	6.9	3.5	9.8	2	5.8

Asphalt Mixture Design Example

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Step 2: Selection/Identification of Design Gradation Type

$$P_{Dens.} = \left(\frac{d}{D_{max}}\right)^{0.45} \times 100\%$$

$$P_d(d) = P(d) - P_{Dens.}$$

P_{dc}	Gradation type
$P_{dc} \le 0$	coarse-graded
$0 < P_{dc} \le 20$	medium-graded
$P_{dc} > 20$	fine-graded

$$P_{dc} = P_d(9.5) + P_d(4.75) + P_d(2.36) + P_d(1.18)$$

Sieve size	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
P(d)	100	96	***85***	***45***	***29***	***19***	14	10	7	5.9
$P_{Dens.}$	100	83	***73***	***54***	***39***	***29***	21	16	11	8.3
$P_d(d)$	0	13	***12***	***-9***	***-10***	***-10***	-7	-6	-4	-2.4
P_{dc}			***-17***							

Asphalt Mixture Design Example

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Step 3: Gradation Adjustment Based on Estimated VMA

$$p = \frac{\sum_{i=1}^{n} f_{vi} V_{ai}}{1 + \sum_{i=1}^{n} f_{vi} V_{ai}}$$

Sieve size	f_v
19	0.411
12.5	0.411
9.5	0.411
4.75	0.410
2.36	0.169
1.18	-0.366
0.6	-0.366
0.3	-0.366
0.15	-0.536
0.075	-0.952

Asphalt Mixture Design Example

❑ Step 3: Gradation Adjustment Based on Estimated VMA

VMA prediction process for initial trial blend

Sieve size(mm)	Passing(%)	Cumulative Retained(%)	Retained(%)	f_v	
A	***B***	***C***	***D***	***E***	***D*E***
19	100	0			
12.5	96	4	4	0.411	1.64
9.5	85	11	[illegible]	[illegible]	4.52
4.75	45	55	[illegible]	[illegible]	16.44
2.36	29	71	[illegible]	[illegible]	6.56
1.18	19	81	10	…169	1.69
0.6	14	86	6	…66	-1.83
0.3	10	90	4	-0.…	-1.46
0.15	7	93	2	-0.36…	-1.10
0.075	5.9	94.1	1.6	-0.536	-0.59
Pan		100.0	5.7	-0.952	-5.62
				Sum of *E*	20.3
				VMA=Sum/(100+Sum)	16.9

Out of requirement

Asphalt Mixture Design Example

❑ Step 3: Gradation Adjustment Based on Estima…

Revised

Revised gradation

	Stockpile X		Stockpile Y		Stockpile Z		…ombined gradation
Sieve Size(mm)	% Passing	Proportion 20%	% Passing	Proportion 60%	% Passing	Proportion 20%	% Passing
19	100	30	100	50	100	20	100
12.5	96	29.7	96	50	98	19.6	96
9.5	67	18	94	49	90	18	81
4.75	73	0.8	20	31	66	13.2	53
2.36	32	0.5	20	19	48	9.6	31
1.18	19	0.5	13	12	33	6.6	20
0.6	13	0.5	10	8.5	23	4.6	14
0.3	14	0.4	5	6	16	3.2	11
0.15	9	0.4	4	4.5	12	2.4	8
0.075	6.6	0.3	3.9	3.5	9.8	2	6.3

Asphalt Mixture Design Example

Step 3: Gradation Adjustment Based on Estimated VMA

VMA prediction process for revised blend

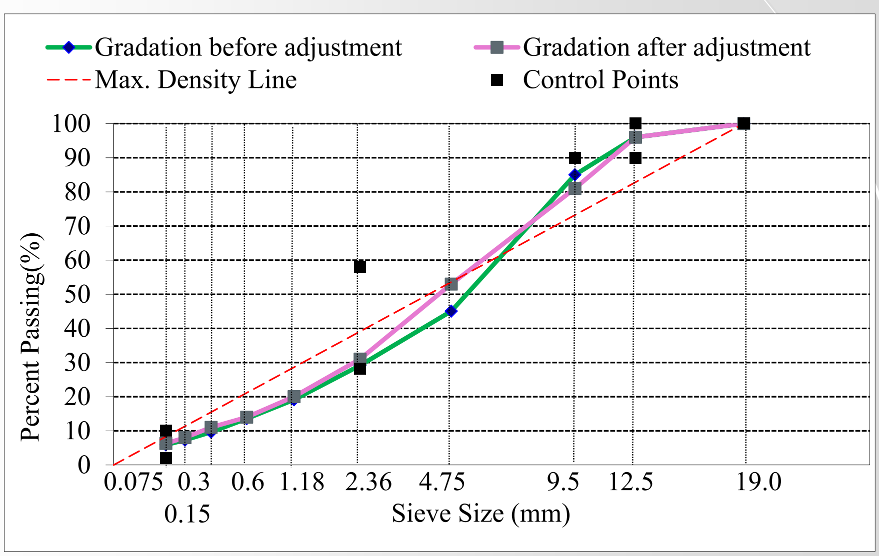
Sieve size(mm)	Passing(%)	Cumulative Retained(%)	Retained(%)	f_v	
A	***B***	***C***	***D***	***E***	***D*E***
19	100	0			
12.5	96	4	4	0.411	1.64
9.5	81	19	[illegible]	[illegible]	6.17
4.75	53	47	[illegible]	[illegible]	11.51
2.36	31	69	[illegible]	[illegible]	9.02
1.18	20	80	11	[illegible]	1.86
0.6	14	86	6	[illegible]	-2.20
0.3	11	89	3	[illegible]	-1.10
0.15	8	92	3	[illegible]	-1.10
0.075	6.3	93.7	1.7	-0.536	-0.91
Pan		100.0	6.3	-0.952	-6.00
				Sum of *E*	18.9
				Sum/(100+Sum)	15.9

