Balanced Mix Design Implementation and Future of Volumetric/Performance-Based Mix Design

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Balanced Mix Design (BMD)

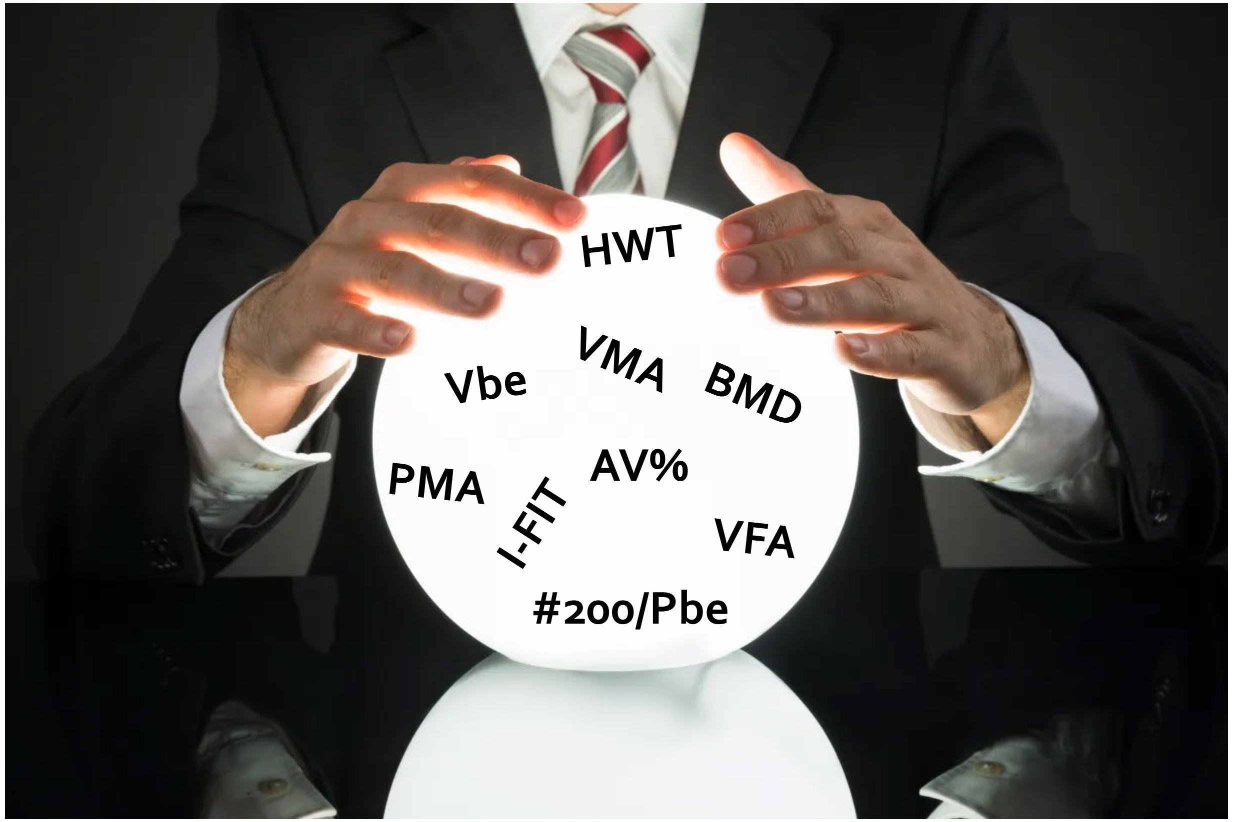
- In simple terms;
  - An asphalt mixture design method that incorporates mixture performance testing with appropriate test conditions and criteria that relate to local field performance
  - The “final” asphalt mixture is one that is optimized to perform well for rutting and cracking distress for the respective traffic, climate, and pavement condition
  - One size does not fit all!

Illinois Modified AASHTO T 324 Requirements [1/]	
PG Grade	Minimum Number of Wheel Passes
PG 58-xx (or lower)	5,000
PG 64-xx	7,500
PG 70-xx	15,000 [2/]
PG 76-xx (or higher)	20,000 [2/]

Illinois Modified AASHTO T 393		
Mixture	Short Term Aging, Minimum FI	Long Term Aging, Minimum FI [2/]
HMA [1/]	8.0	5.0 [3/]
SMA	16.0	10.0
IL-4.75	12.0	-

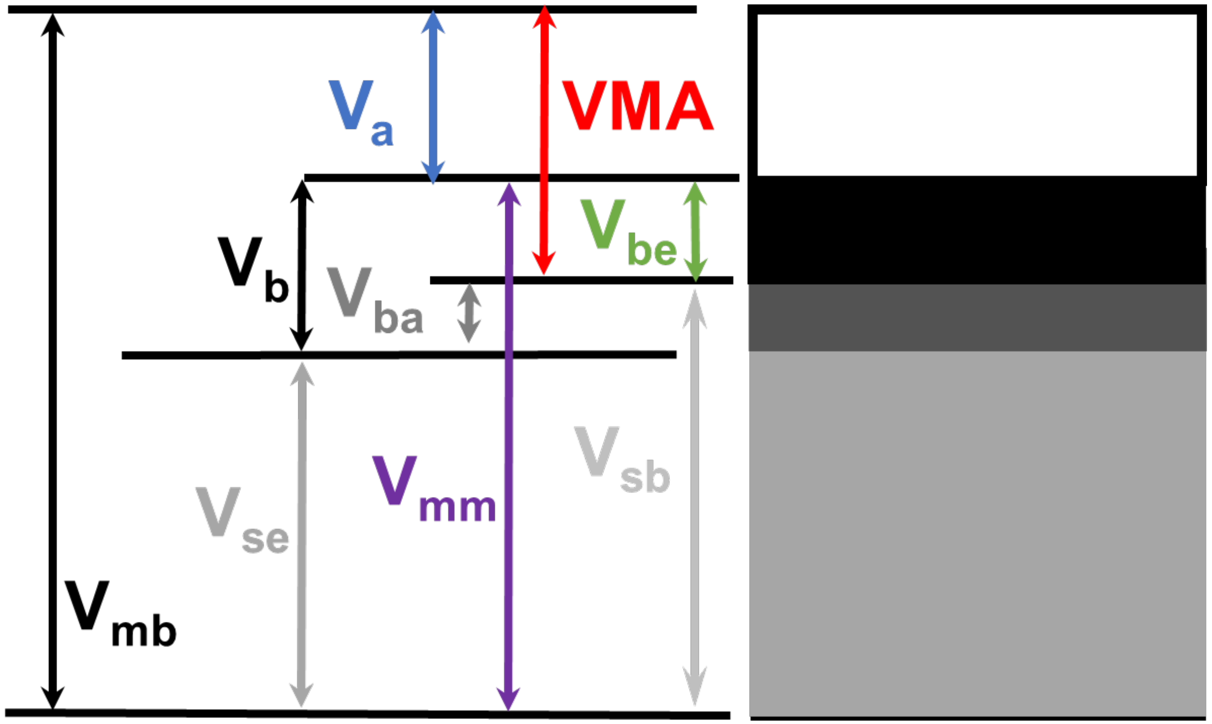
Future of Volumetric Design

- We do not want to demonize volumetrics or volumetric design
  - But we must acknowledge there are limitations due to today's materials and production practices
- The extent of future use will depend on confidence in the BMD performance tests
  - More confidence, more relaxation
  - Less confidence, less relaxation
  - Volumetrics still hold value!!



History of Volumetrics

- Concept of volumetrics can be traced back to work by Clifford Richardson (1905)
  - Concept of "relative proportions by volume"
- Bruce Marshall (1940's) designed based on volumetric percentage of air voids and degree of void saturation by asphalt
- Norman McLeod (1950's) showed importance of determining effective asphalt binder (i.e. – VMA) and highlighted importance of aggregate gravities/absorption in volumetric design
  - Grandfather of current volumetric design system



Coree (TRR No. 1681, 1999)

Volumetric Influence on Mix Performance

- By far the most influential volumetric parameter is volume of effective binder (Vbe)
  - Vbe is directly in VMA calculation and indirectly in the VFA calculation
  - Vbe "balances" mixture performance
    - Low Vbe: ↑ Rutting resistance; ↓ Cracking resistance
    - High Vbe: ↑ Cracking resistance; ↓ Rutting resistance

$$VMA = Vbe + AV$$

$$VFA = \frac{VMA - AV}{VMA} \ x\ 100$$

$$VFA = \frac{(Vbe + AV) - AV}{Vbe + AV} \ x\ 100$$

$$VFA = \frac{Vbe}{Vbe + AV} \ x\ 100$$

where,

VMA = voids in mineral aggregate, %
Vbe = effective volume of asphalt, %
AV = air voids, %
VFA = voids filled with asphalt, %

Asphalt Institute Fatigue Equation (1982)

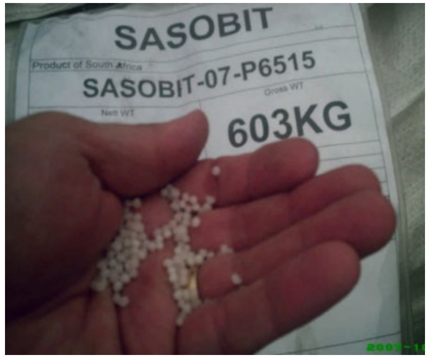
$$N_f = 18.4 \times 0.00432 \times 10^{[4.84 \times (VFA - 0.69)]} \times \left(\frac{1}{\varepsilon_t}\right)^{3.291} \times \left(\frac{1}{|E^*|}\right)^{0.859}$$

What's in Your Volume?

- **Current Problems:** .
  - Volumetrics alone **can not** adequately evaluate "volume" components, such as recycle, warm-mix additives, polymers, recycling agents, fibers and even production factors
- **Including Performance Testing Allows Us to:**
  - **Recognize performance issues**
  - **Increase understanding** of the factors which drive mix performance
  - **Design for performance** on critical infrastructure
  - **Evaluate changes** in asphalt mixture performance due to production factors
  - **Innovate! Asphalt is an engineered material!**





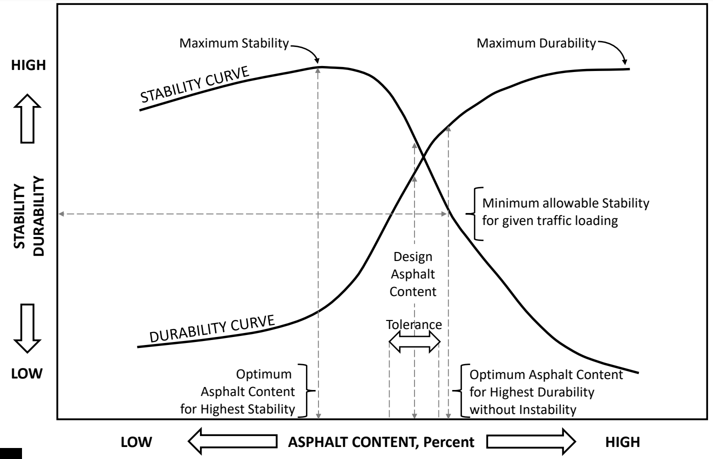


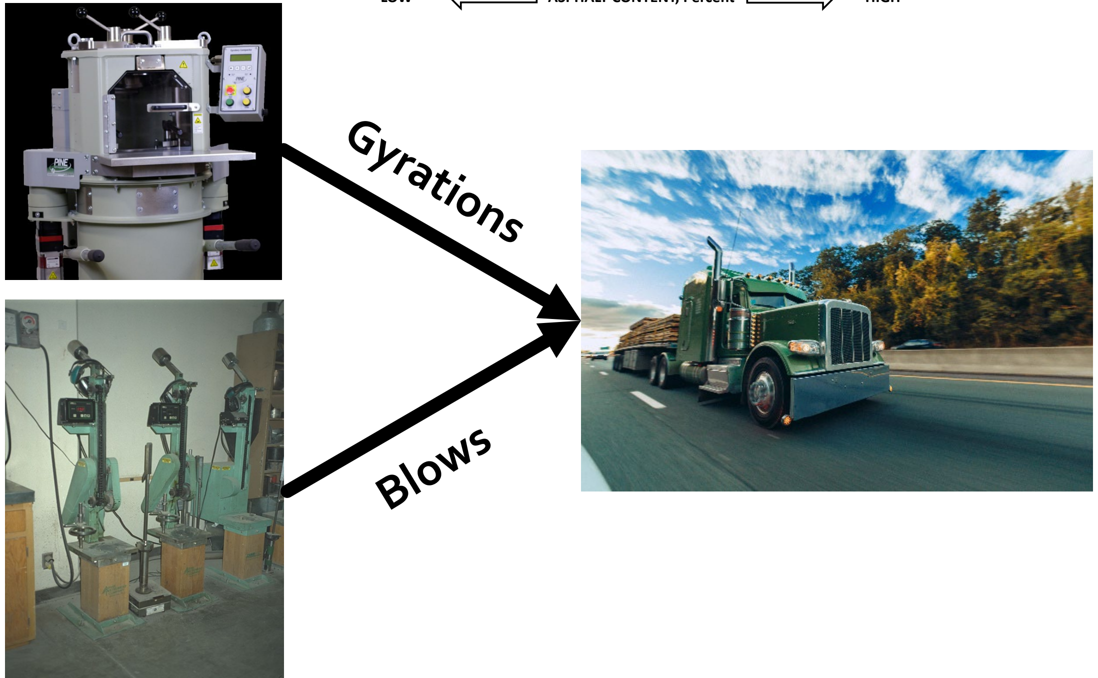
Let's Take a Look at AV% and Vbe%

How does the "volume" impact mixture performance?

Design Air Voids – Where Did They Come From?

