Enhanced Durability Through Increased In-Place Pavement Density

Mark D. Blow, P.E.

Sr. Regional Engineer

Understanding the Importance of Density

Evolution of Traffic

- Interstate highways - 1956
- AASHO Road Test - 1958-62
  - still widely used for pavement design
  - legal truck load - 73,280 lbs.
- Legal load limit to 80,000 lbs. - 1982
  - 10% load increase
  - 40-50% greater stress to pavement
- Radial tires, higher contact pressure
- FAST Act raising load limit to 120,000 lbs. (in select locations)

Led to Rutting in 1980s

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Courtesy of pavementinteractive.org

Which led to…Superpave

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- Fixed the rutting problem
- Gyratory compaction lowered binder contents
- Add in higher and higher recycled materials?

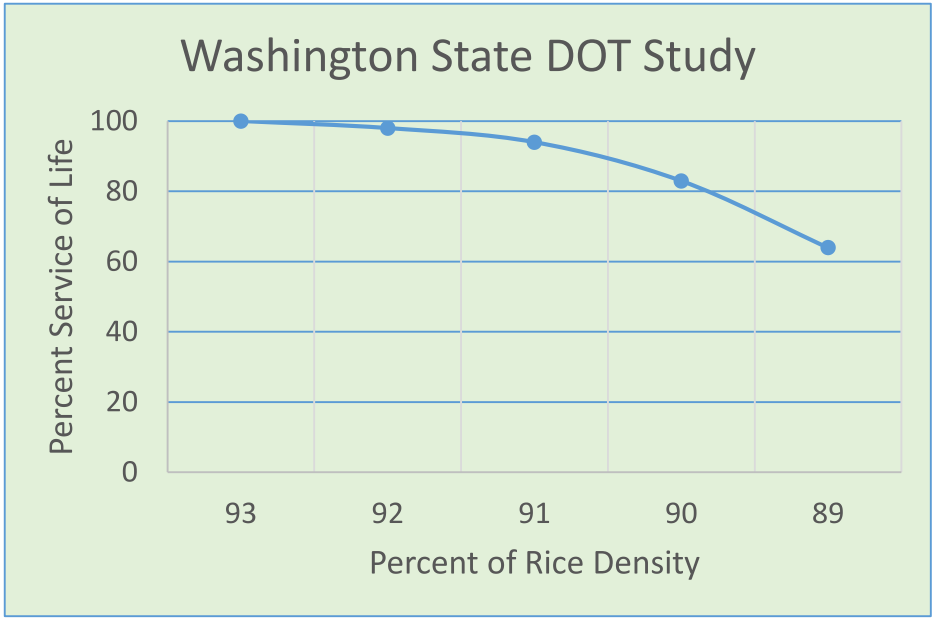
Linking Density to Pavement Durability

Improved Compaction = Improved Performance

A BAD mix with GOOD density out-performed a GOOD mix with POOR density for ride and rutting.

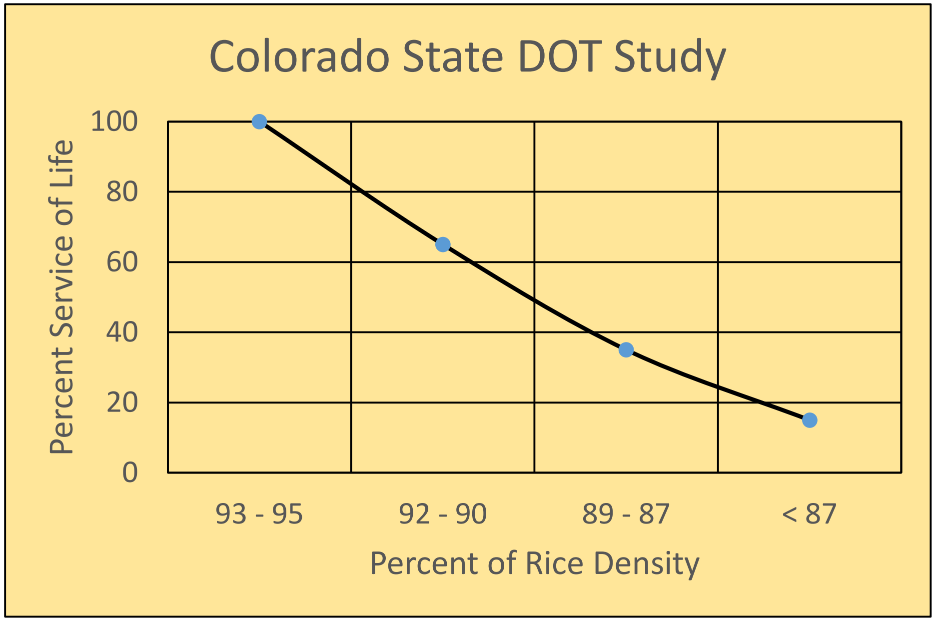
WesTrack Experiment

Density vs. Loss of Pavement Service Life



Thicker Pavements

TRR 1217, 1989



Typical Pavements

CDOT 2013-4, 2013

For both thicker and thinner, reduced in-place density at the time of construction results in significant loss of Service Life!

In-Place Voids vs Fatigue Life

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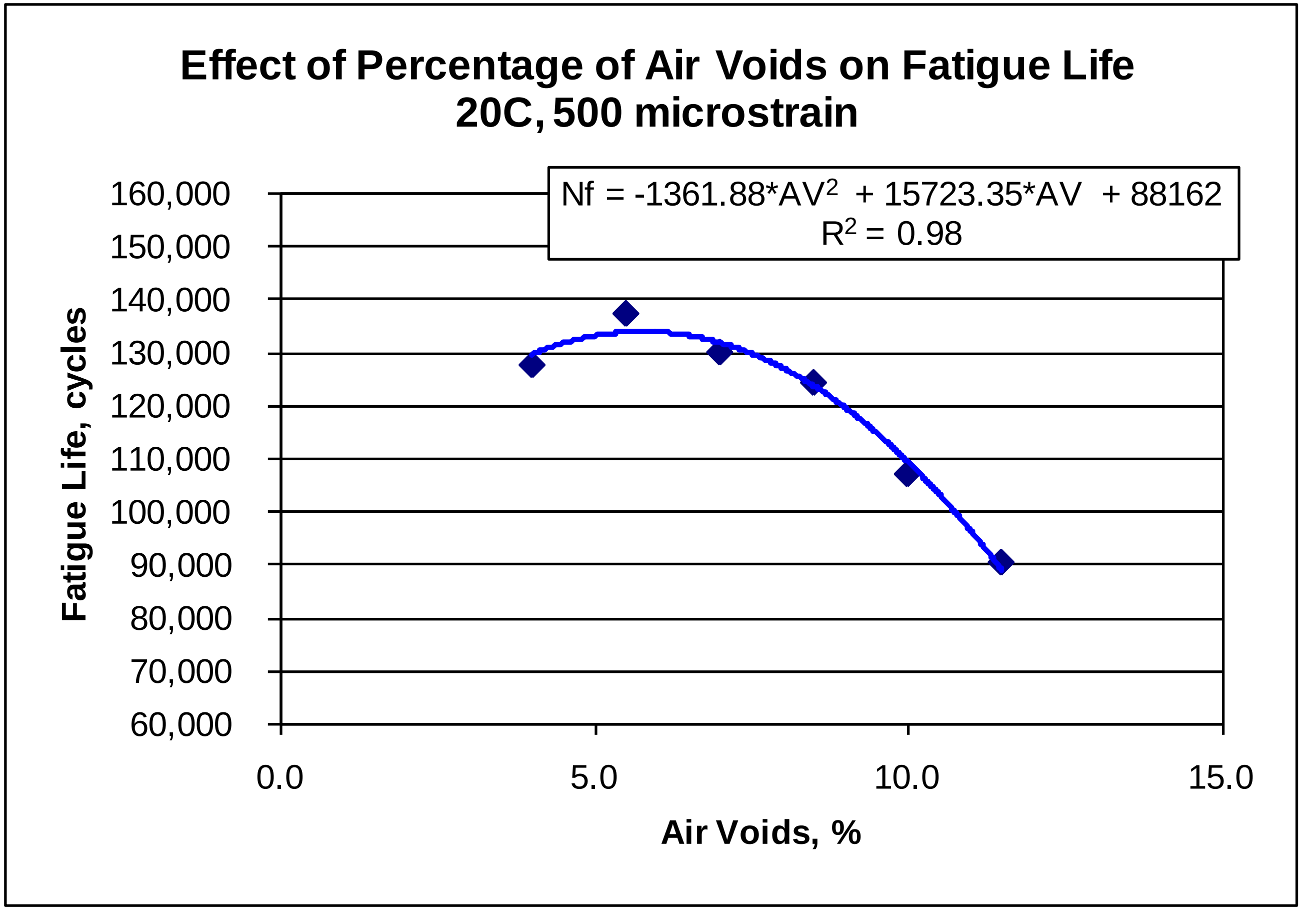

UK-AI Study

1.5% increase in density leads to 10% increase in fatigue life.