Satisfy requirement

Asphalt Mixture Design Example

Step 3: Gradation Adjustment Based on Estimated VMA

Comparison of initial and revised gradations



Asphalt Mixture Design Example

- **Step 4: Estimate design binder content**

Based on the design air voids of 4%

VFA=100*(1-Va/VMA)

$$P_{be} = \frac{(VMA - Va) \times G_b \times 100}{(100 - VMA)G_{sb} + (VMA - Va)G_b}$$

$$P_{b,estimate} = P_{be} + \frac{P_{ba}}{100}(1 - P_{be})$$

Predicted VMA of 15.9%, design air voids of 4%, specific gravity of asphalt (G_b) of 1.02, and the bulk specific gravity of aggregate (G_{sb}) of 2.680

P_{be} = 4.53%

Using the asphalt absorption rate of 1% as determined from previous experiments

P_b = 4.53 + (100-4.53) *1.0%=5.48%

Asphalt Mixture Design Example

- **Step 5: Dynamic Modulus Prediction**

$$|E^*| = Pc\left[1.0E7\left(1 - \frac{VMA}{100}\right) + 3|G_m^*|\left(\frac{VFA \times VMA}{10{,}000}\right)\right] + (1 - Pc)\left[\frac{1 - \frac{VMA}{100}}{1.0E7} + \frac{VMA}{3VFA|G_m^*|}\right]^{-1}$$

$$Pc = \frac{\left(20 + \frac{VFA \cdot 3|G_m^*|}{VMA}\right)^{0.67}}{10{,}000 + \left(\frac{VFA \cdot 3|G_m^*|}{VMA}\right)^{0.67}}$$

Note:

Correct VMA to 7% air voids for E* testing, if necessary.

Recommend adding 2.5% to the originally estimated VMA (corresponding to 4% AV) to obtain the corrected VMA (7% AV) for E* specimens.

Asphalt Mixture Design Example

Step 6: Mix Design Verification

- Two gyratory specimens - design volumetrics

  Design example: two samples with 5.48% AC and 100 N_{design}

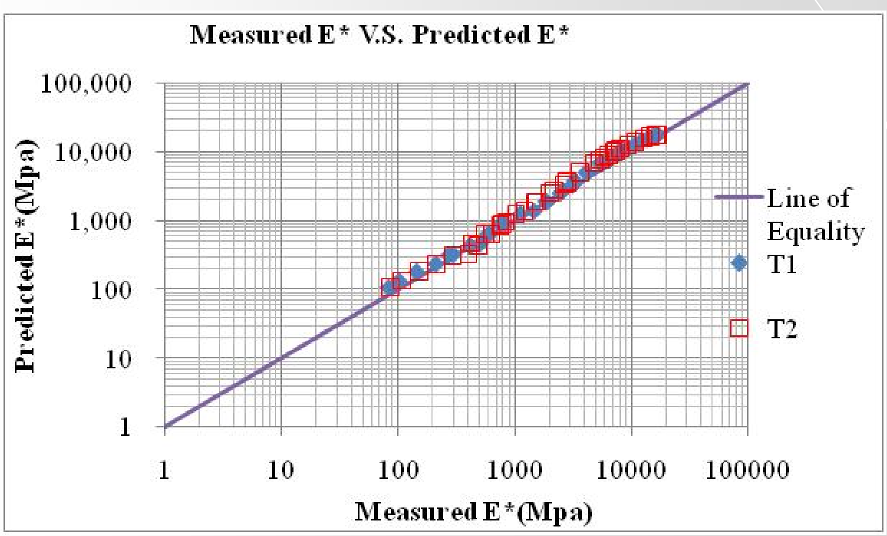
	Air Voids (%)		VMA (%)		VFA (%)	
Sample	Target	Measured	Predicted	Measured	Predicted	Measured
T-1	4.0	4.3	15.9	15.3	74.8	71.9
T-2	4.0	4.5	15.9	15.7	74.8	71.3
Target Spec	**4.0**		**>14.0**		**65-75**	

Asphalt Mixture Design Example

Step 6: Mix Design Verification

- Two gyratory specimens – dynamic modulus

  Design example: two samples with 5.48% AC to 7% air voids



Summary Remarks

- **A new aggregate and asphalt mixture design concept is developed based on packing and volumetrics, which can**
  - Characterize the gradation types quantitatively
  - Use fv values to predict VMA and estimate design AC at early stage of design
  - Determine the mechanical performance of mixture (E*) at design stage

Designers have better knowledge and understanding about the expected properties of the mix; may potentially lead to improved field performance.

Acknowledgment

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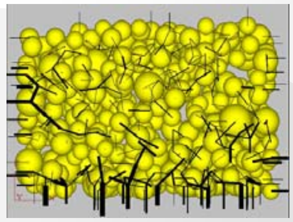

Thanks!

Questions???