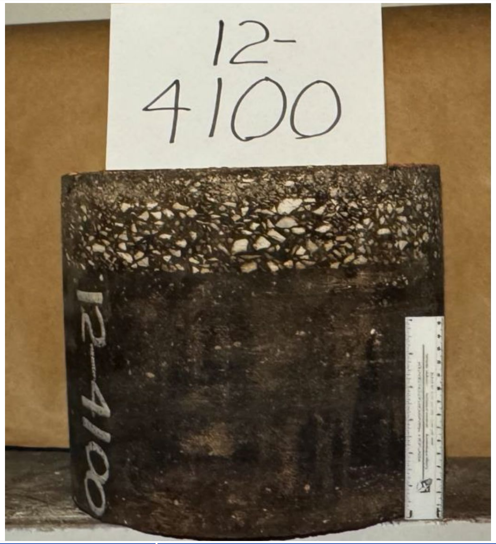
- Design AV% determine opt AC% (obviously influences Vbe)
- They were intended to represent in-place density in wheelpath after densification finished for "well performing" pavements
  - Hveem – less emphasis on air voids and more emphasis on stability but recognized importance of air voids on durability
  - Marshall (USACE) – calibrated laboratory compaction effort to densification that occurred with accelerating loading sections
    - General approach taken today where field densification levels are "calibrated" to gyrations

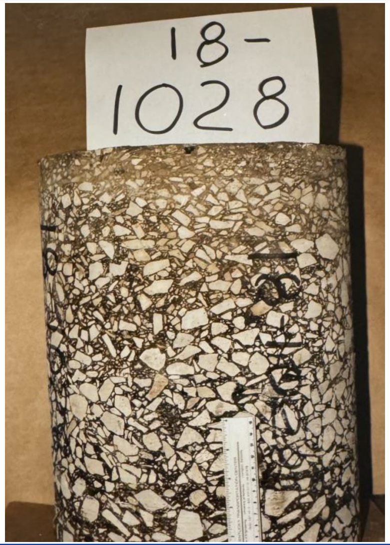




Design Air Voids & Gyration Table

- Superpave used methodology to develop Gyration Table
- Cored large number of in-service pavements
  - 12″ diameter cores
  - Determined Gmb and Gmm
  - Recovered binder and aggregates
  - Recompacted at identical proportioning using different gyration levels
  - Determine # of gyrations to achieve in-place density
    - Phil Blankenship M.S. Thesis!



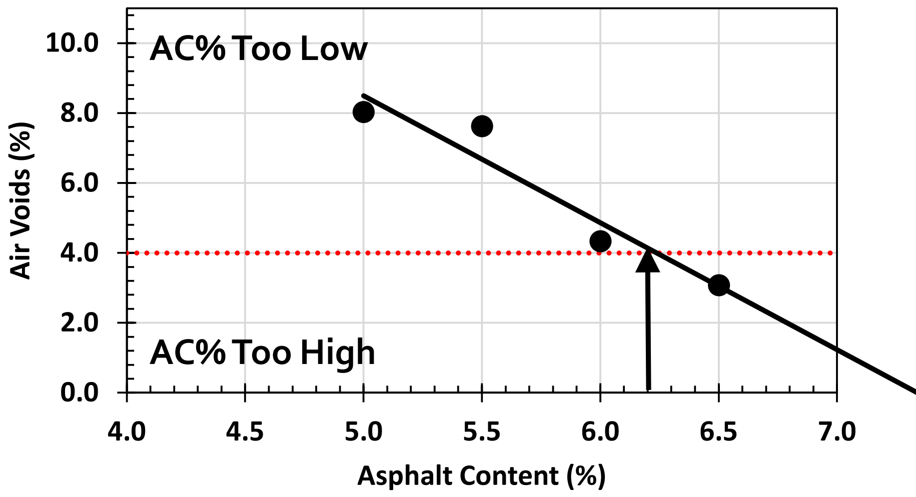


Design ESALs (millions)	Environment								
	Cool (<32°C)			Warm (32 – 38°C)			Hot (>38°C)		
	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
<0.3	6	50	90	7	**72**	137	7	82	159
0.3 - 1	6	55	100	7	**81**	157	8	93	184
1 - 3	6	61	113	8	**92**	181	8	105	211
3 – 10	7	67	126	8	**103**	206	9	119	244
10 – 30	7	74	141	9	**118**	241	9	135	282
30 – 100	7	84	163	9	**136**	284	10	153	325
>100	8	93	184	10	**155**	330	10	172	372

SHRP Report, SHRP-A-408 (1994)

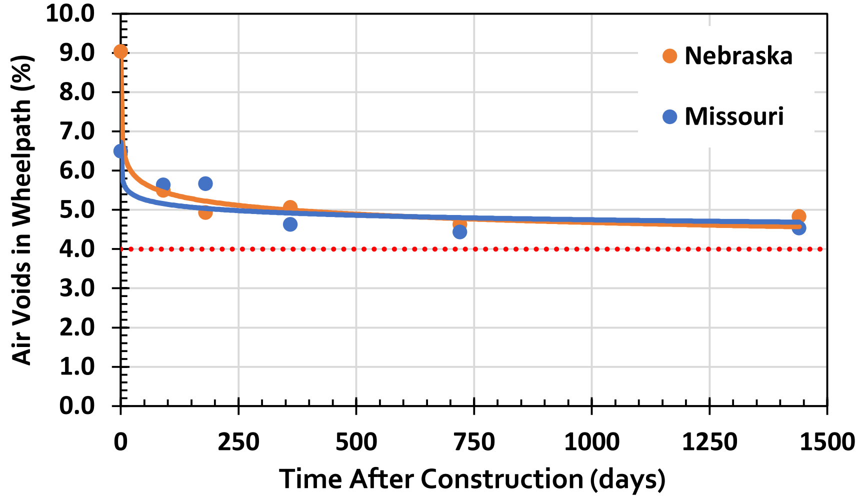
Design Air Voids & Wheelpath Densification

- Wheelpath Densification
  - Mix design assumes we want to optimize asphalt content to provide stable and durable mix after densification has taken place (i.e. ≈ 4% air voids)
    - Increase asphalt content when voids high – decrease asphalt content when voids low



Example: NCHRP 9-9A (2000 – 2006)

State	Initial AV%	4 Yr ΔAV%
Nebraska	9.0	-4.8%
Missouri	6.5	- 2.0%



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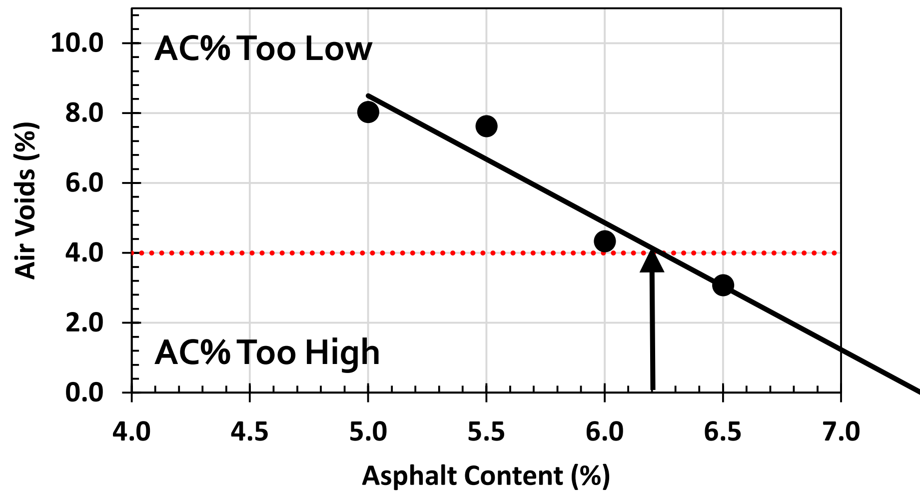
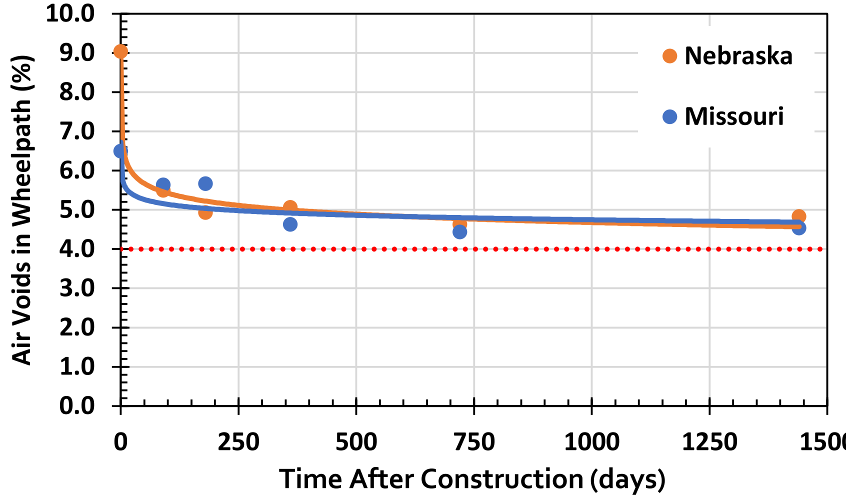


Example: NCHRP 9-9A (2000 – 2006)

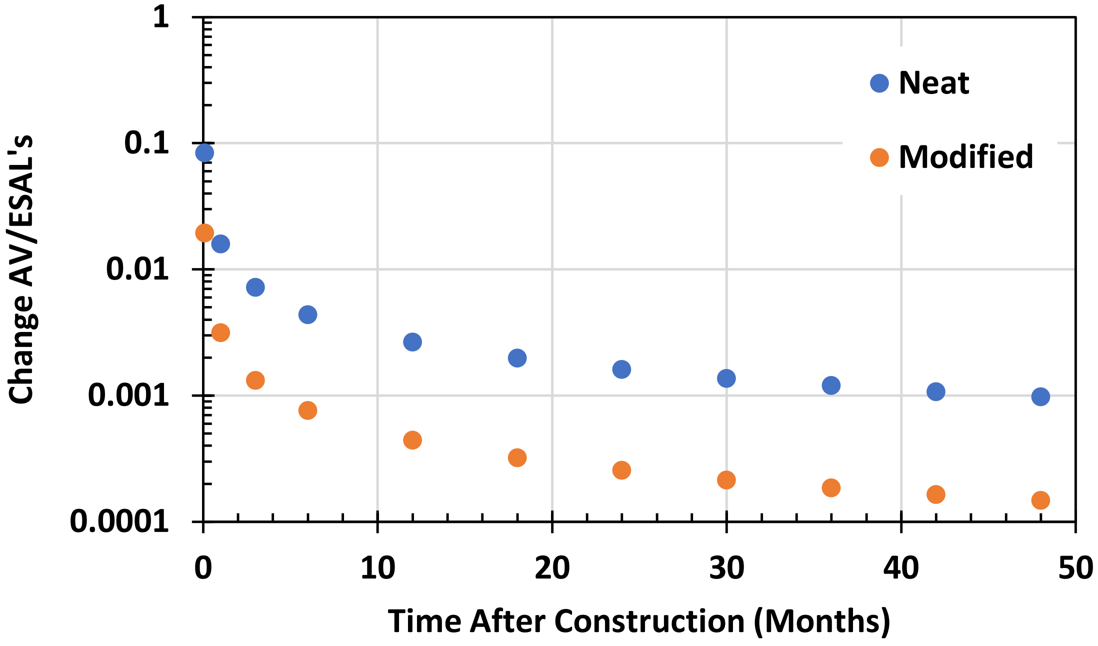
State	Initial AV%	4 Yr ΔAV%	4 Yr MESAL
Nebraska	9.0	-4.8%	0.068
Missouri	6.5	- 2.0%	8.4

Unmodified
PMA



Design Air Voids & Wheelpath Densification

- NCHRP 9-9A Data (Brian Prowell's Ph.D. thesis)
  - Pavements with neat binders consolidated at a rate 6 times more than modified binders (40 projects)
  - According to volumetric mix design rules if air voids above 4% after compaction, additional asphalt binder needed
    - For **same aggregate gradation**; lower gyration level ≈ increased AC
    - We do not take into consideration stiffness of binder with respect to densification
      - Equi-viscous temperature for mix design!