Performance Tests @ 7% Air Voids

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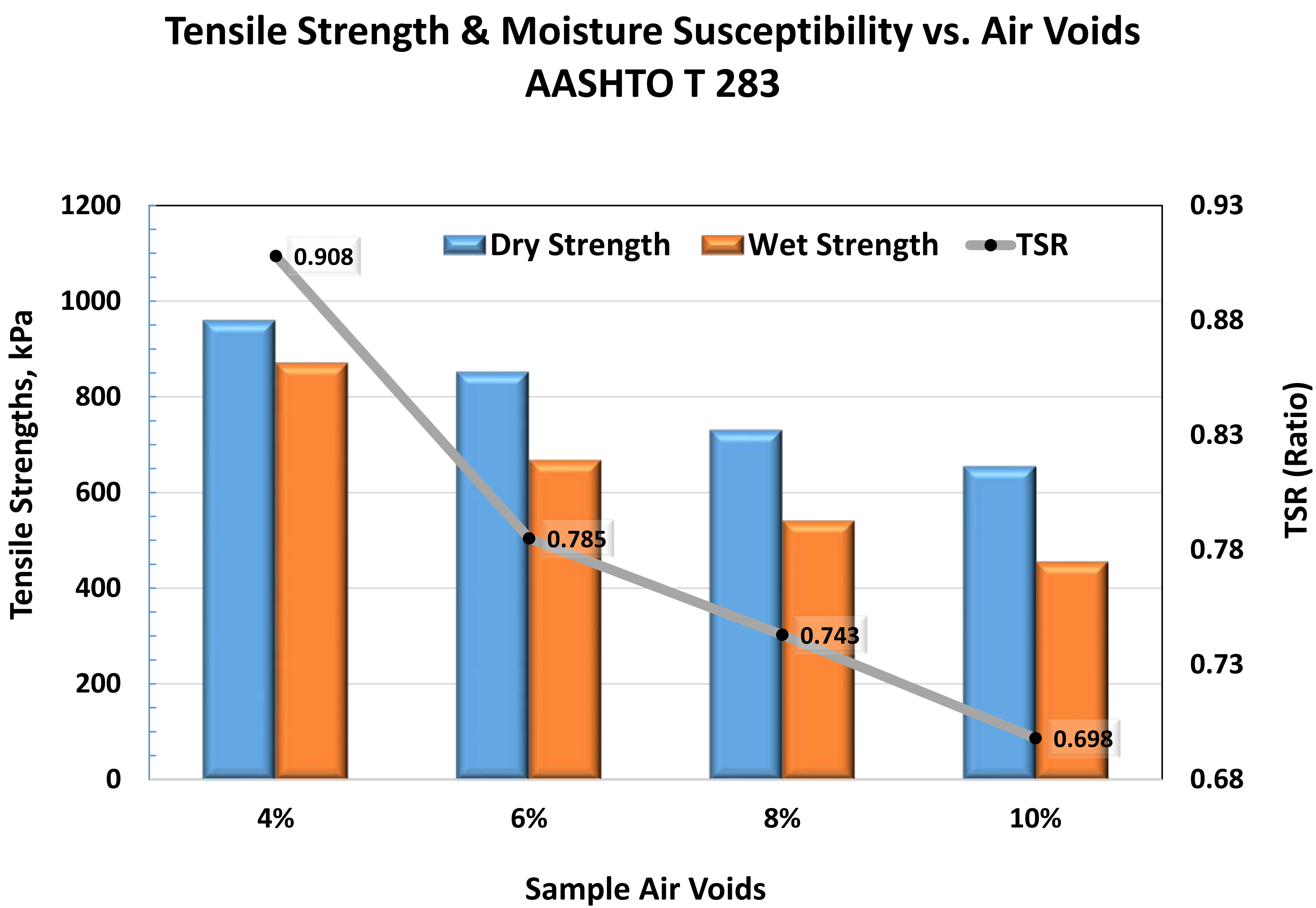

Asphalt Institute Research

NCAT Report 16-02 (2016)

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Literature Review on connecting in-place density to performance

- 5 studies cited for fatigue life
- 7 studies cited for rutting
- "A **1% decrease in air voids** was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8%, to improve the rutting resistance by 7.3 to 66.3%, and to **extend the service life by conservatively 10%**."

Research from New Jersey

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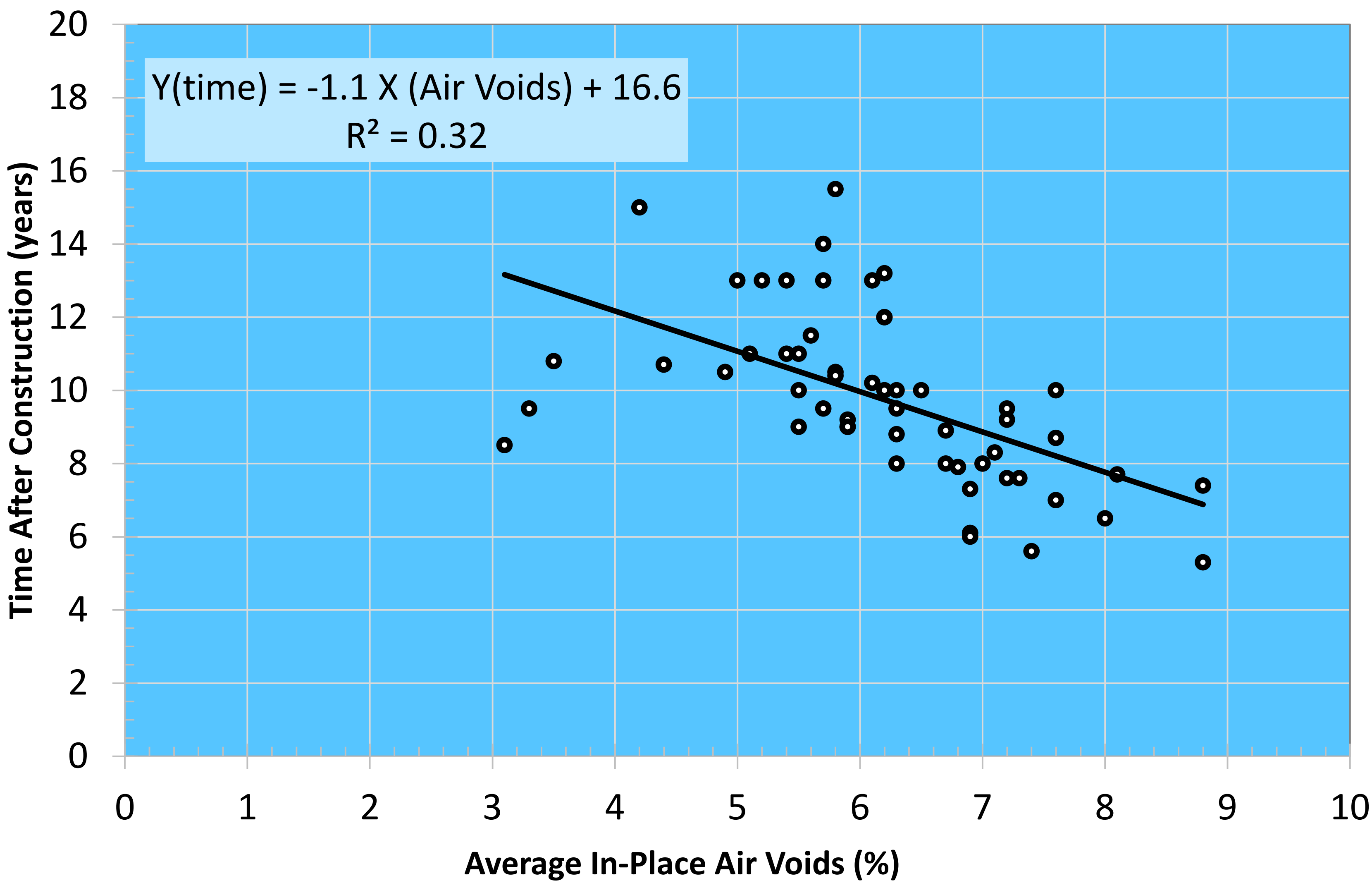
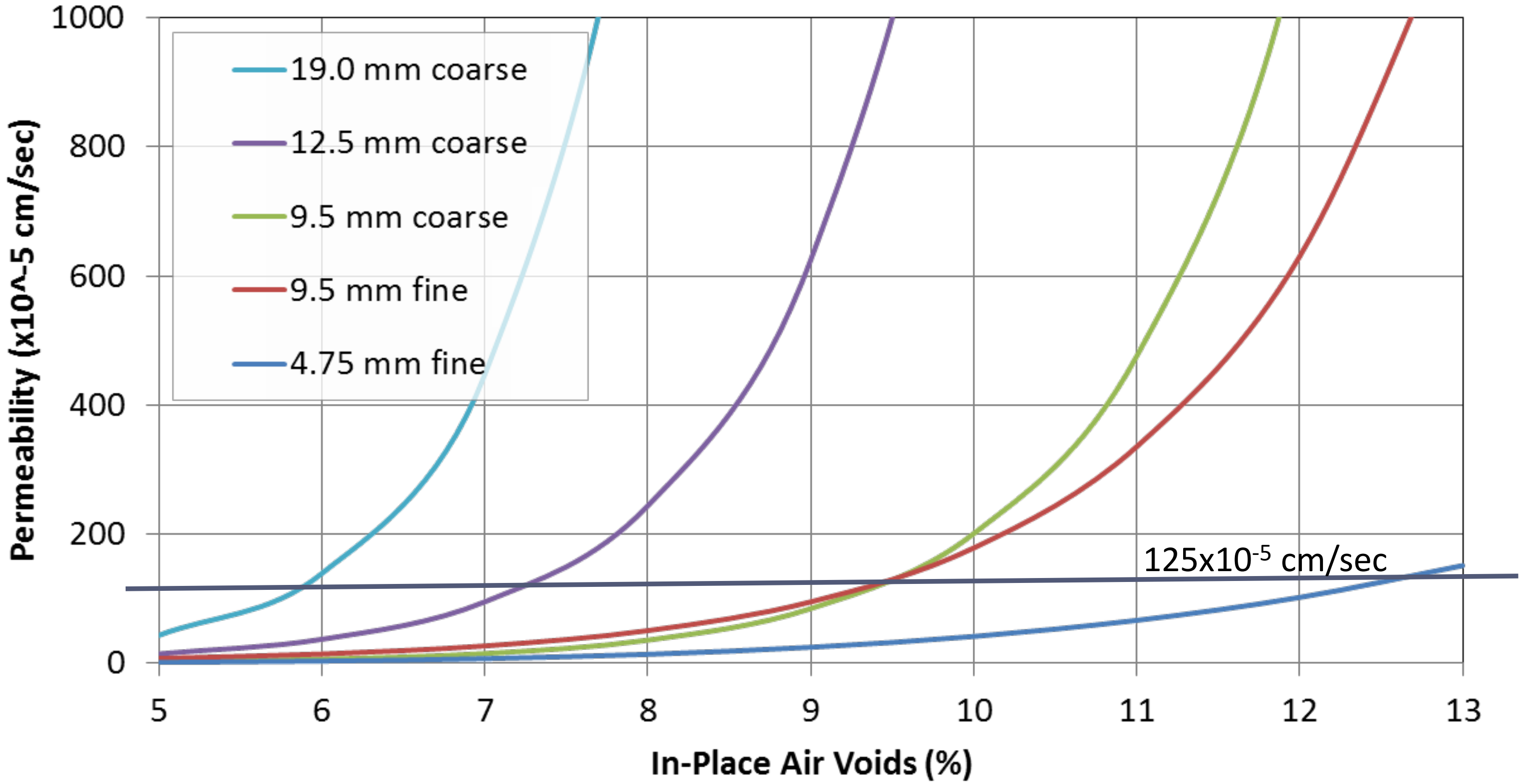


Permeability can be Catastrophic

NCAT Permeability Study



Finer NMAS mixes generally less permeable at equivalent air void levels!