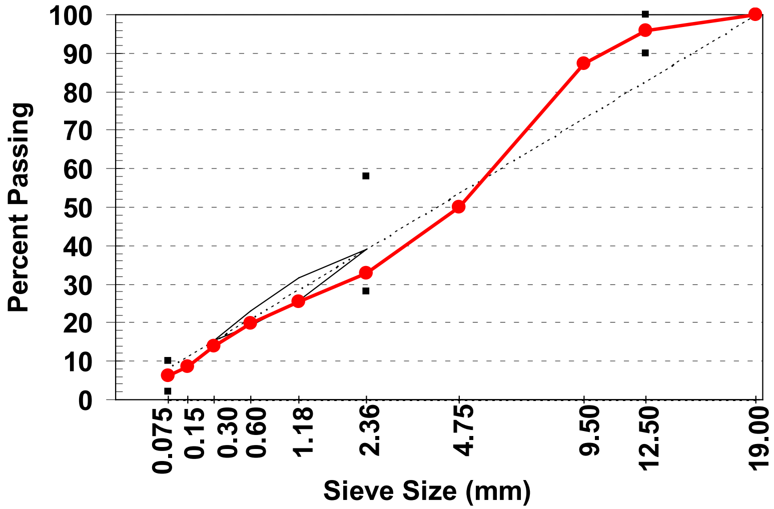
20 Yr MESAL's	N_{des} (<PG76)	N_{des} (>PG76)
< 0.3	50	N.A.
0.3 to 3	65	50
3 to 30	80	65
> 30	100	80

(Prowell & Brown, 2007)

Binder Impact on Mixture Performance

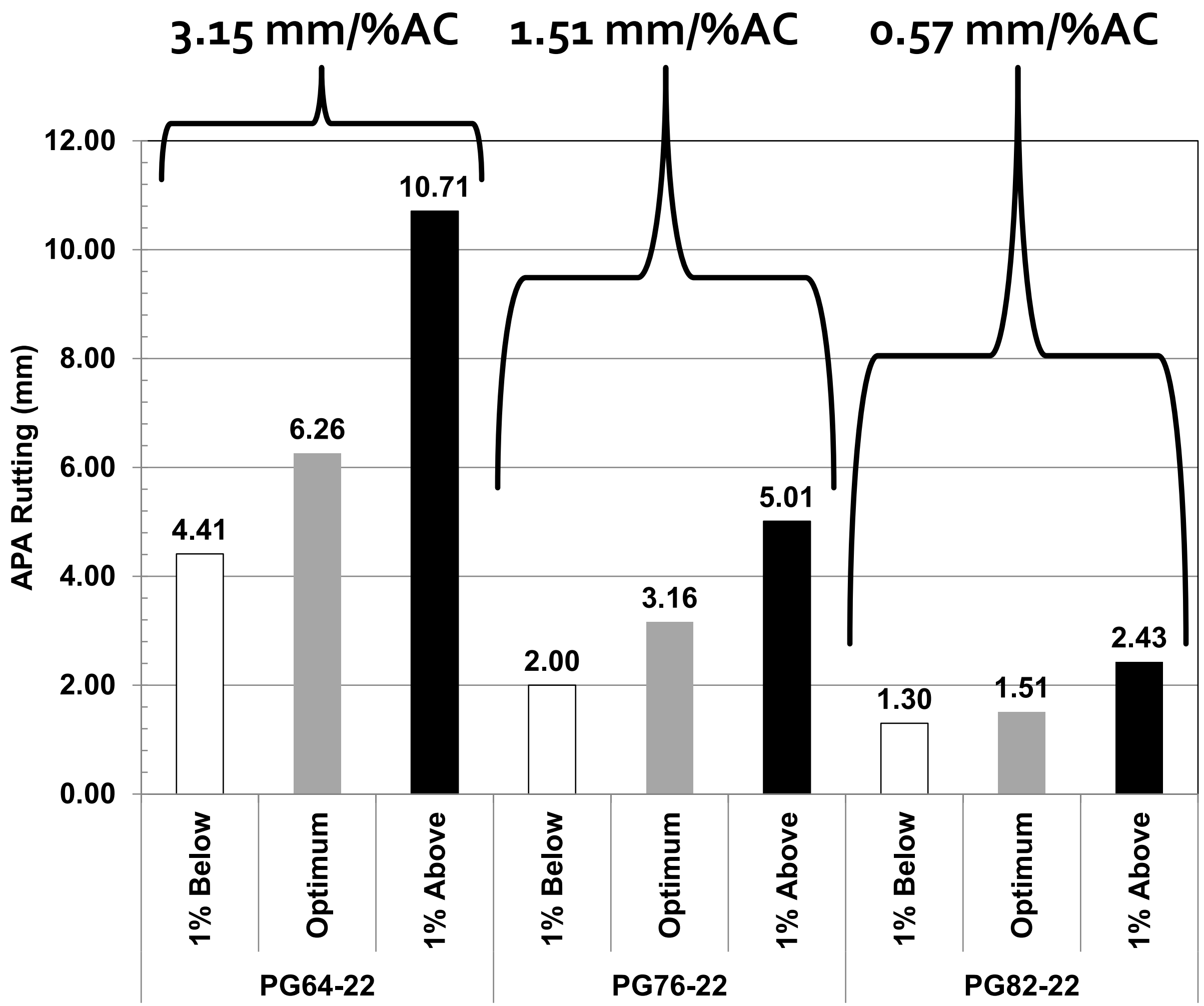
- NJDOT began utilizing performance testing in mixture design in 2006
  - Increase binder content until mixes reaches maximum rutting threshold
    - APA for rutting; Increased VMA at design for cracking
- Starting evaluating BMD after reading AAPT paper by Zhou et. al, (2007)
  - Test specimens compacted to anticipated in-service air voids (6 to 7%)
  - Asphalt content below, at, and above volumetric optimum
    - Vbe changes
  - Different binder grades
    - Binder characteristic changes

Binder Content (%)	4.9%
VMA (%)	14.9%
G_{mm} (g/cm^3)	2.712
G_{sb} (g/cm^3)	2.91
Percent Passing	
19mm	100
12.5mm	95.9
9.5mm	87.3
4.75mm	50.1
2.36mm	32.9
1.18mm	25.5
0.6mm	19.9
0.3mm	13.9
0.15mm	8.7
0.075mm	6.2



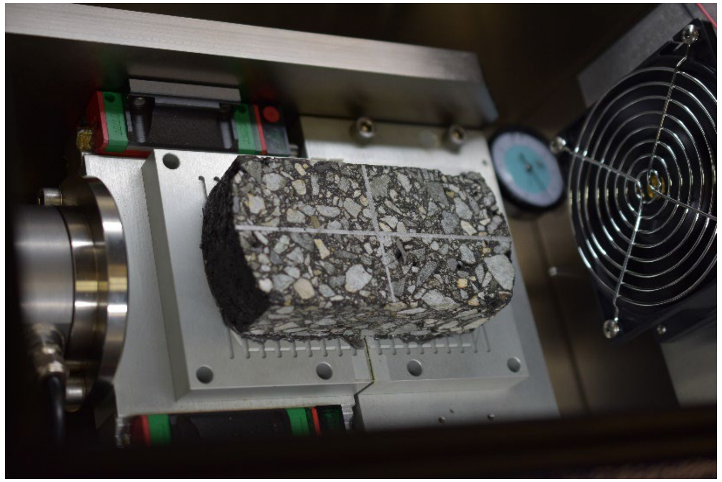
Early NJ BMD Research

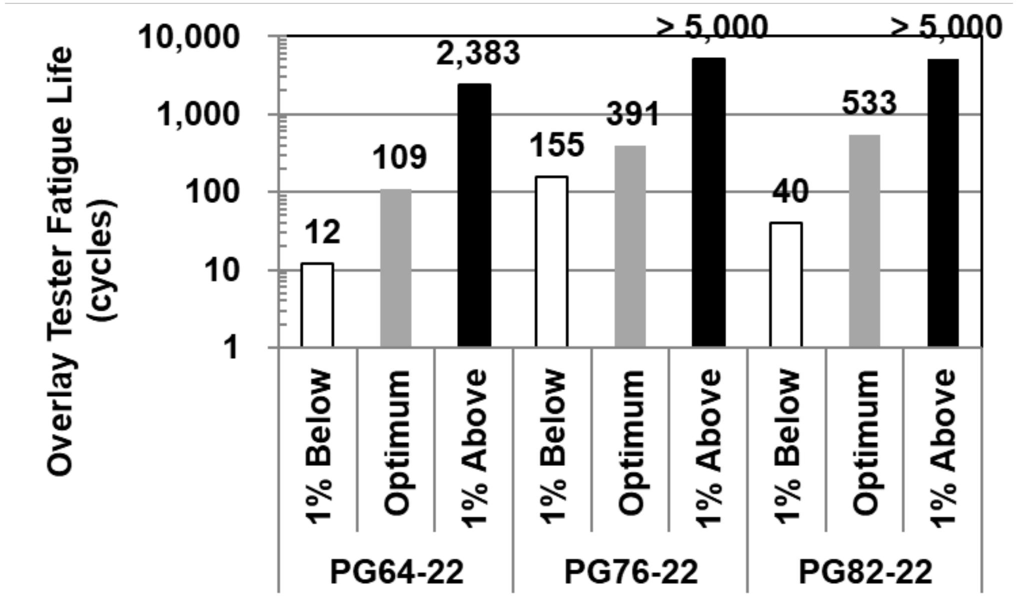
- Asphalt Pavement Analyzer Rutting (AASHTO T340)
  - As binder content increased, rutting increased
  - But magnitude lessened when binder grade improved
    - Volume (Vbe) of binder the same but what made up the volume was different (i.e. – stiffer binder in relationship to the test temperature)



Early NJ BMD Research

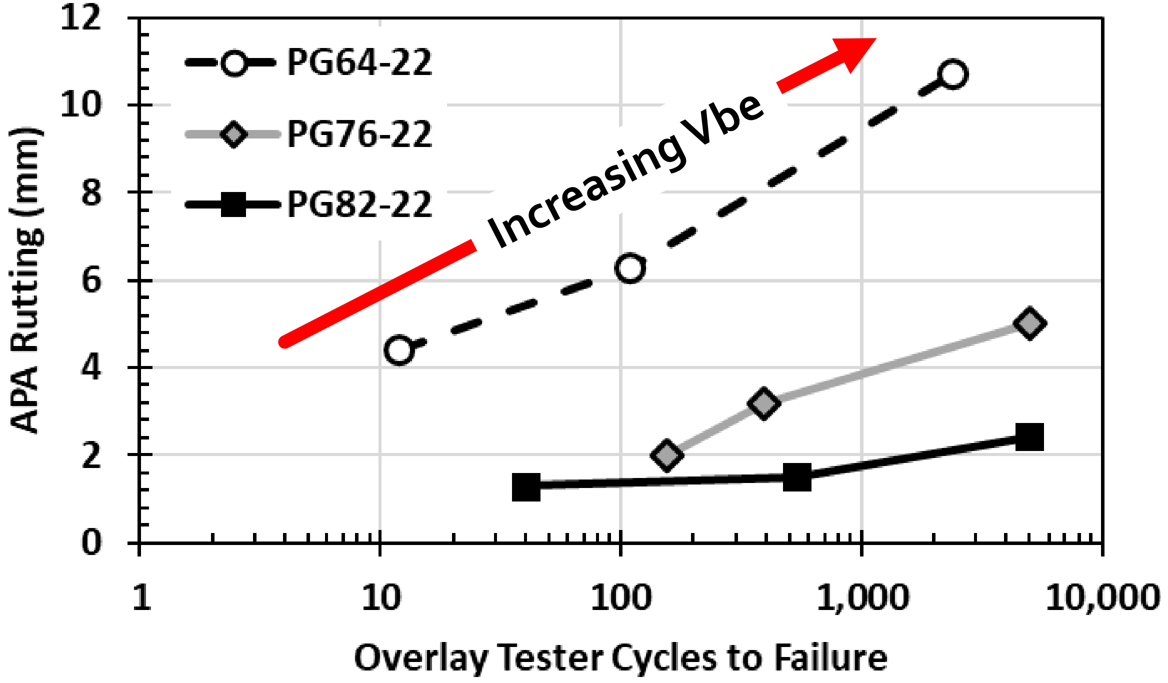
- Overlay Tester Cracking (NJDOT B-10)
  - As binder content increased, resistance to fatigue cracking improved
  - At low Vbe, all 3 binders were consistently poor in cracking performance
  - At higher Vbe, performance improved with PMA better than neat even at identical Vbe



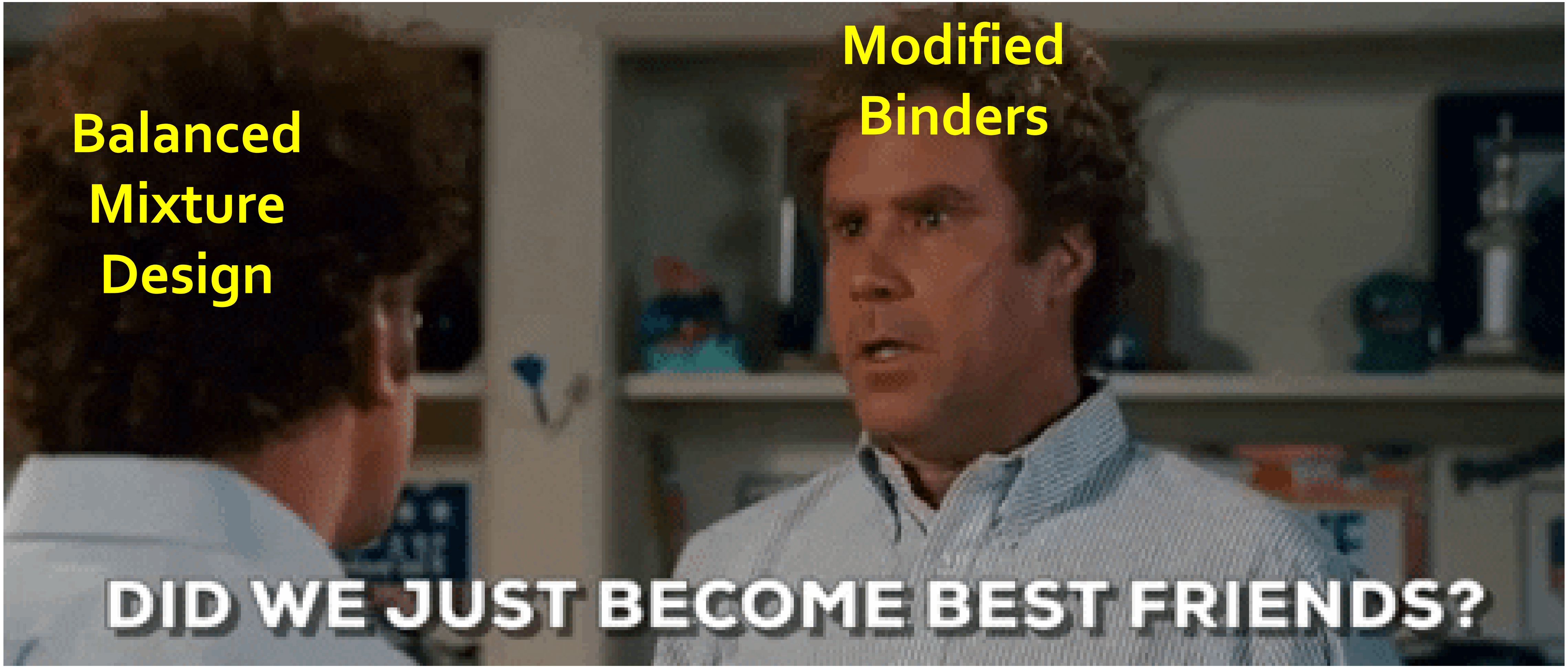


Early NJ BMD Research

- Mixture performance
  - To improve mixture performance, an increase in Vbe required to improve cracking resistance
  - In order to minimize potential for rutting, PMA (i.e. – stiffer binder) utilized
    - “BMD Cheat Code”



BMD and Modified Binders – Perfect Together!