From NCAT Report 03-02

Mix Design Properties that Affect Compactibility and Durability

Mixture Factors Affecting Compaction

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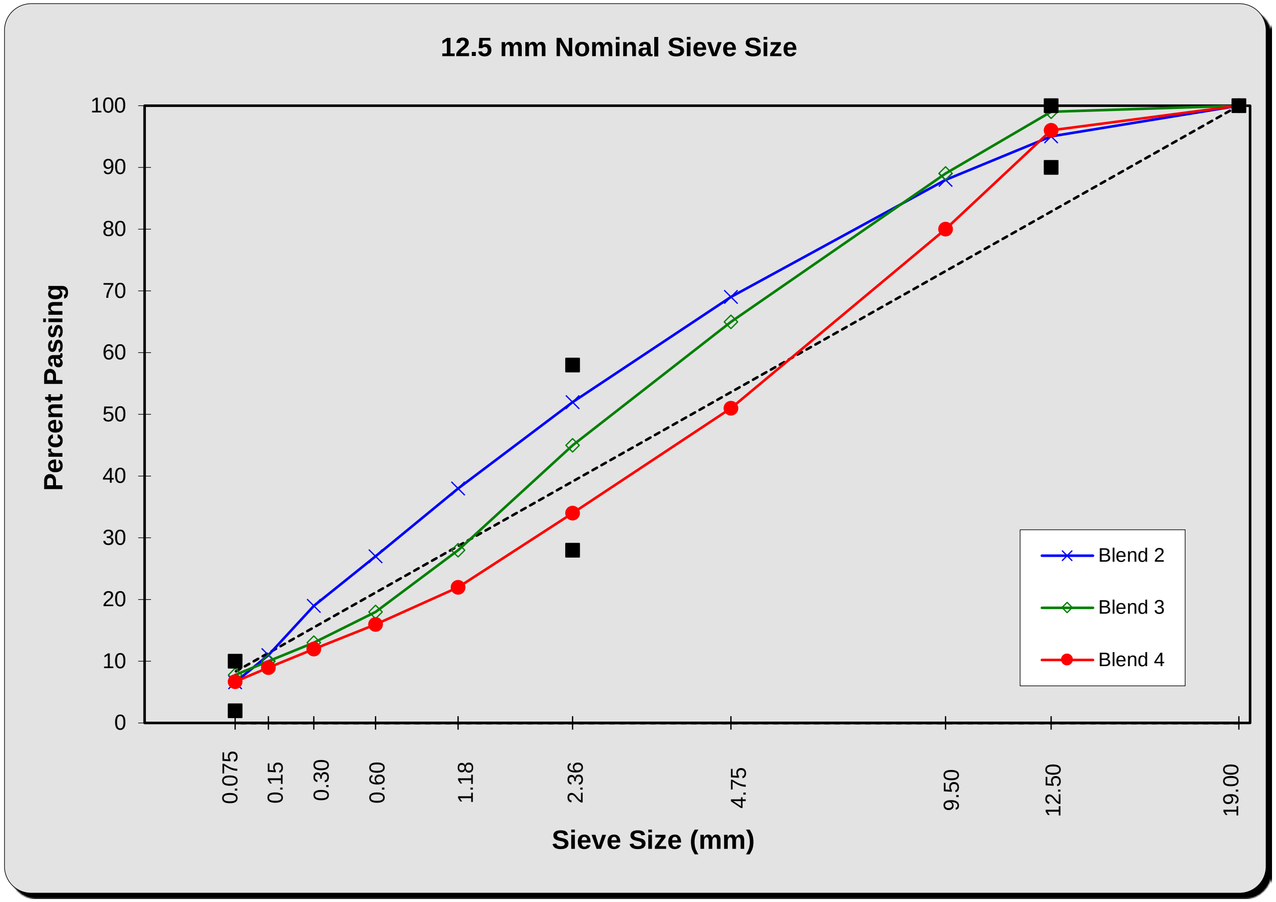
- Mix Properties
  - Aggregate
    - Gradation
    - Angularity
  - Asphalt Cement
    - Grade
    - Quantity
  - Volumetrics
    - Air Voids
    - VMA
    - VFA
  - Balancing a Mix

Choosing a Gradation



Courtesy of NCAT

NCAT Test Track 1st Cycle

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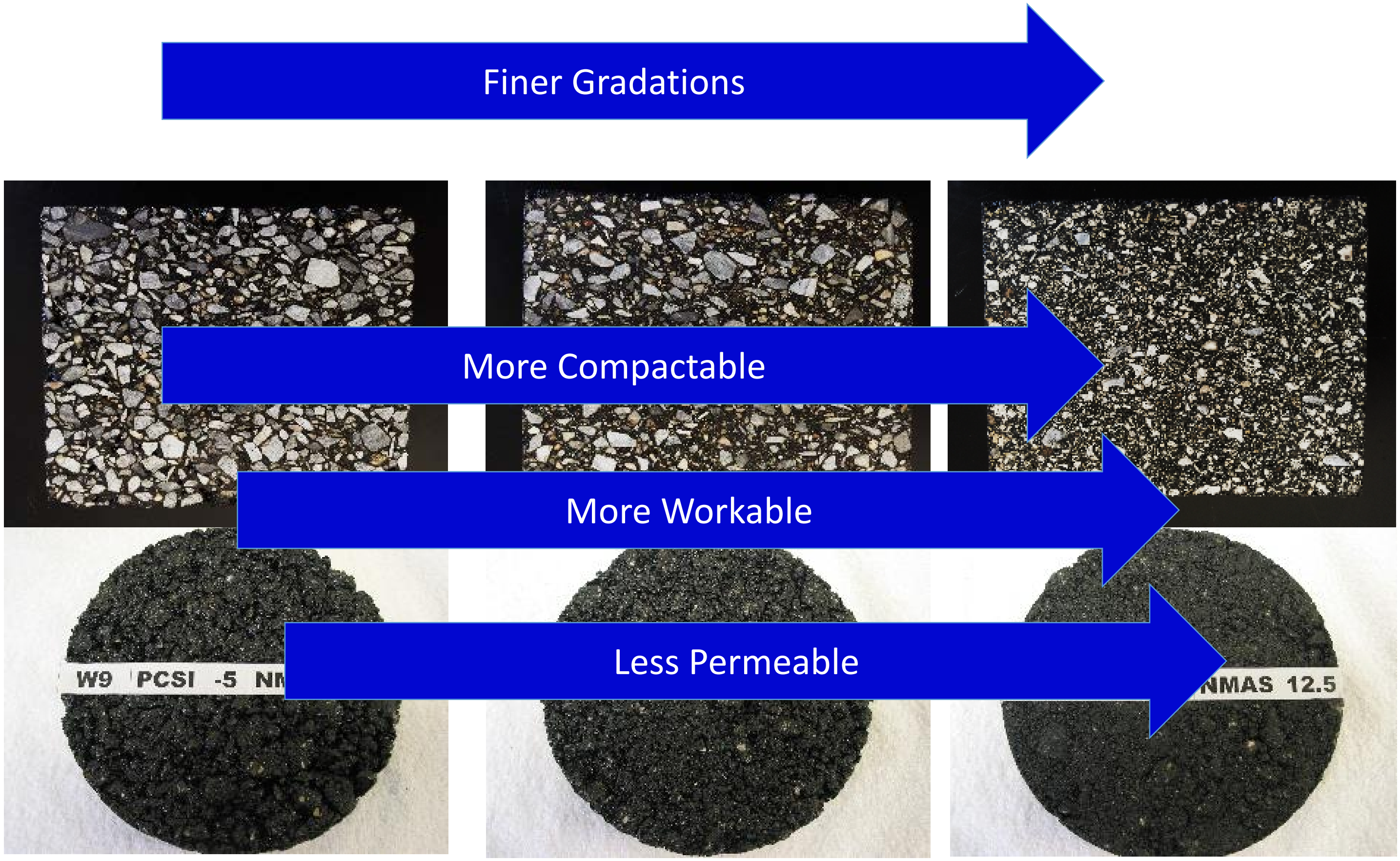
Larger Aggregate Size ≠ Increased Strength

Coarse, intermediate, and fine gradations. No differences in rutting performance!

Courtesy of NCAT

Choosing a Gradation



Courtesy of NCAT

Effect of Aggregate on Compaction

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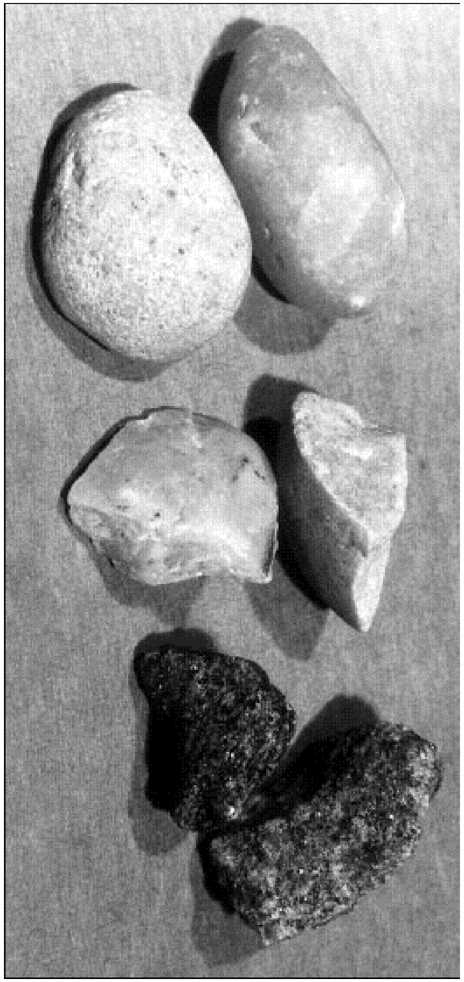
- **GRADATION**
  - continuously-graded, gap-graded, etc.
- **SHAPE**
  - flat & elongated, cubical, round
- **SURFACE TEXTURE**
  - smooth, rough
- **STRENGTH**
  - resistance to breaking, abrasion, etc.



Balanced Mix Design

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"Asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure."

Balanced Mix Design Approach

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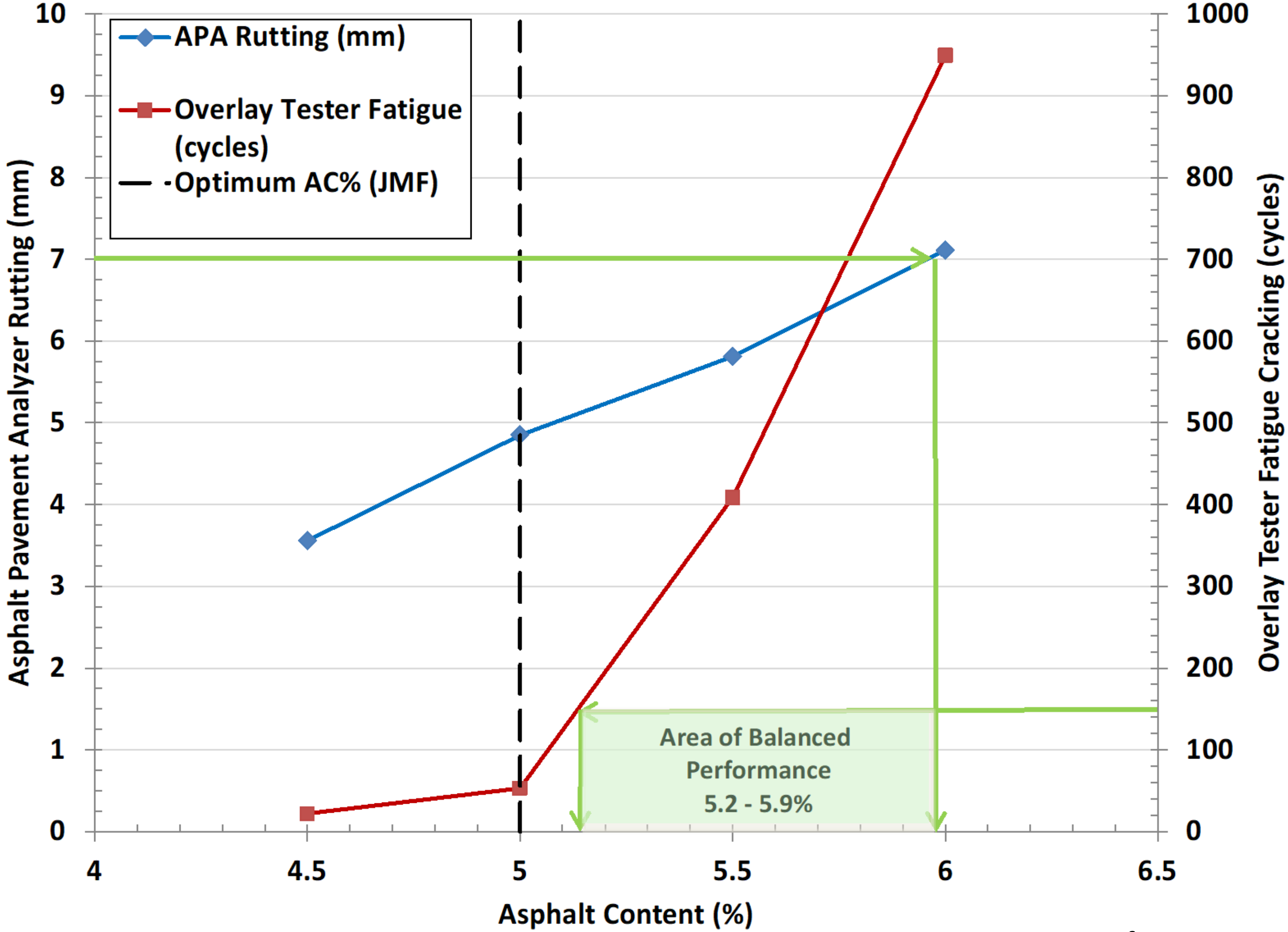
- General Procedure
  - Design and test mix for Rutting
  - Test mix for Cracking and/or Durability
  - Performance Testing
- States that are using this approach
  - Texas
  - Louisiana
  - New Jersey
  - Illinois
  - California
  - Wisconsin

New Jersey Balanced Design



Courtesy of Tom Bennert

FHWA Performance Based Mix Design

	Fatigue Cracking	Rutting
Design Air Voids For every 1% increase	40% increase	22% decrease
Design VMA For every 1% increase	73% decrease	32% increase
Compaction Density For every 1% lower in-place Air Voids **(Increasing Density Improved Both!)**	19% decrease	10% decrease

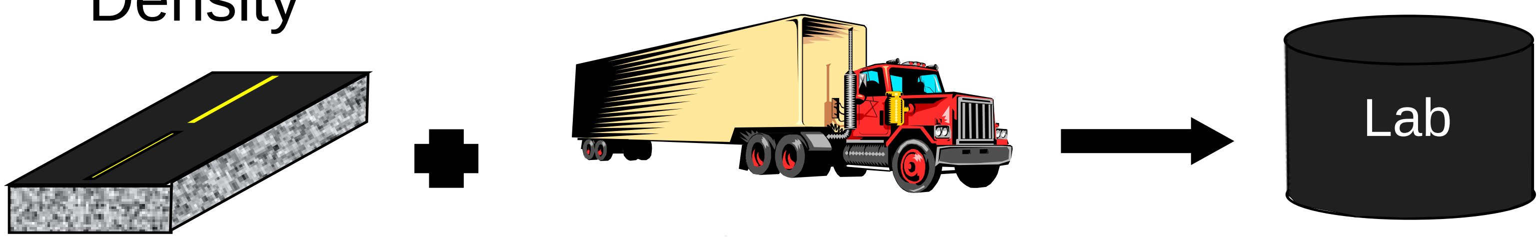
Courtesy of Nelson Gibson

Lab-Molded / Roadway Air Voids

Why are the target values for lab-molded air voids and roadway air voids different? Lab-molded air voids simulate the in-place density of HMA after it has endured several years of traffic in the roadway.

In-place Density

Lab-Molded Density



Future Traffic

<u>Air Voids</u>

≈15-25% Before Rolling

6 - 8 % After Rolling

<u>Air Voids</u>

4% Superpave

Superpave 5 – Purdue Research

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- Design at 5% air voids and compact to 5% voids in field (95% G_{mm})
- Lower design gyration to increase in-place density
  - No change in rutting resistance
  - No change in stiffness
  - Improve pavement life
    - Reduced aging
- Maintained Volume of Eff. Binder (V_{be})
  - Increased VMA by 1%

Courtesy of Gerald Huber

Factors Affecting Compaction

Lift Thickness Effect on Compaction

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- Aggregates need room to densify
- Too thin vs. NMAS leads to:
  - Roller bridging
  - Aggregate lockup
  - Aggregate breakage
  - **Compaction Difficulties**

Superpave Size Designations

Superpave Designation	Nom Max Size, mm	Max Size, mm
37.5 mm	37.5	50.0
25.0 mm	25.0	37.5
19.0 mm	19.0	25.0
12.5 mm	12.5	19.0
9.5 mm	9.5	12.5

Mix Type

NMAS grading is different than older "Topsize" Grading

Old Rule of Thumb - Minimum lift thickness = 2x Topsize

✓NCHRP Report 531 (2004)

- Thicker lifts are easier to compact
- Cool slower, providing longer compaction time
- Reduce paver speed

NMAS - Minimum compacted thickness

✓4 times nominal aggregate size

✓3 times nominal aggregate size for fine graded mixtures

Minimum - NOT MAXIMUM !

Design Problems

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- The job mix formula (JMF) typically requires a gradation be developed that meets the specifications.
- Field production gradation tolerances are then applied to the JMF to account for variations during production.
- Lift thickness that meet the minimum guidelines for the specified mixture NMAS are often selected during project design.
- If the JMF falls at the lower limit of the gradation specified for the NMAS mix selected, and
- The field production goes coarse as allowed by the production tolerances,
- The actual NMAS placed is different than that specified in the plans
- This can result in poor placement, compaction and durability

Wisconsin DOT Specified Mix Gradations

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Standard Superpave Gradation Recommendations

TABLE 460-1 AGGREGATE GRADATION MASTER RANGE AND VMA REQUIREMENTS

SIEVE	PERCENT PASSING DESIGNATED SIEVES						
	NOMINAL SIZE						
	No. 1 (37.5 mm)	No. 2 (25.0 mm)	No.3 (19.0 mm)	No. 4 (12.5 mm)	No. 5 (9.5 mm)	SMA No. 4 (12.5 mm)	SMA No. 5 (9.5 mm)
50.0-mm	100						
37.5-mm	90 –100	100					
25.0-mm	90 max	90 -100	100				
19.0-mm	___	90 max	90 -100	100		100	
12.5-mm	___	___	90 max	90 -100	100	90 - 97	100
9.5-mm	___	___	___	90 max	90 -100	58 - 72	90 - 100
4.75-mm	___	___	___	___	90 max	25 - 35	35 - 45
2.36-mm	15 - 41	19 - 45	23 - 49	28 - 58	32 - 67	15 - 25	18 - 28
75-µm	0 - 6.0	1.0 - 7.0	2.0 - 8.0	2.0 - 10.0	2.0 - 10.0	8.0 - 12.0	10.0 - 14.0
% MINIMUM VMA	11.0	12.0	13.0	14.0[1]	15.0[2]	16.0	17.0

[1] 14.5 for LT and MT mixes.