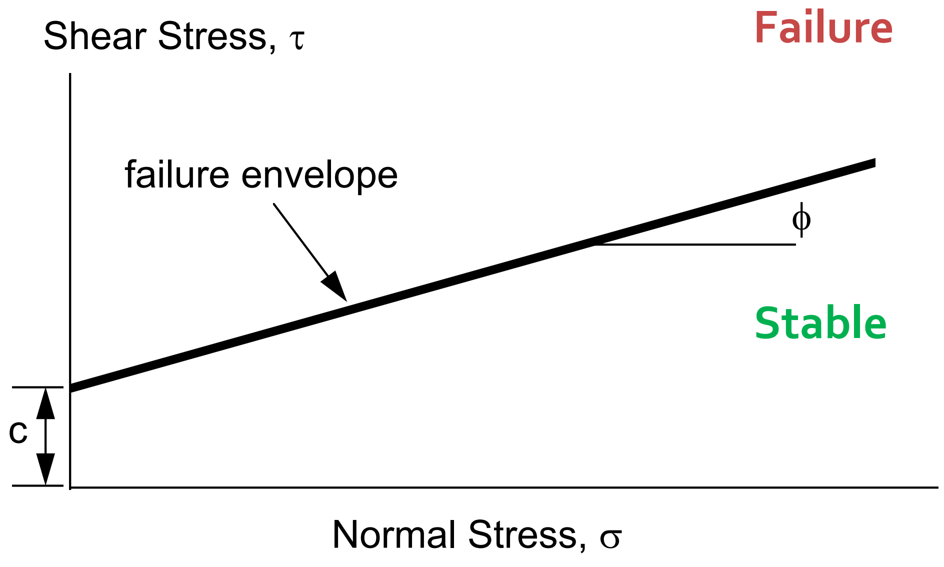


BMD In Practice – Managing Rutting Resistance

- Developing rutting resistance
  - Using Mohr-Coulomb theory as simple example
    - Cohesion (C) = binder property
    - Friction Angle (ϕ) = aggregate angularity
  - Failure envelope can be improved by improving cohesion component (binder contribution) or friction angle (aggregate contribution) or a combination of both
    - Final approach would be a function of costs and availability

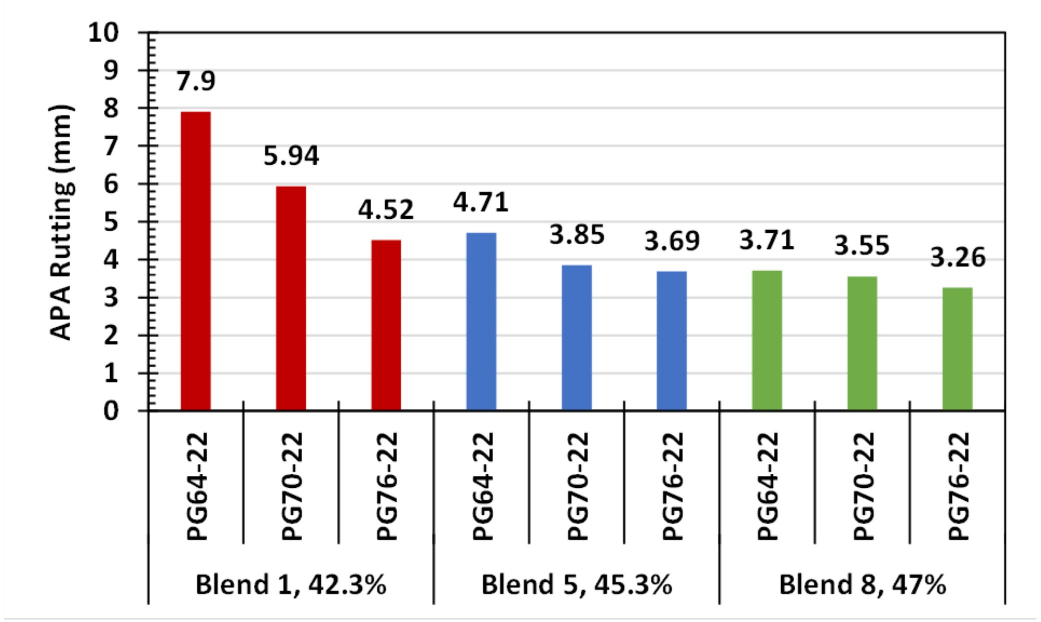
$$\tau = C + \sigma \times \tan \phi$$

τ = shear strength
C = cohesion (asphalt binder)
ϕ = friction angle (aggregate)
σ = normal stress applied to material

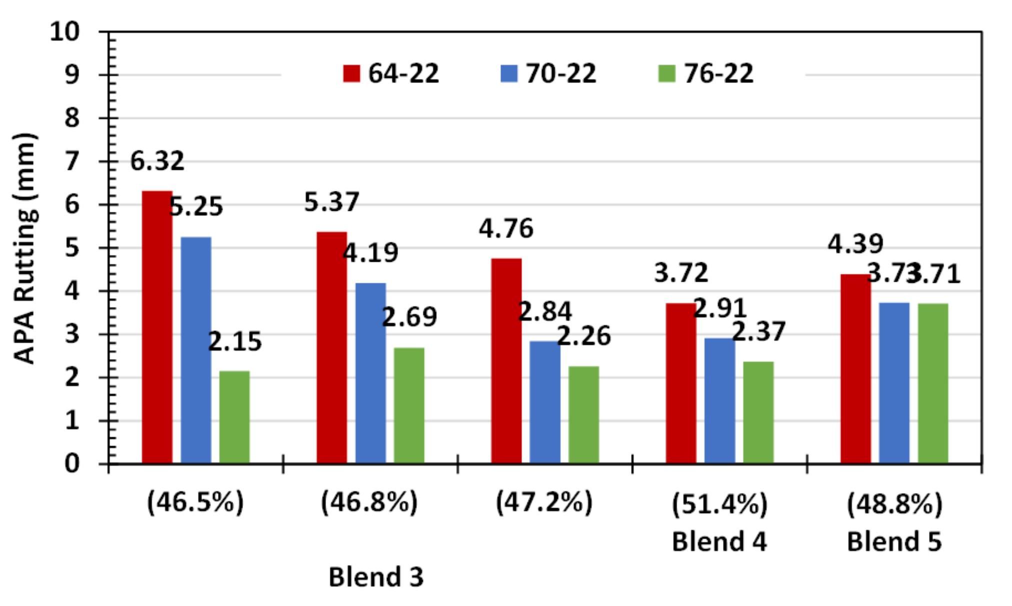


Inter-relationship Between High Temp PG and Aggregate Angularity

- To improve rutting resistance, PMA is not the only answer ("cheat code")
- Aggregate angularity can be improved as well
  - Potency of angularity decreases at HT PG grade increases further from test temperature (impact more significant with "softer" binders)



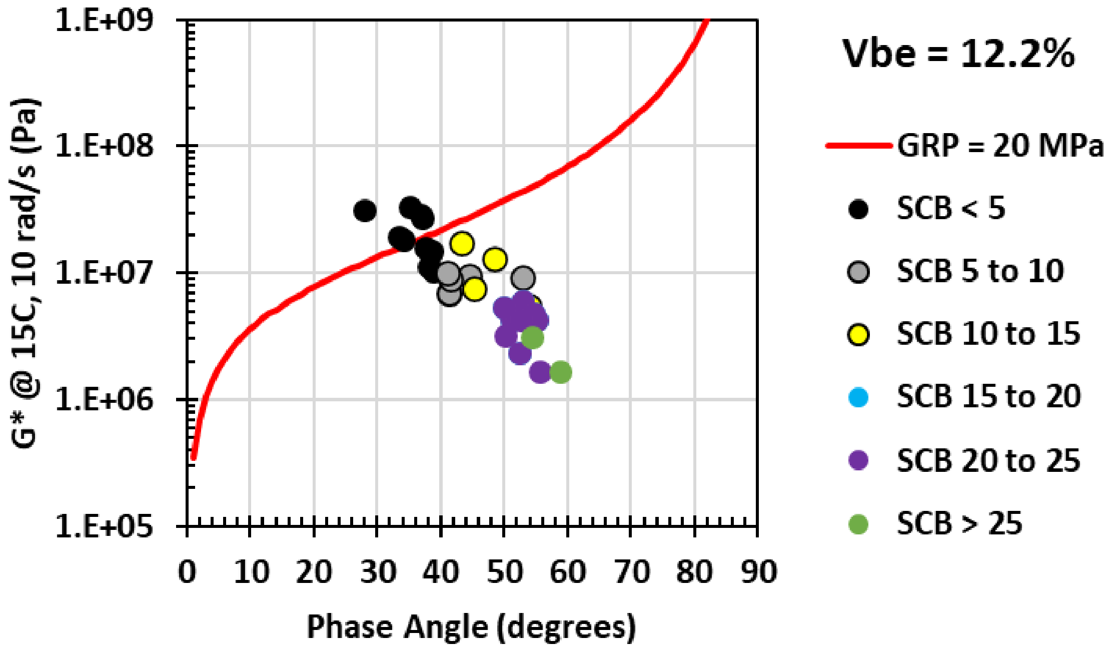
Fine Aggregate Angularity (AASHTO T304)



Coarse Aggregate Angularity (AASHTO T326)

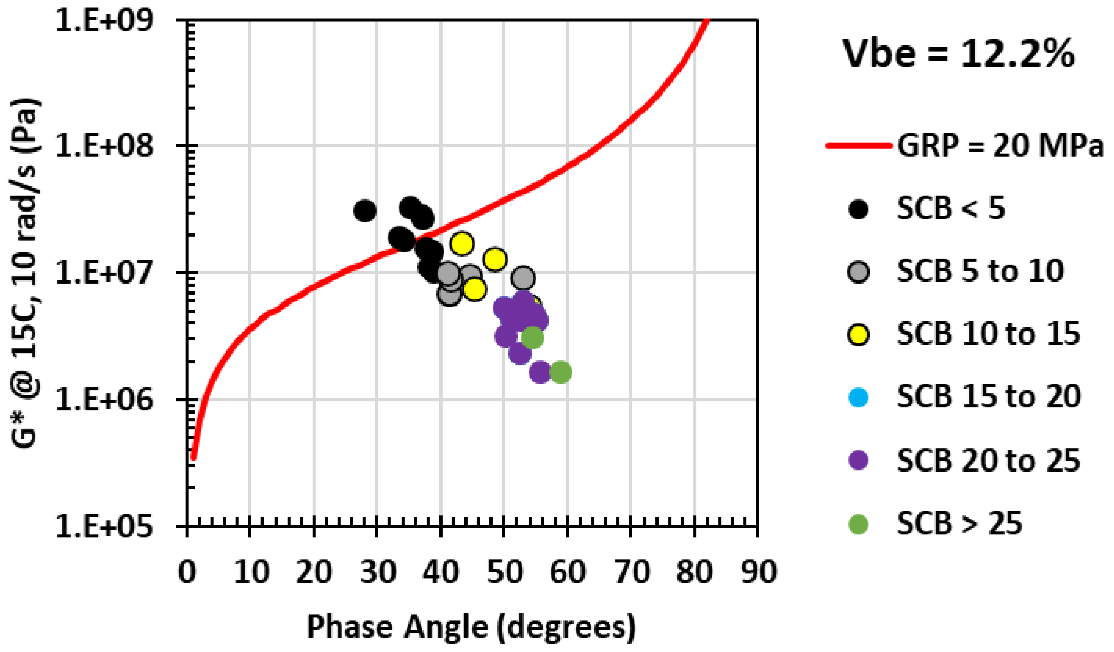
BMD In Practice – Managing Cracking Resistance