[2] 15.5 for LT and MT mixes.

NYSDOT - Marshall Mix Gradations

TABLE 403-1 COMPOSITION OF HOT MIX ASPHALT MIXTURES

Mixture Requirements[1]	Base				Binder		Shim		Top[3,4]			
	Type 1		Type 2		Type 3		Type 5		Type 6, 6F2, 6F3		Type 7, 7F2, 7F3	
Screen Sizes	General limits % Passing	Job Mix Tol. %	General limits % Passing	Job Mix Tol. %	General limits % Passing	Job Mix Tol. %	General limits % Passing	Job Mix Tol. %	General limits % Passing	Job Mix Tol. %	General limits % Passing	Job Mix Tol. %
50.0 mm	100	-	100	-	-	-	-	-	-	-	-	-
37.5 mm	90 -100	-	75 - 100	7	100	-	-	-	-	-	-	-
25.0 mm	78 - 95	5	55 - 80	8	95 - 100	-	-	-	100	-	-	-
12.5 mm	57 - 84	6	23 - 42	7	70 - 90	6	-	-	95-100	-	100	-
6.3 mm	40 - 72	7	5 - 20	6	48 - 74	7	100	-	65 - 85	7	90 -100	--
3.2 mm	26 - 57	7	2 - 15	4	32 - 62	7	80 - 100	6	36 - 65	7	45 - 70	6
850 µm	12 - 36	7	-	-	15 - 39	7	32 - 72	7	15 - 39	7	15 - 40	7
425 µm	8 - 25	7	-	-	8 - 27	7	18 - 52	7	8 - 27	7	8 - 27	7
180 µm	4 -16	4	-	-	4 - 16	4	7- 26	4	4 - 16	4	4 - 16	4
75 µm	2 - 8	2	-	-	2 - 8	2	2- 12	2	2- 6	2	2 - 6	2
PGB Content,	4.0 - 6.0	0.4	2.5 - 4.5	0.4	4.5 - 6.5	0.4	7.0-9.5	0.4	5.4- 7.0	NA	5.7 -8.0	NA

Ex. - FAA P-401 Gradation Specs.

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AGGREGATE - BITUMINOUS PAVEMENTS

Sieve Size	Percentage by Weight Passing Sieves			
	1-1/4"max	1"max	3/4"max	1/2"max
1-1/4 in. (30.0 mm)	100	--	--	--
1 in. (24.0 mm)	86-98	100	--	--
3/4 in. (19.0 mm)	68-93	76-98	100	--
1/2 in. (12.5 mm)	57-81	66-86	79-99	100
3/8 in. (9.5 mm)	49-69	57-77	68-88	79-99
No. 4 (4.75 mm)	34-54	40-60	48-68	58-78
No. 8 (2.36 mm)	22-42	26-46	33-53	39-59
No. 16 (1.18 mm)	13-33	17-37	20-40	26-46
No. 30 (0.600 mm)	8-24	11-27	14-30	19-35
No. 50 (0.300 mm)	6-18	7-19	9-21	12-24
No. 100 (0.150 mm)	4-12	6-16	6-16	7-17
No. 200 (0.075 mm)	3-6	3-6	3-6	3-6
Asphalt percent:				
Stone or gravel	4.5-7.0	4.5-7.0	5.0-7.5	5.5-8.0
Slag	5.0-7.5	5.0-7.5	6.5-9.5	7.0-10.5

NMAS in SGC Experiment

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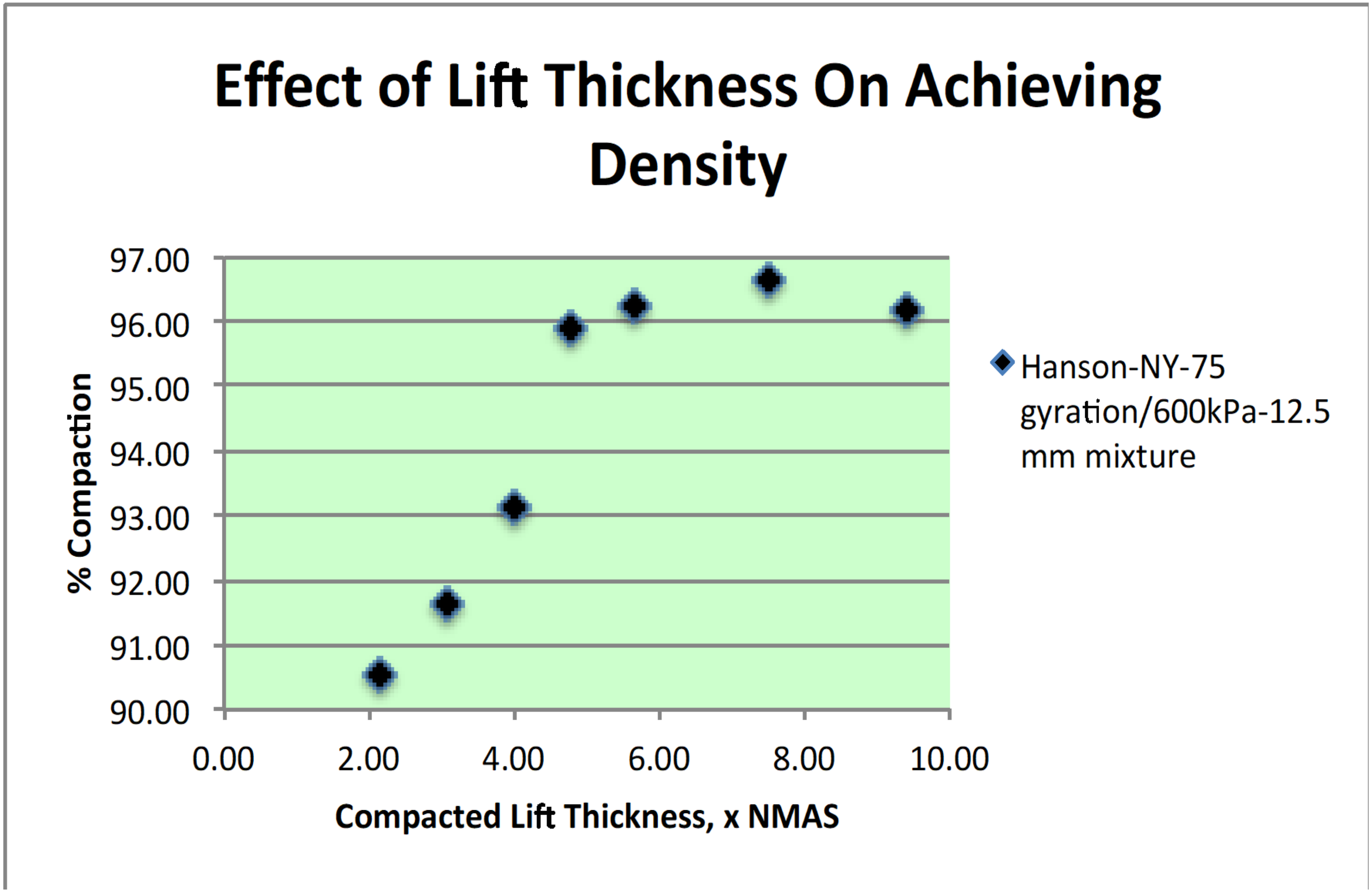
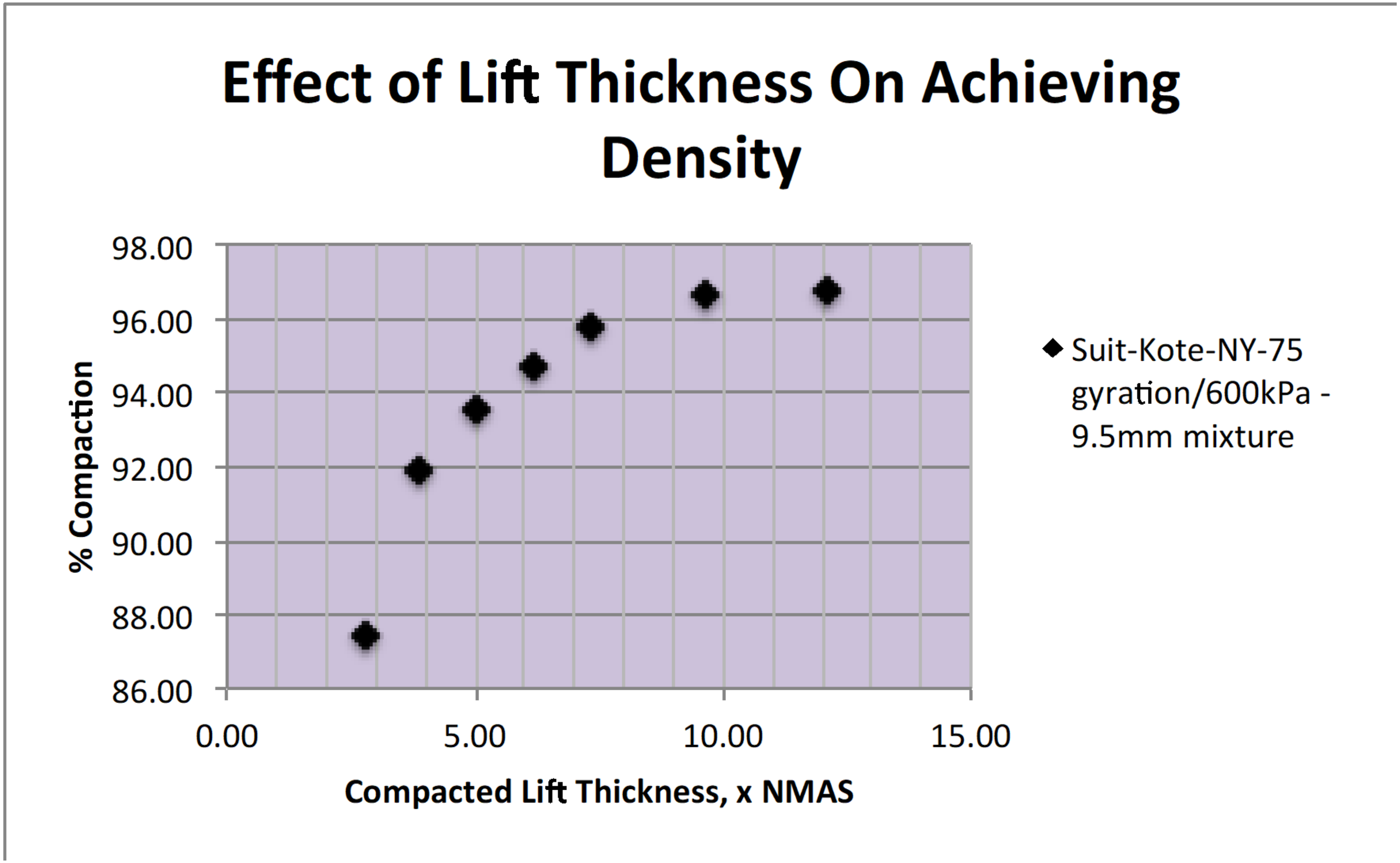


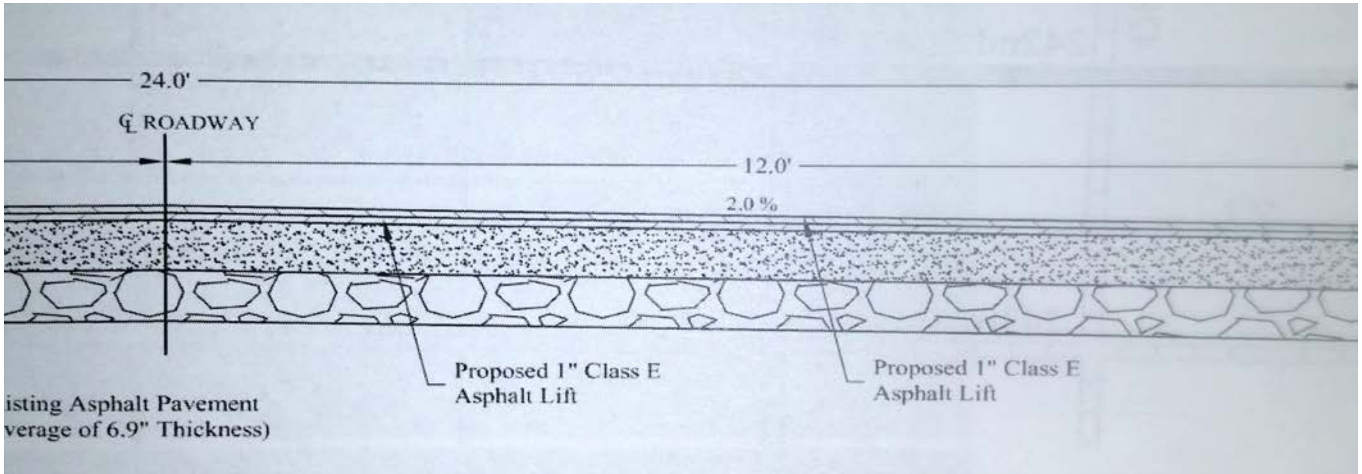
12.5 mm Limestone mix @ 75 gyrations

SGC Density vs. Lift Thickness



9.5 mm crushed gravel @ 75 gyrations

Lift Thickness



Lift Thickness

Thin lift overlays require finer mixture types!!

Superpave Mix Designations

Superpave Mix Designations	Maximum Size	Minimum Compacted Lift Thickness (Fine)	Minimum Compacted Lift Thickness (Coarse)
37.5 mm (1-1/2 inch)	50.0 mm (2 inch)	112.5 mm (4-1/2 inch)	150 mm (6 inch)
25.0 mm (1 inch)	37.5 mm (1-1/2 inch)	75 mm (3 inch)	100 mm (4 inch)
19.0 mm (3/4 inch)	25.0 mm (1 inch)	57 mm (2-1/4 inch)	76 mm (3 inch)
12.5 mm (1/2 inch)	19.0 mm (3/4 inch)	37.5 mm (1-1/2 inch)	50 mm (2 inch)
9.5 mm (3/8 inch)	12.5 mm (1/2 inch)	28.5 mm (1-1/8 inch)	38 mm (1-1/2 inch)
4.75 mm (3/16 inch)	9.5 mm (3/8 inch)	14.25 mm (9/16 inch)	19 mm (3/4 inch)

Thicker lifts are easier to compact !!

Effect of Temperature on Compaction

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Material Cooling

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- Thicker = More Time for Compaction
- Free tools for estimating compaction time
  - PaveCool—single lift (generation 1)
    - PC
    - iOs App
    - Google App
  - MultiCool—multiple lifts (generation 2)
    - PC
    - Google App
    - Mobile Web

PaveCool Example

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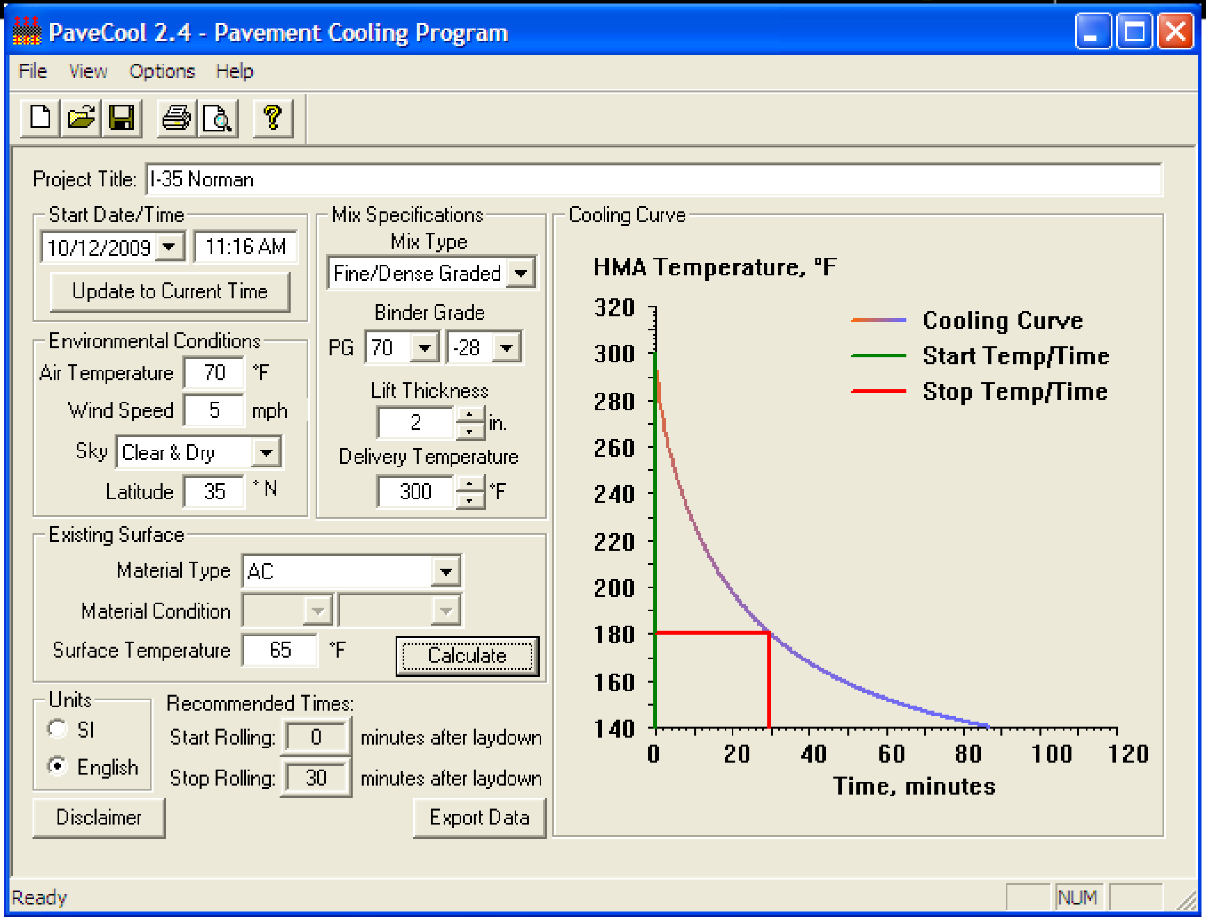
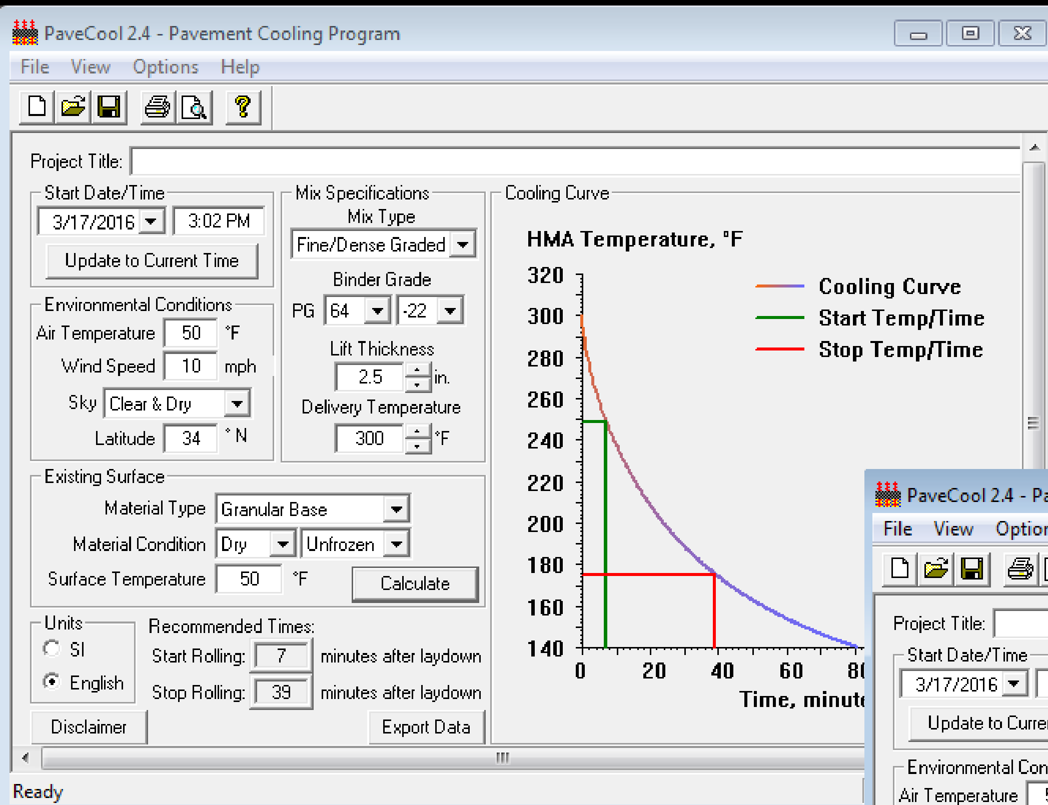
- Key Inputs
  - Temperature
    - Air
    - Base
    - Mix Delivery
  - Wind Speed
  - Lift Thickness