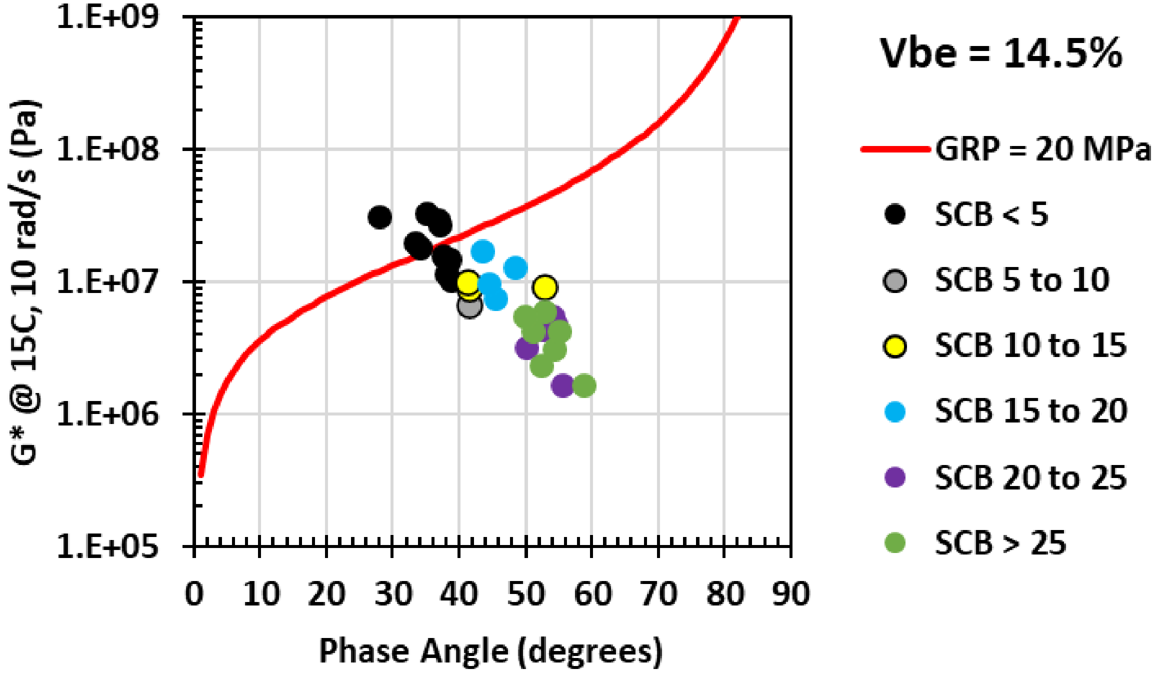
- Cracking performance a balance of Vbe and the binder characteristics
  - Ex. - variety of binders and sources: neat 58-28 to PMA 76-34



BMD In Practice – Managing Cracking Resistance

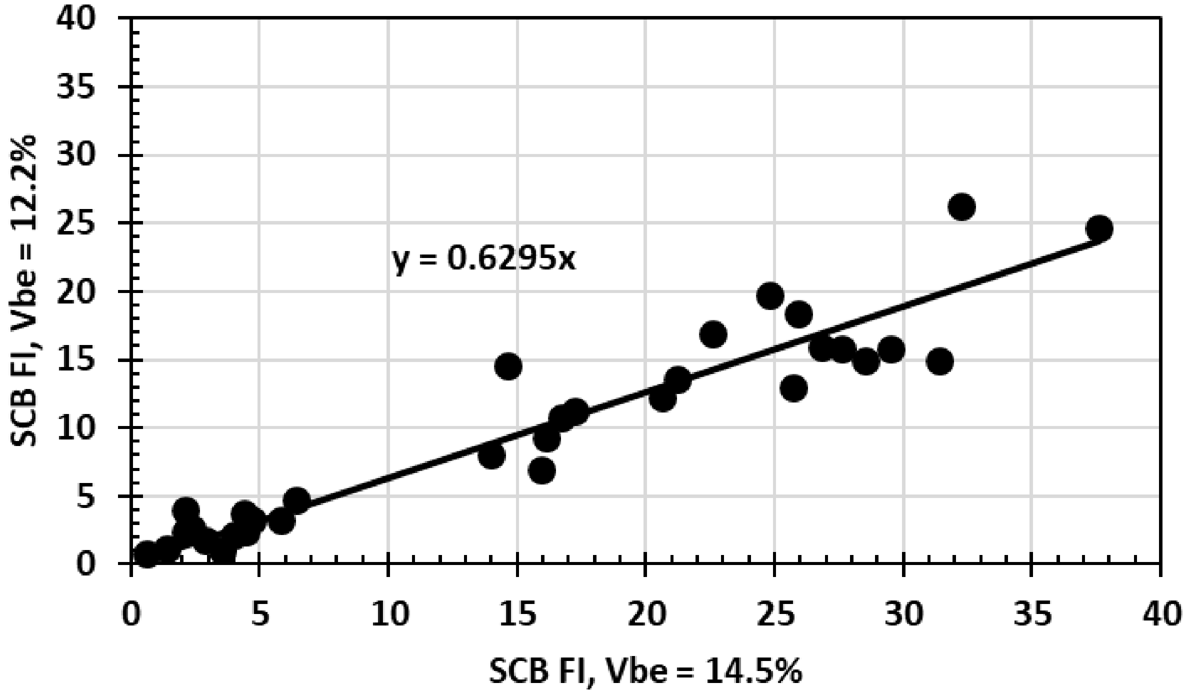
- Cracking performance a balance of Vbe and the binder characteristics
  - Ex. - variety of binders and sources: neat 58-28 to PMA 76-34
  - Increase in Vbe of "same" binder improved SCB FI





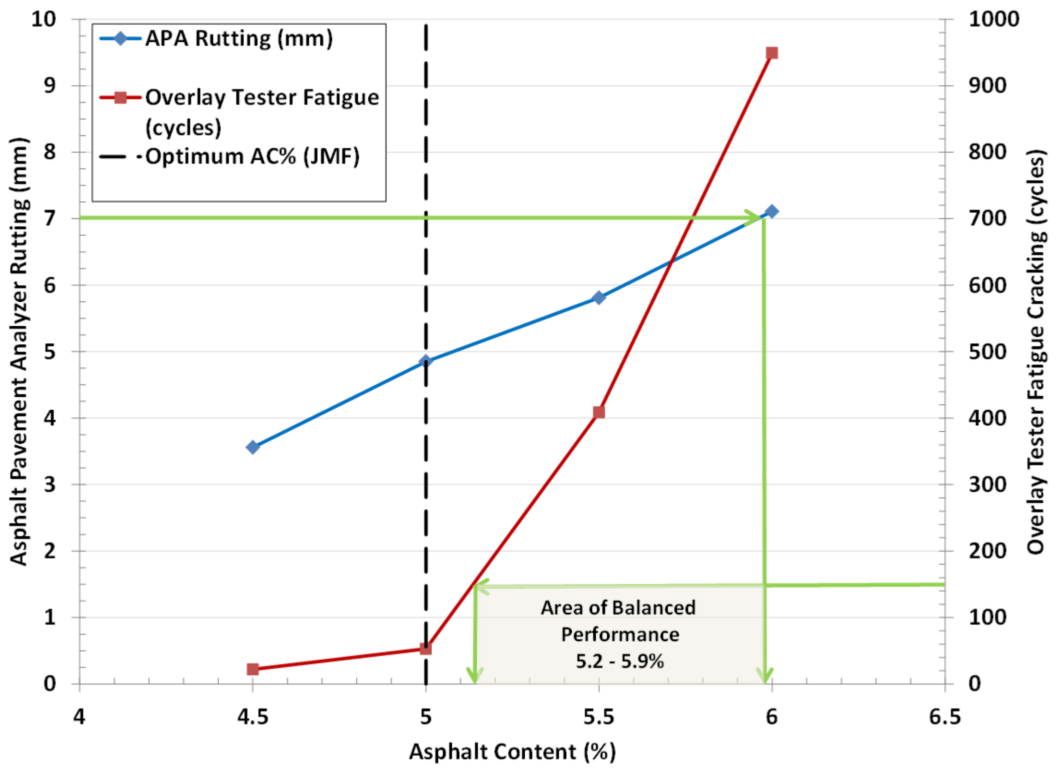
BMD In Practice – Managing Cracking Resistance

- Cracking performance a balance of Vbe and the binder characteristics
  - Neat 58-28 to PMA 76-34
  - Increase in Vbe of "same" binder improved SCB FI
    - "Good" binders will result in "good" mixture performance
    - "Bad" binders will result in "bad" mixture performance
    - Average binders can result in "bad" or "good" performance depending on the Vbe
  - A combination of both the binder property and Vbe required to achieve good fatigue performance!



What is and How Much in Your "Volume" Matters!

- By far the most influential volumetric parameter is volume of effective binder (Vbe)
  - Vbe is directly in VMA calculation and indirectly in the VFA calculation
  - Vbe "balances" mixture performance
    - Low Vbe: ↑ Rutting resistance; ↓ Cracking resistance
    - High Vbe: ↑ Cracking resistance; ↓ Rutting resistance
- As the properties of the "volume" improves with respect to the distress mode, mix performance becomes less sensitive to volumetrics
- **Cost effective mixes will balance volumetrics and material properties to meet BMD criteria**



What's in Your Volume Matters

NJDOT High RAP Specification and Field Projects

Implementation of BMD - NJDOT HRAP

- Performance Testing (BMD)
  - NJDOT HRAP - no maximum RAP content, must meet BMD and "relaxed" volumetrics
  - Sampling and specimen compaction was conducted at plant
    - Sampling occurred every 700 tons to coincide with plant's QC testing
      - Lot #1 – Samples 1, 2, 3
      - Lot #2 – Samples 4, 5, 6
      - Random numbers generated to select 3 specimens for rutting & 3 specimens for cracking
    - Performance testing every 1400 tons or at least per night (whichever comes first)

Table 902.11.04-1 HMA HIGH RAP Requirements for Control

Compaction Levels	Required Density (% of Theoretical Max. Specific Gravity)	Voids in Mineral Aggregate (VMA), % (minimum)					Dust-to Binder Ra
		Nominal Max. Aggregate Size, mm					
	@Ndes[1]	25.0	19.0	12.5	9.5	4.75	
L, M	95.0 – 98.5	13.0	14.0	15.0	16.0	17.0	0.6 - 1.

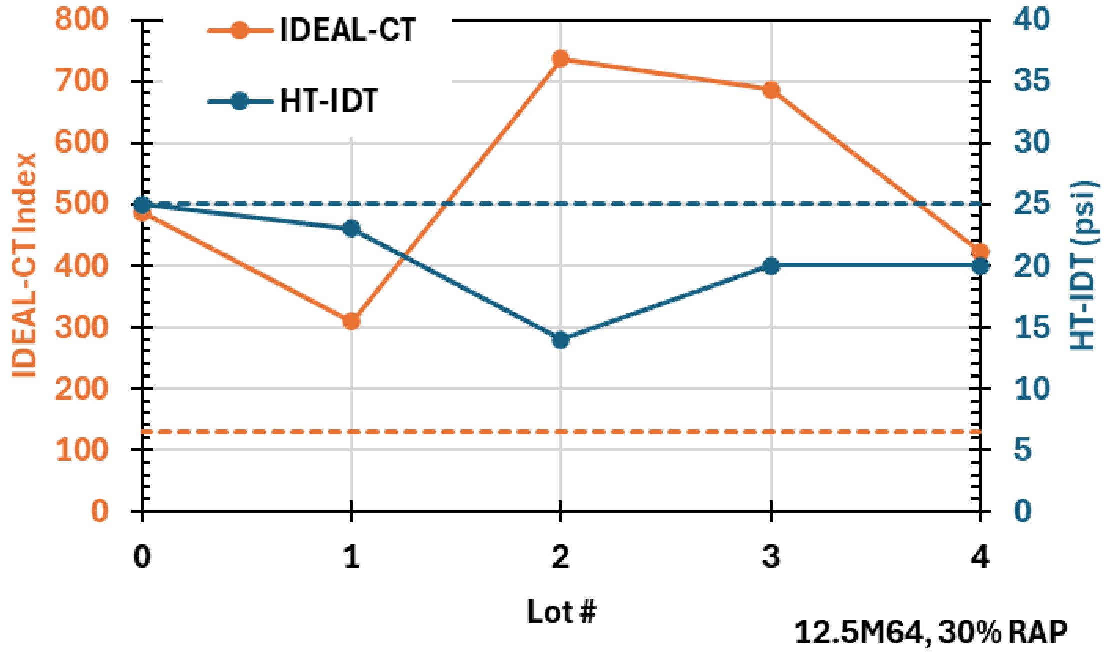
1. As determined from the values for the maximum specific gravity of the mix and the bulk specific gravity of the compa mixture. Maximum specific gravity of the mix is determined according to AASHTO T 209. Bulk specific gravity of compacted mixture is determined according to AASHTO T 166.