- Output
  - Cooling Curve
  - Estimated Compaction Time

PaveCool Example

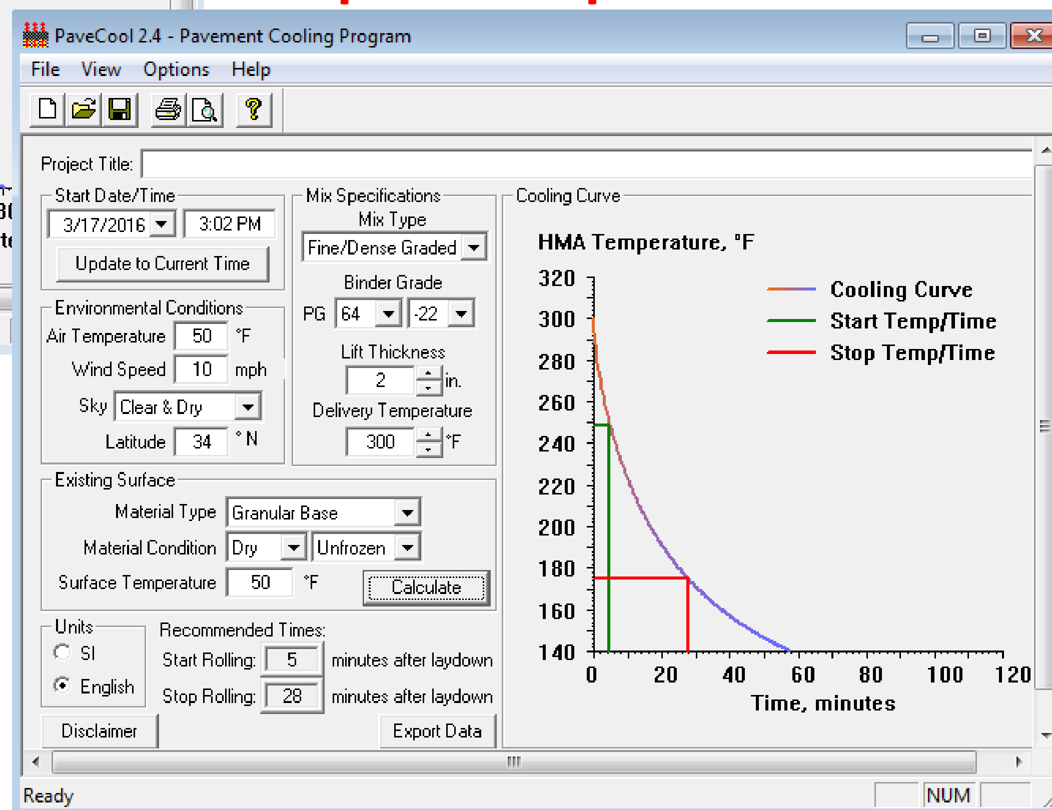


2.5 Inch Lift

50°F Air, Surface Temp

Mix Delivery temp - 300°F

39 minutes to complete compaction operations



2 Inch Lift

50°F Air, Surface Temp

Mix Delivery temp - 300°F

28 minutes to complete compaction operations

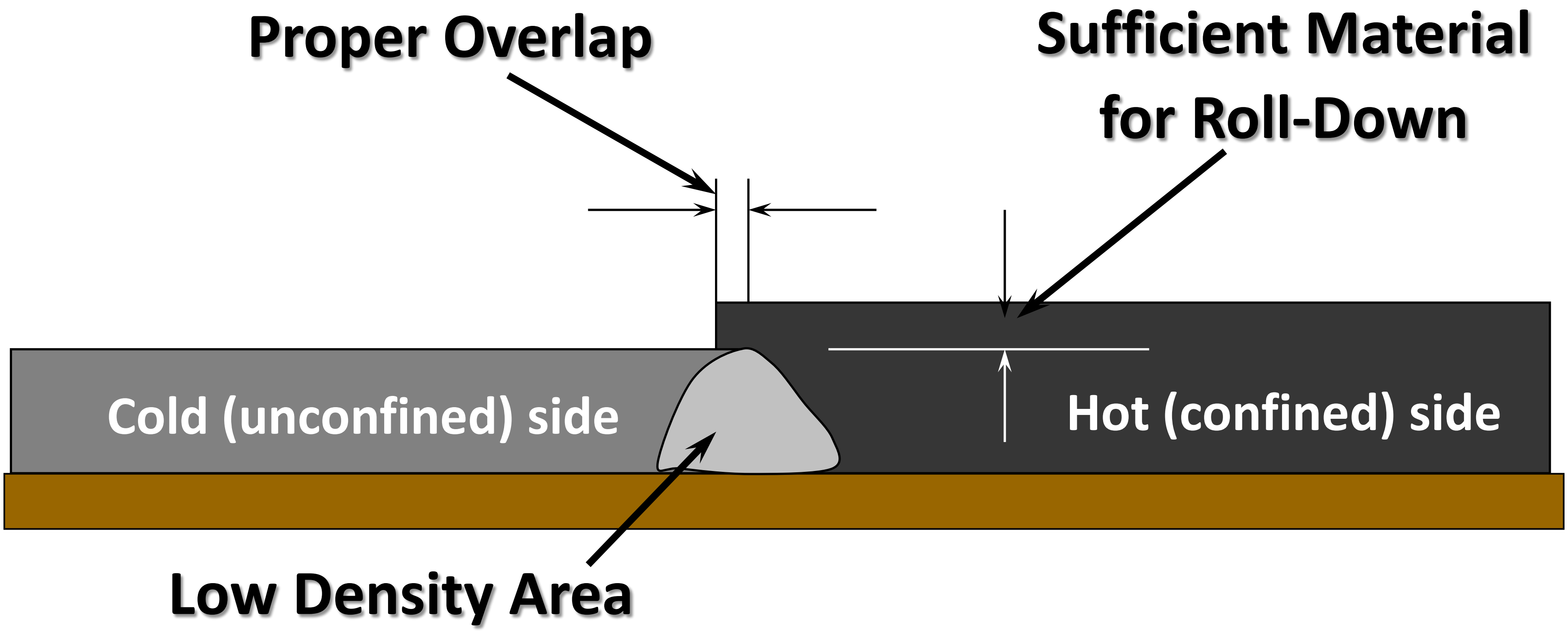
Paving Goals

- Continuous Operations
  - Hot plant running nonstop
  - Paver running at constant speed nonstop
- Production = Hauling = Paver Processing = Compaction Speed

Achieving Density on HMA Joints

Longitudinal Joints

We Know Unsupported Edge Will Have Lower Density



Please note Cold side and Hot side, as they are terms used throughout this Workshop.