Table 902.16.03-2 Performance Testing Requirements for High RAP Pilot Project Design

Test	Requirement			
	Surface Course		Intermediate and Base Course	
	PG 64S-22	PG 64E-22	PG 64S-22	PG 64E-22
High Temperature IDT (psi) (ASTM D6931)	≥ 25	≥ 34	≥ 25	≥ 34
IDEAL-CT Index (ASTM D8225)	≥ 130	≥ 150	≥ 110	≥ 120

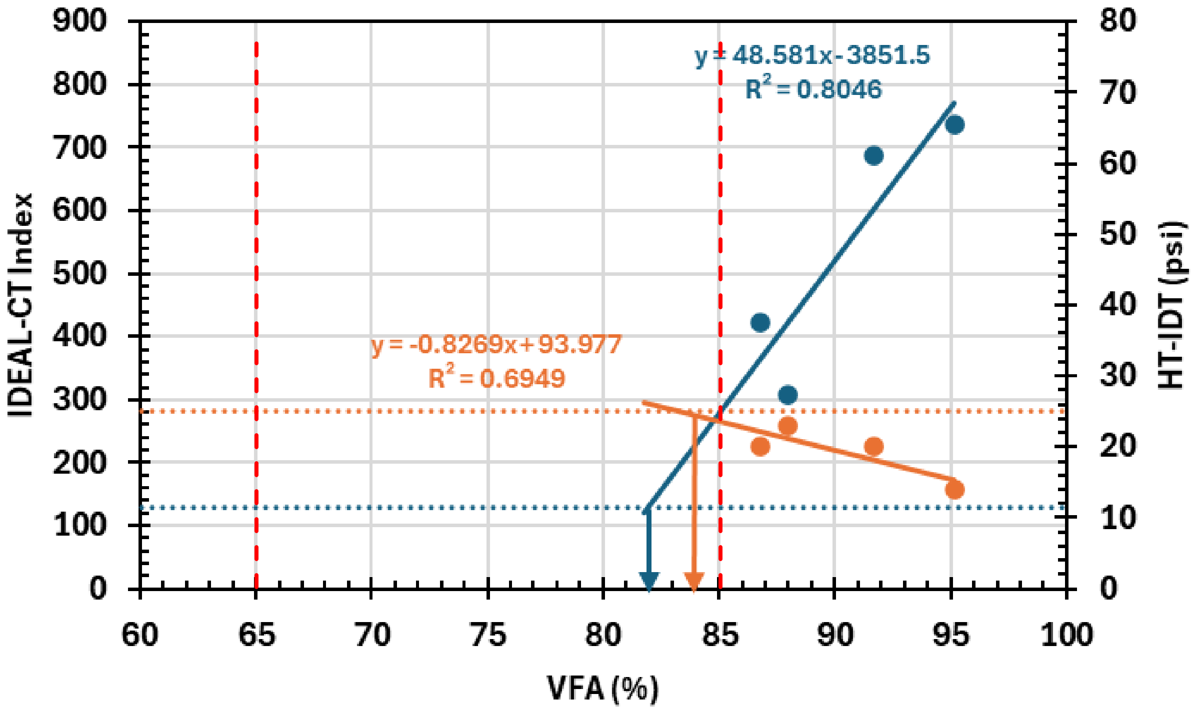
NJDOT HRAP – 2024 Projects (I295 Example)

- 12.5mm, PG64S-22, 30% RAP
  - Total of 8 Lots sampled; 4 sets of performance tests
  - Mix met cracking for all Lots (IDEAL-CT > 130)
  - Mix failed for rutting for all Lots (HT-IDT > 25 psi)



NJDOT HRAP – 2024 Projects (I295 Example)

- Good example that even when using BMD, basic volumetrics should be followed
- The selection of the HT-IDT and IDEAL-CT tests appear to be sensitive to the volumetric properties
- The criteria also appear to pick up when poor volumetrics are achieved



<u>Continuous PG Grade</u>

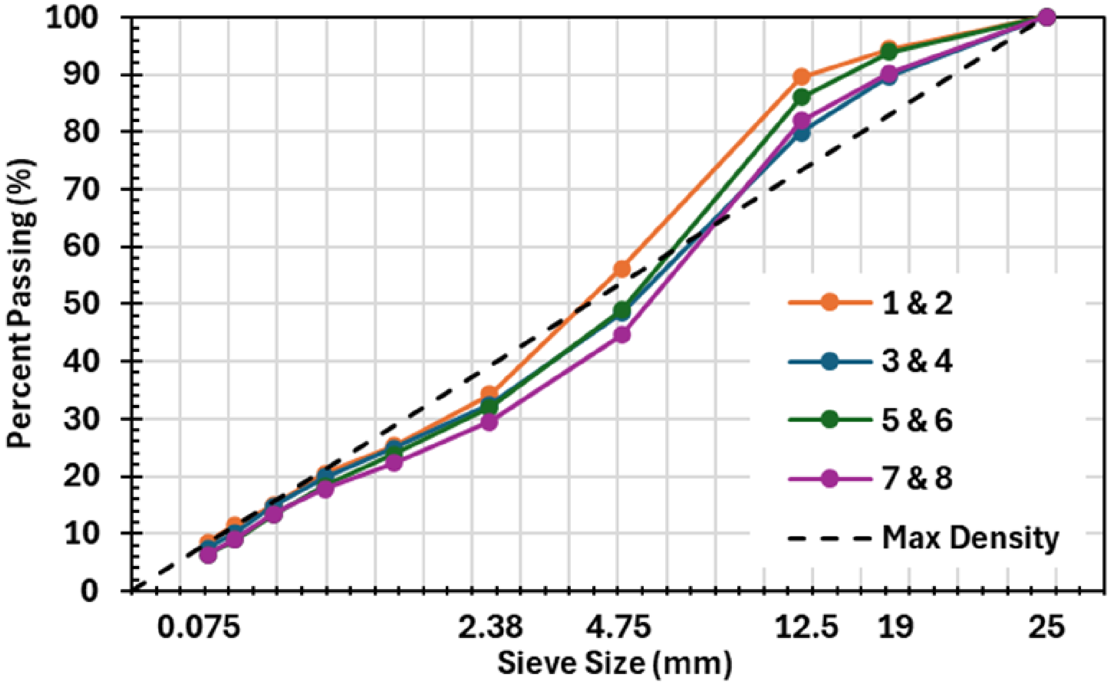
PG68.5-24.4 (24.7)

Jnr = 2.47 1/kPa

(PG64S-22)

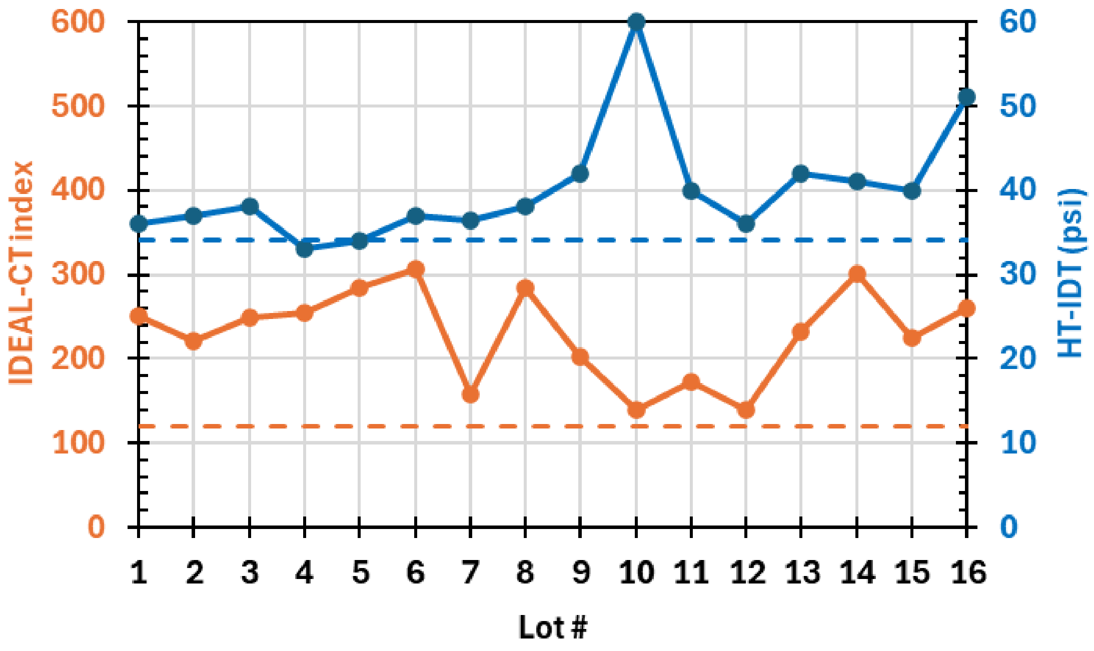
NJDOT HRAP – 2024 Projects (I295 Example)

- Good example that even when using BMD, basic volumetrics should be followed
  - Poor control of aggregate gradation resulted in an increase in "void space"
  - To meet air void requirements, supplier increased binder content



NJDOT HRAP – 2024 Projects (I295 Example)

- 19mm, PG64E-22, 40% RAP
  - Total of 30+ Lots sampled; 15+ sets of performance tests
  - Able to meet all IDEAL-CT Index and all but one for HT-IDT (33 psi < 34 psi)



Continuous PG Grade

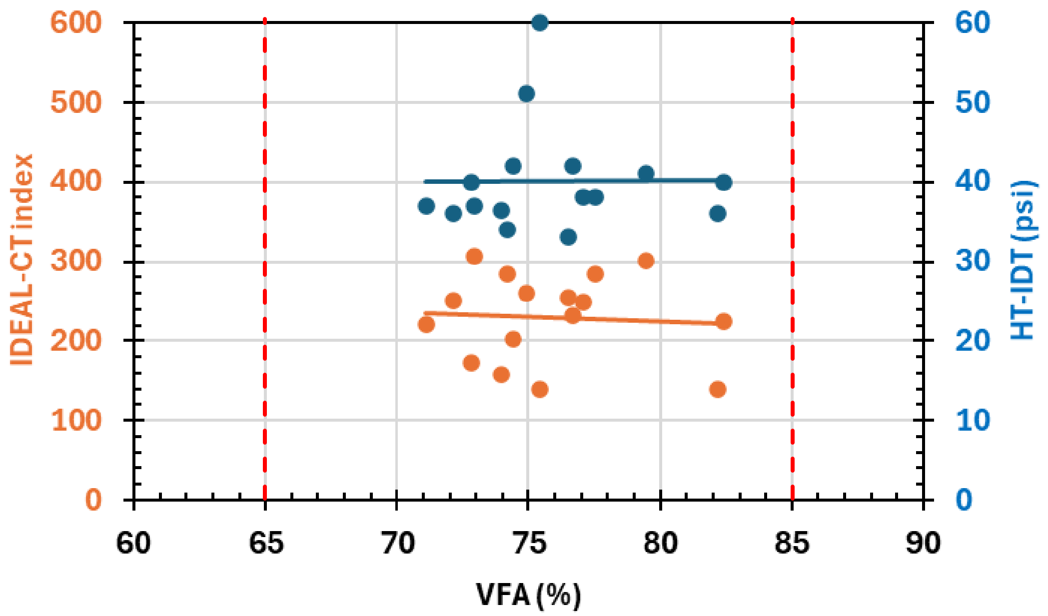
PG81.4-26.2 (24.4)

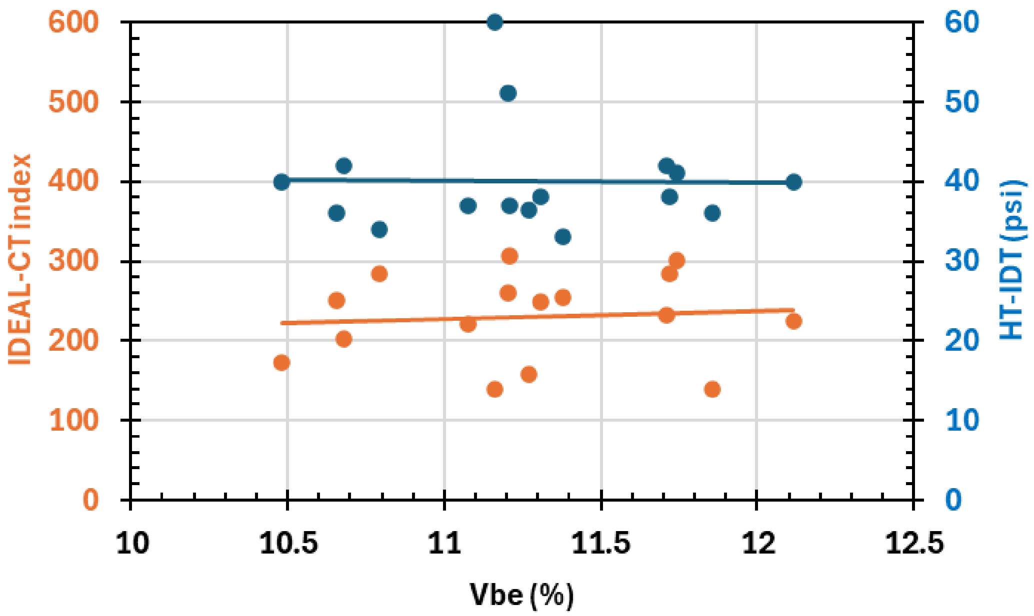
Jnr = 0.24 1/kPa

(PG64E-22)

NJDOT HRAP 2.0 – 2024 Projects (I295 Example)

- 19mm, PG64E-22, 40% RAP
  - IDT performance tests were not as sensitive to volumetrics as the 12.5mm NMAS, PG64S-22, 30% RAP





Moving Forward in BMD

Flexibility of Future Specifications

- Flexibility comes with confidence!
- Aggregate Properties
  - Consensus and Source properties
- Asphalt Binder Properties
  - High Temperature
  - Low Temperature
  - Intermediate/Cracking(?)
- Volumetrics
  - Effective Binder properties, air voids

NAPA BMD IWG

Property		Example #1	Example #2	Example #3
Aggregates	FAA (T 304)	Min.	Report only	Report only
	CAA (T 335)	Min.	Min.	Report only
	Flat and Elongated Particles (ASTM D4791)	Max.	Max.	Max.
	Sand equivalent (T 176)	Min.	Min.	Min.
	LA abrasion (T 96)	Max.	Max.	Report only
	Polish Value (ASTM D3319)	Min.	Report only	–
	Natural sand content	Report only	–	Report only
Binder	Delta Tc (T 387)	Min.	Min.	Report only
	PGHT (M 320)	Min.	Min.	Report only
	PGLT (M 320; M 332)	Max.	Max.	Max.
	GRP (T 315)	Max.	Max.	Max.
	MSCR recovery (R 92)	Min.	Min.	Min.
Additives	Polymer content	Min.	Report only	Report only
	Antistrip type and dose	Min.	Report only	Report only
Design gyrations by traffic level (R 35)		Value	Value	Value
Va (M 323)		Range	Min.	–
VFA (M 323)		Max.	Report only	Report only
VMA (M 323)		Min.	Min.	Report only
$P_{0.075}/P_{be}$ (M 323)		Range	Range	Report only
Aggregate gradation		Report only	Report only	Report only
Design asphalt binder content		Report only	Report only	Report only
Design Va		Report only	Report only	Report only
Gmm (T 209)		Report only	Report only	Report only

Volumetric Criteria & Pavement Distress

Related Distress	Low End of Range	Volumetric Parameter	High End of Range	Related Distress
Bleeding/ Stability	2.0	AV% (Production)	6.0	Durability/ Rutting
Durability	-1.0% (of Min.)	VMA (Production)	+3.0% (of Min.)	Rutting/ Stability
Durability		VFA (Design)		Rutting/ Stability/ Bleeding
Stability	0.4	#200/Pbe (Production)	1.6	Durability

Relaxation in BMD – Example NJDOT's BRIC

Table 902.09.03-2 Volumetric Requirements for Design and Control of BRIC					
	Required Density (% of Max Sp. Gr.)		Voids in Mineral Aggregate (VMA)	Dust to Binder Ratio	Draindown AASHTO T 305
	@ N_{des} (50 gyrations)	@ N_{max} (100 gyrations)			
Design Requirements	97.5	≤ 99.0	≥ 18.0 %	0.6 – 1.2	≤ 0.1 %
Control Requirements	96.5 – 98.5	≤ 99.0	≥ 18.0 %	0.6 – 1.3	≤ 0.1 %

Design AV = 2.5%
Production AV = 1.5 to 3.5%

Table 902.09.03-3 Mix Design Performance Testing Requirements for BRIC	
Test	**Requirement**
Asphalt Pavement Analyzer (AASHTO T 340)	< 6 mm@ 8,000 loading cycles
Overlay Tester (NJDOT B-10)	>700 cycles

Table 902.09.03-4 Production Performance Testing Requirements for BRIC	
Test	**Requirement**
Asphalt Pavement Analyzer (AASHTO T 340)	< 7 mm@ 8,000 loading cycles
Overlay Tester (NJDOT B-10)	> 650 cycles

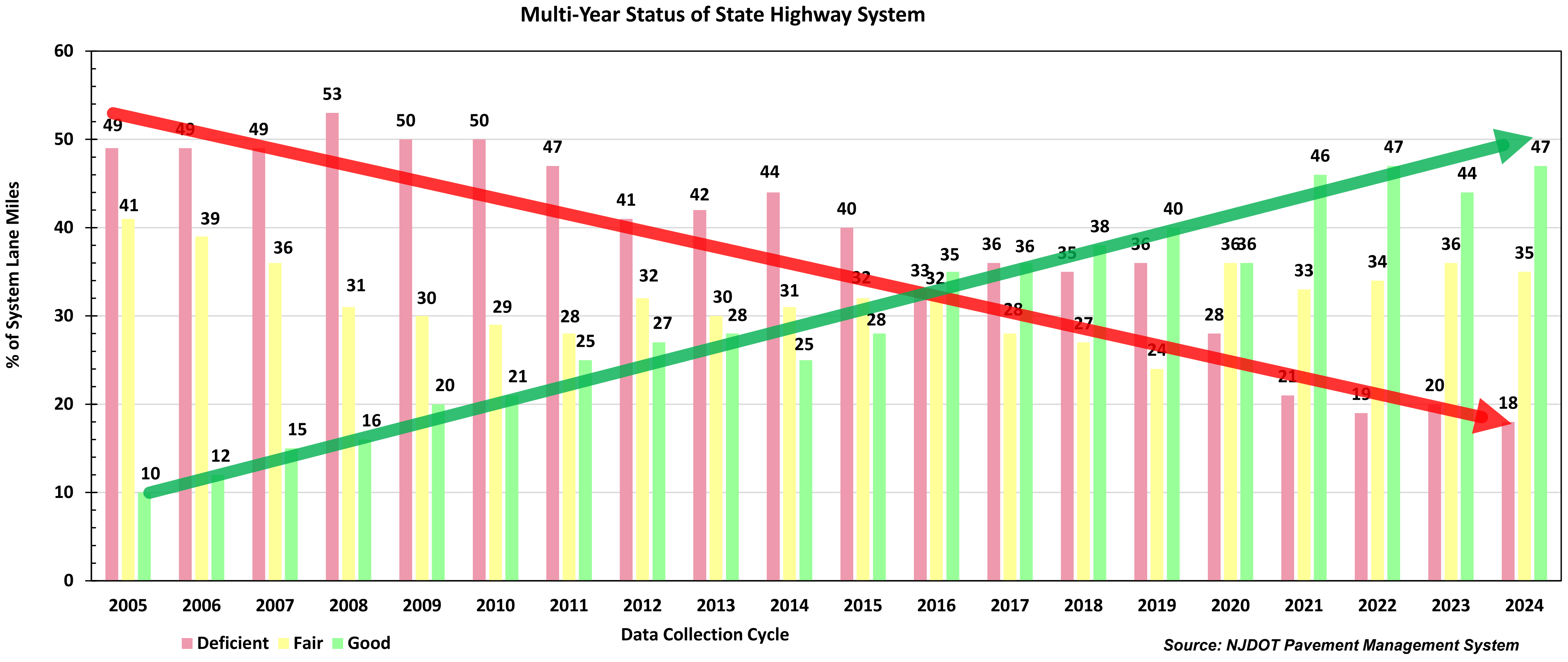
Relaxation in BMD – Example NJDOT's BRIC and HPTO

- NJDOT High Performance Thin Overlay (HPTO) and Bituminous Rich Intermediate Course (BRIC) have no binder grade requirement

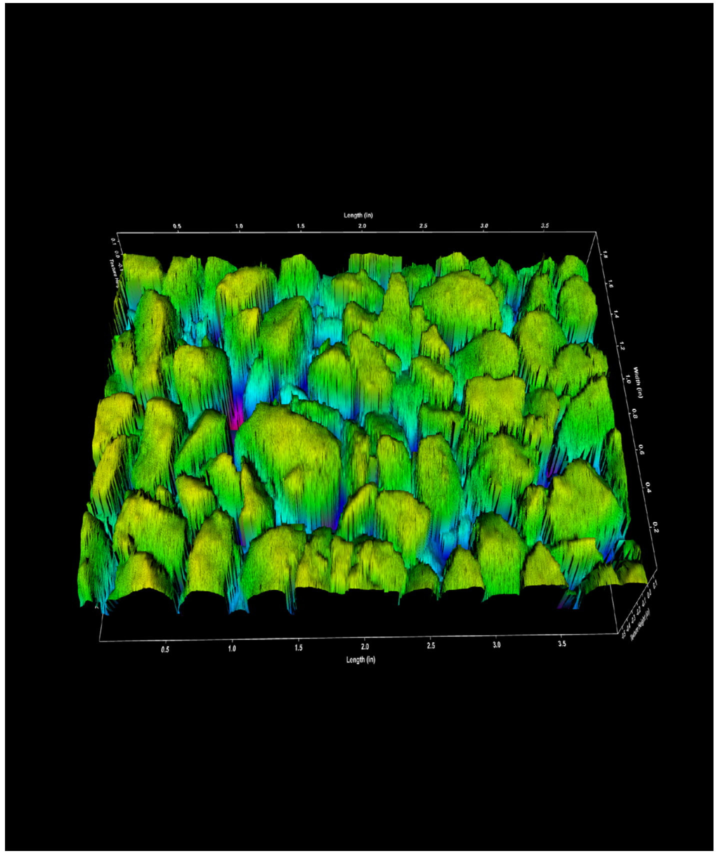
Use polymer modified asphalt binder that is specially formulated for meeting the mix performance criteria as specified in 902.08.02. Consult with the asphalt binder supplier to obtain the appropriate material for the specific mix design. Submit a certificate of analysis (COA) showing the PG continuous grading (AASHTO R 29) for the asphalt binder used in the mix design.

For quality assurance testing of the asphalt binder, the ME may sample the asphalt binder during production of the mix and compare the results with the COA submitted at the time of test strip. To analyze the binder the ME will test the binder at the nearest standard PG temperature then compare the results with the COA. If the high ($G^*/\sin\delta$) and low (stiffness and m value) temperature passing test results are within 5 percent of the results from the passing temperature on the COA, then the ME will consider the asphalt binder comparable to the binder used during test strip.

Potential Benefits of BMD – End Result



Including Friction and Texture in Future BMD

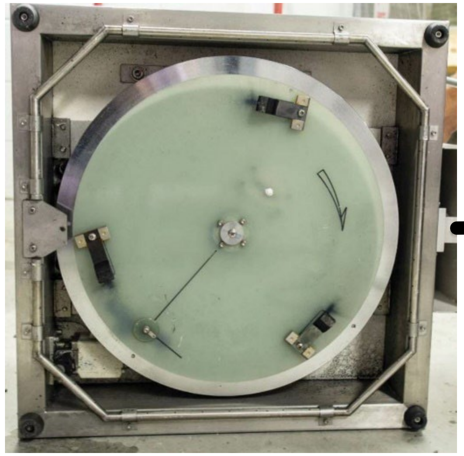


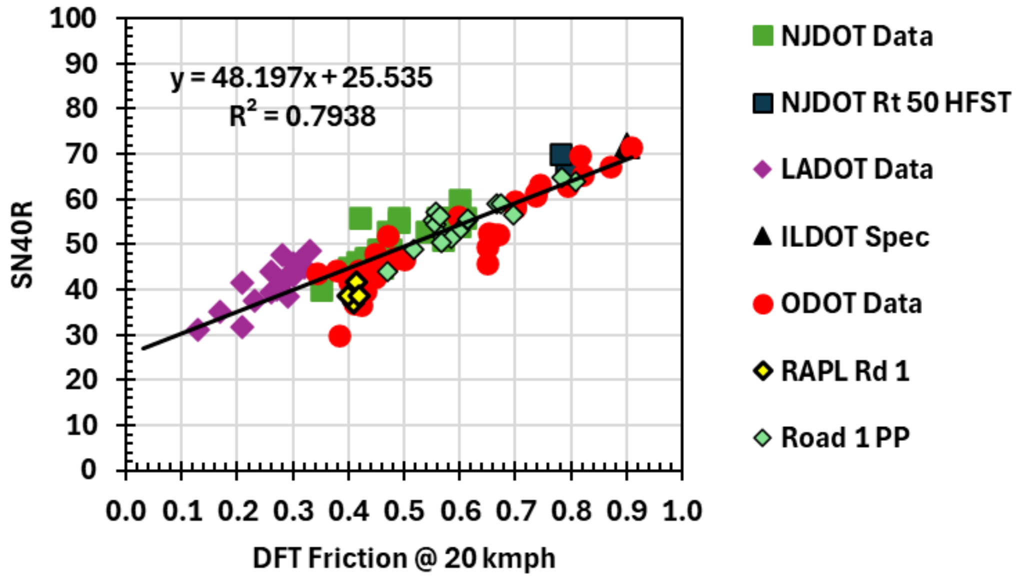
Developing Field Data for Performance Criteria

- Similar to BMD, can we correlate field functional performance (locked wheel skid & surface texture) to lab measurements
  - "Relaxed" BMD specifications may need to be checked to ensure materials/designs do not cause safety issues
  - Confidence to reproduce pavement surface conditions
  - Confidence in measurement representation
    - Lab friction vs field (vs time/traffic?)

Locked Wheel (SN40R) vs DFT

- Over past 2 years, developed correlation between field SN40R and DFT (ASTM E1911)
  - Allows for quickly measuring friction in field
  - Can relate lab compacted materials to anticipated field performance



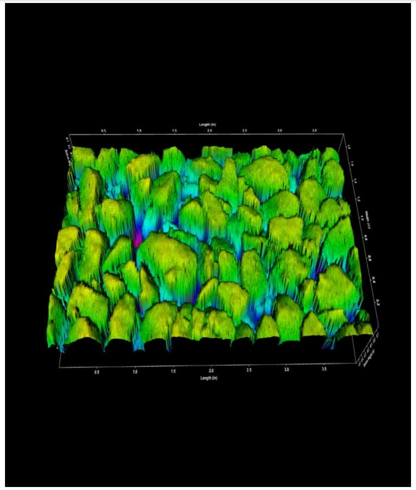


Frictional Performance of Different Mixes

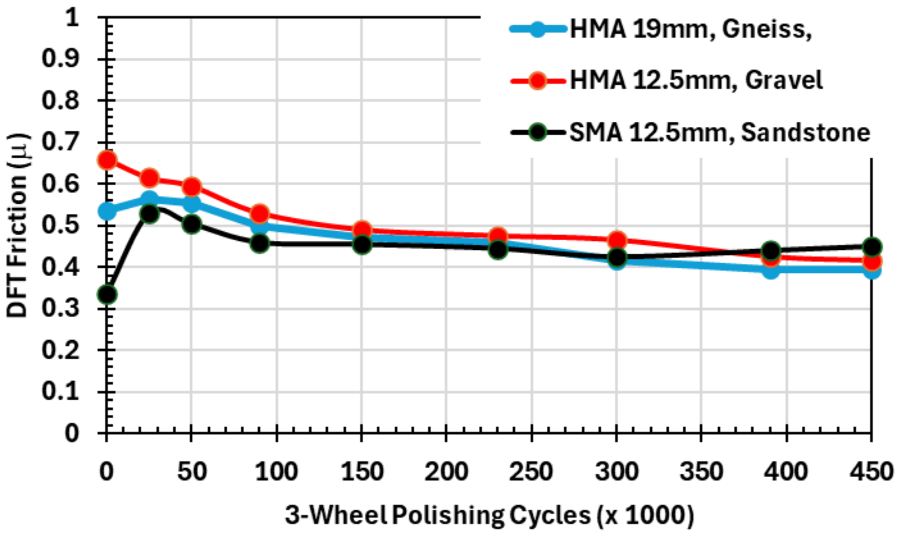
Lab Slab Compactor

DFT Setup for Lab

3 Wheel Polisher

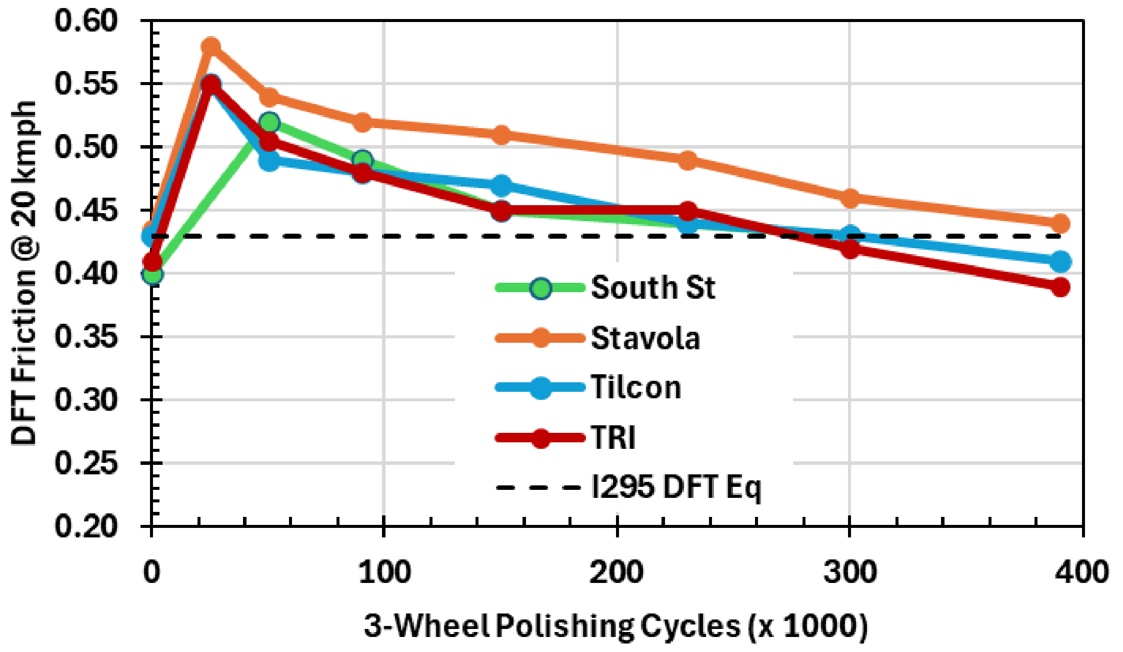


Laser Texture Measurement



Frictional Performance of NJDOT High Performance Thin Overlay (HPTO)

- Fine, 9.5 mm NMAS
- VMA > 18%
- Design AV = 3%
  - Concerns over frictional performance
    - When overcompacting in field, voids low and slight flushing
  - Field testing after 7 years service life compared to same mix (South St) and other HPTO mixes from other suppliers



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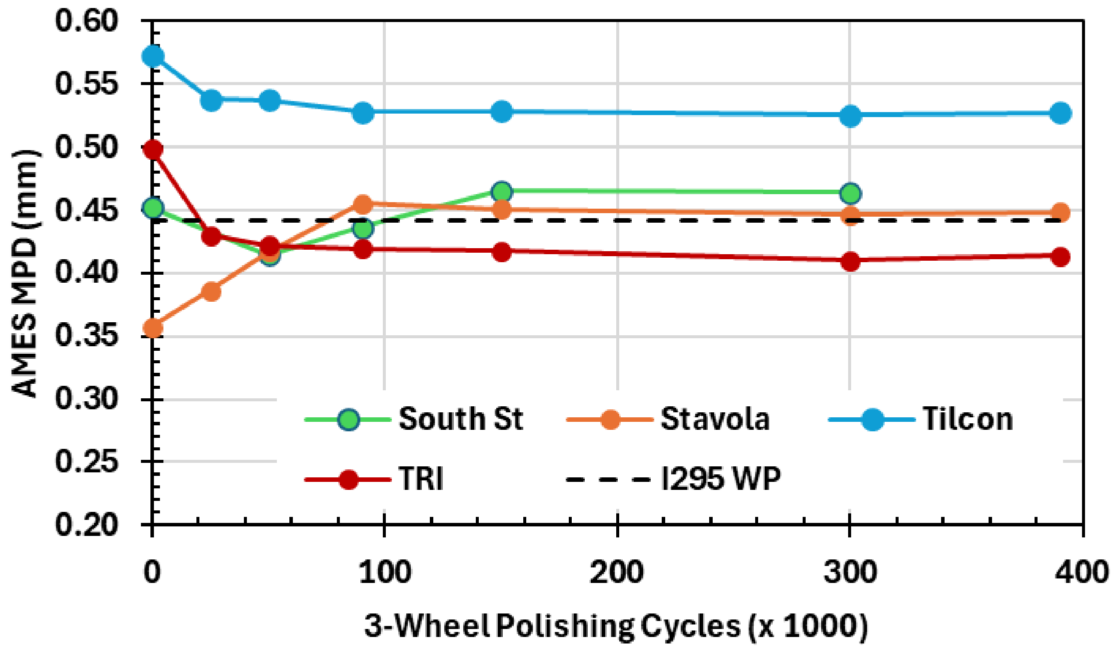


Validating Use of Recycled Aggregate

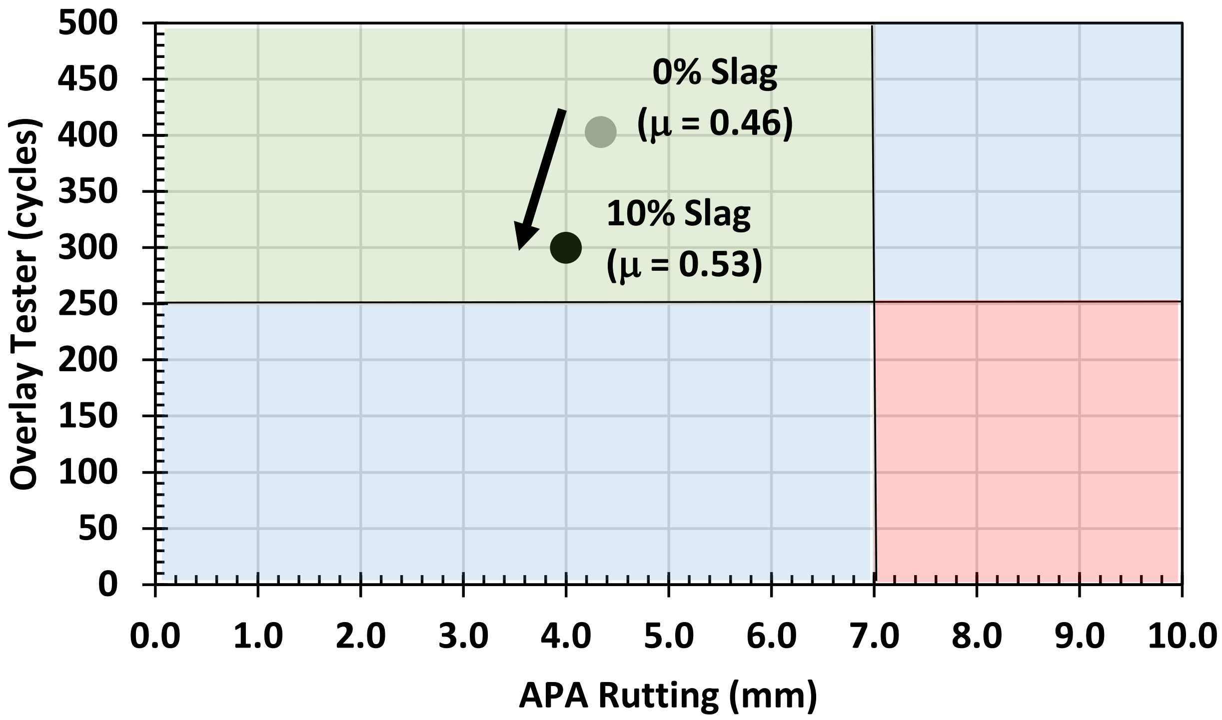
- As BMD currently addresses structural needs, can we incorporate functional needs?
  - Electric Arc Furnace (EAF) slag crushed to #10 size aggregate
  - Substituted at 10% of a washed stone sand for 10% of EAF slag
    - 9.5M64 with 0% RAP
      - Rutting: APA Rutting
      - Cracking: Overlay Tester
      - Friction: Dynamic Friction Tester (DFT)

EAF Slag

Washed Stone Sand

Validating Use of Recycled Aggregate

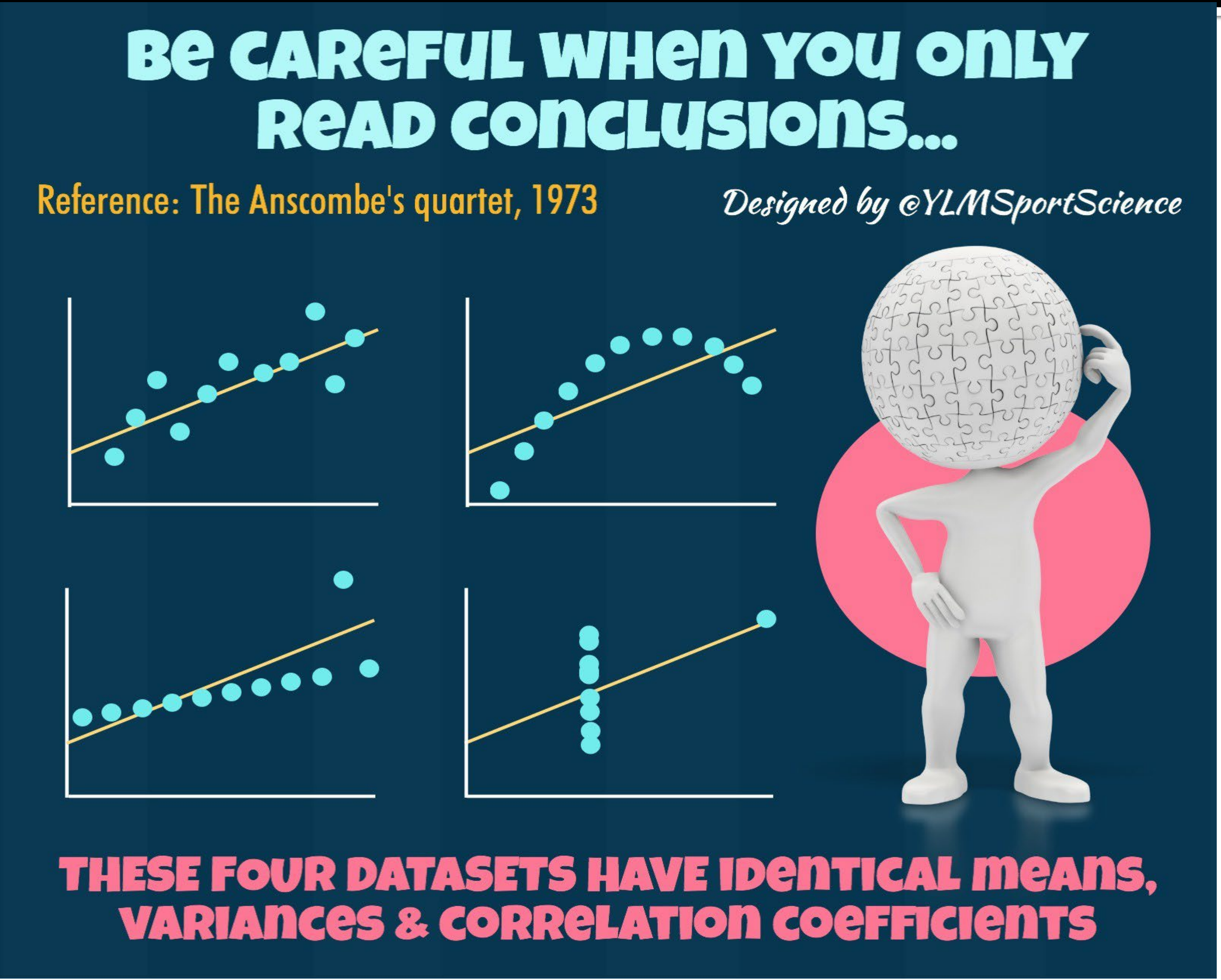
- EAF slag has higher absorption than typical NJ stone
  - At same AC%, reduction in Vbe occurred
- Even though reduction in cracking, improvement in rutting and surface
  - Confidence in performance and functional tests & criteria can allow for volumetric and constituent freedom during design and production



Summary – Future of Volumetrics & BMD

- During "simpler times", volumetrics were extremely helpful in understanding general mixture performance
  - Basic mixes; Neat binders; No RAP; No additives; Conventional batch plant production
- Current materials and production practices reduces some of sensitivity of volumetrics with respect to performance
  - Guidance not gospel!
    - Value within each specific mix
- BMD implementation will be a function of confidence and flexibility
  - Performance testing providing agency with confidence in final product
  - Relaxation of specification parameters to provide flexibility to the supplier to achieve a cost-effective final product
- With specification relaxation in lieu of mix performance testing, agencies may need to better understand functional properties

Thank you for your time!
Questions?



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Predicting Friction from Mixture Constituents

- Work from NC State identified key mix parameters
  - Gradation Parameters
    - Cc = coefficient of curvature
    - Cu = uniformity coefficient
  - MPD (texture mean profile depth) a function of aggregate gradation shape, VFA and P200
  - Friction a function of aggregate gradation shape, significance of texture, Pb and P200

$$Cc = \frac{D_{30}^2}{D_{10} \times D_{60}}$$

$$Cu = \frac{D_{60}}{D_{10}}$$

$$MPD = 0.674 + 0.150 \times Cc - 0.00088 \times P_{200} \times VFA$$

$$Friction = 0.645 + 0.141 \times (Cc + Peak + Valley) - 0.00548 \times (Pb \times P_{200})$$