Joint vs. Mat Density

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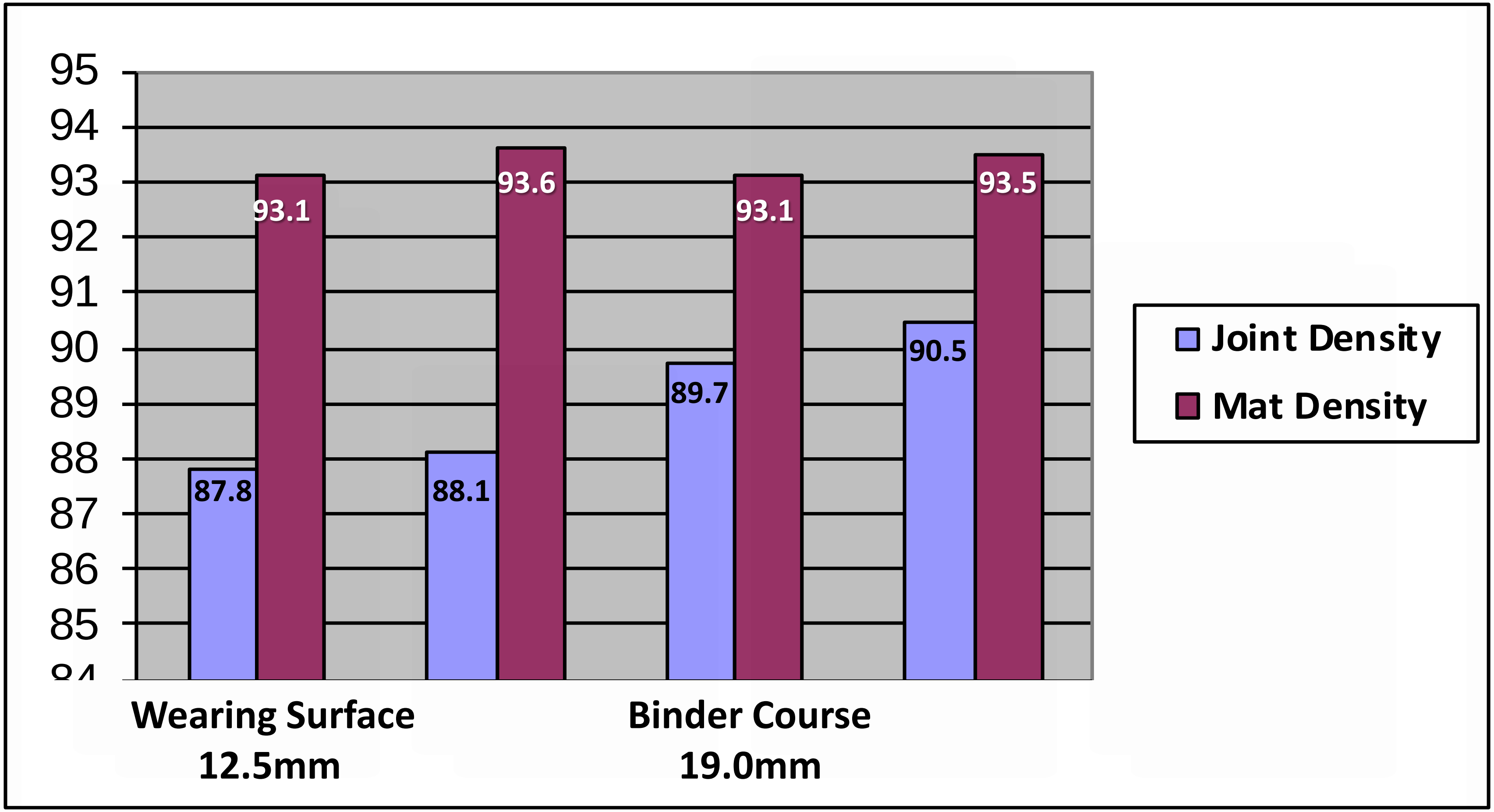
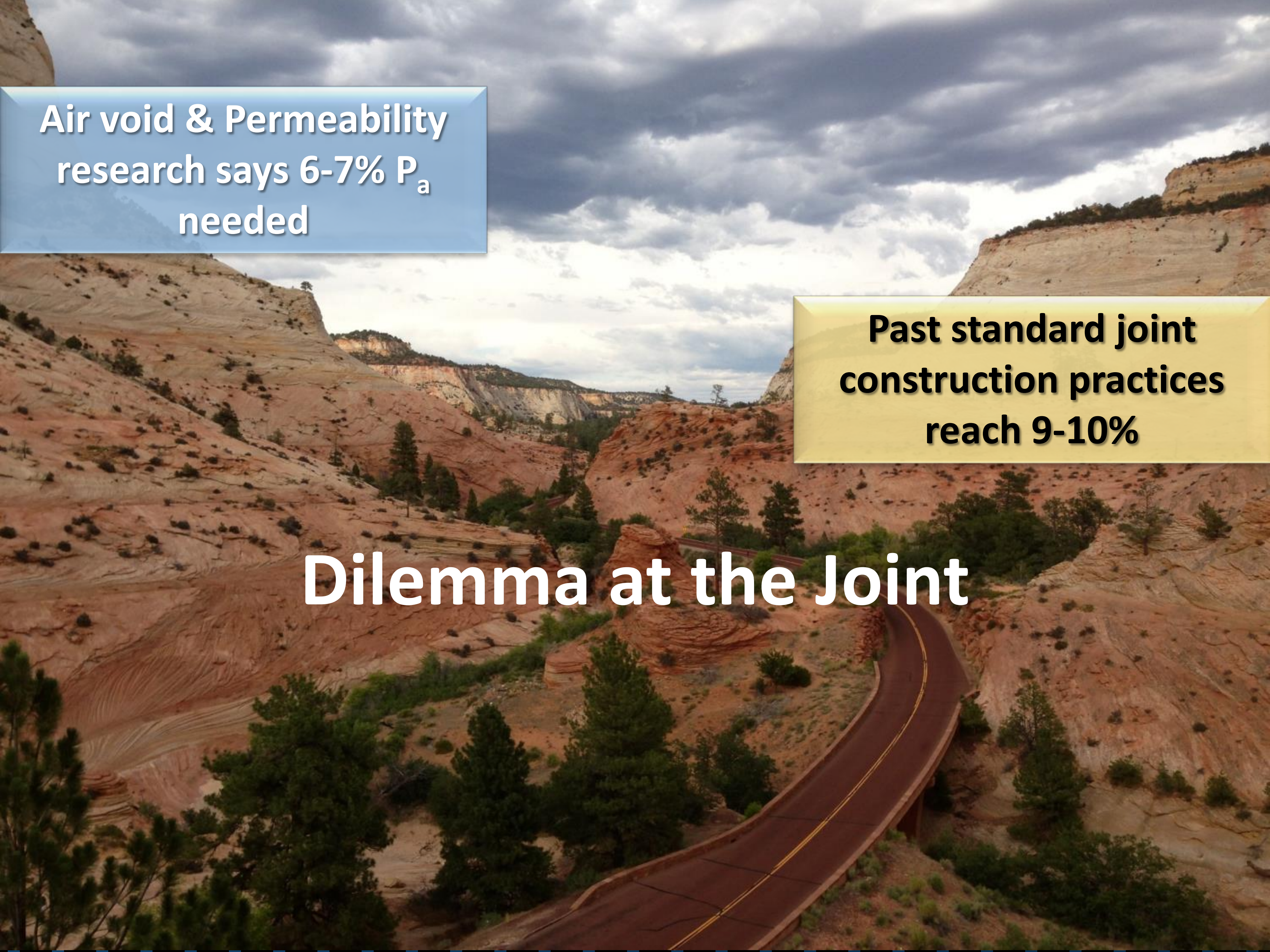


2006-2007, with 6" cores taken over joint


Air void & Permeability research says 6-7% P_a needed
Past standard joint construction practices reach 9-10%
Dilemma at the Joint

The Pennsylvania Example

Joint Issues

In PA

PA Joint Density Spec Highlights

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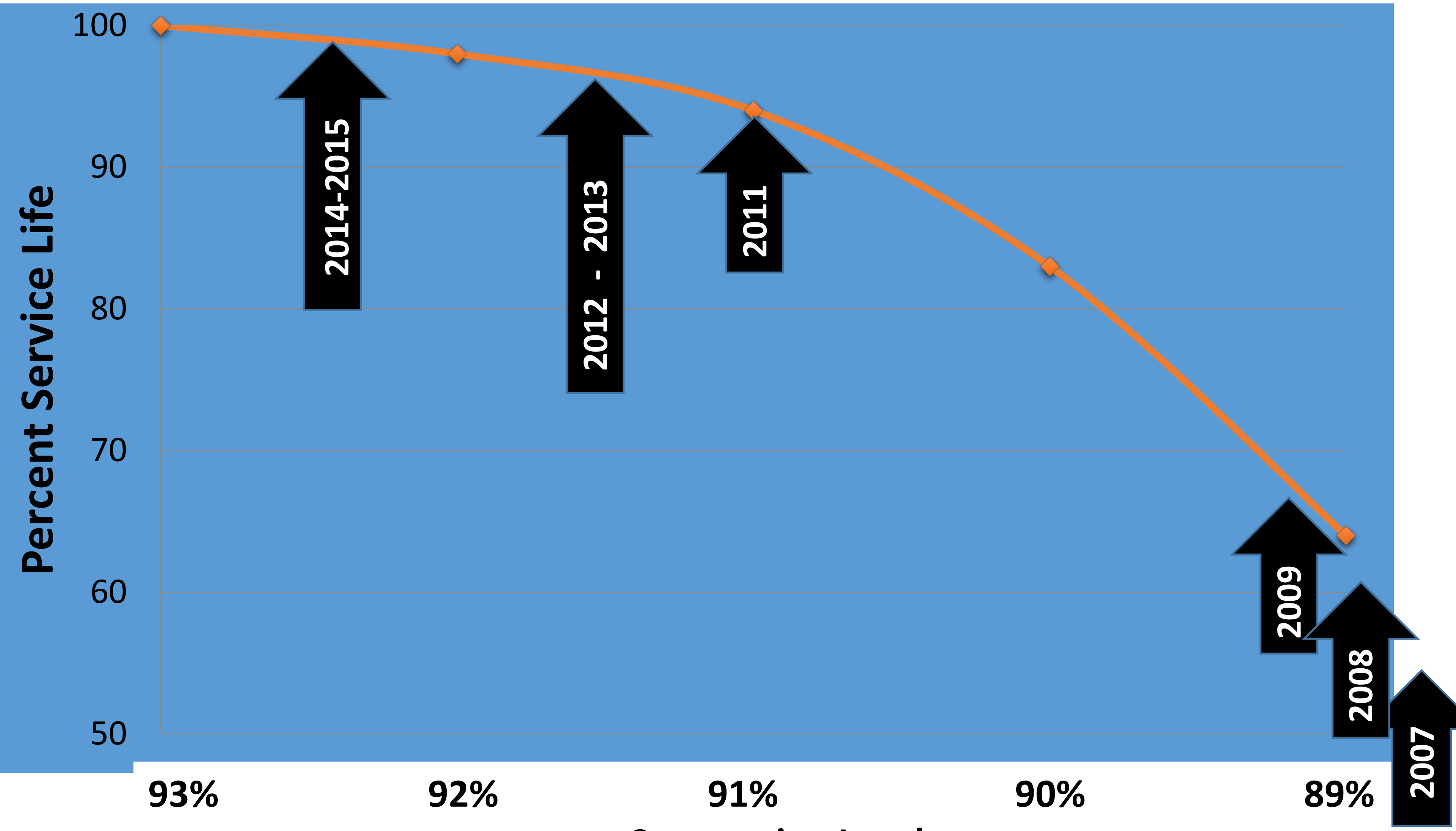
- Both type of LJs allowed (butt or notch wedge)
- Joint Lot = 12,500'.   Core every 2,500'.   5 cores per lot.
- Core location
  - For Butt: directly over visible joint
  - For Notch Wedge: middle of wedge
- Percent Within Limits (PWL)
  - Incentive starts at 80% PWL
  - Disincentive at <50% PWL
- Lower Specification Limit
  - 2010-2013: 89% TMD
  - 2014-2015: 90% TMD
- Corrective action for < 88% TMD

PA: How Did it Work?

In-place Density Summary, Reported by PA DOT				
Year	# Lots	Avg. Roadway Density, %TMD	**Avg. Joint Density, %TMD**	
2007	18	93.9	**87.8**	begin measuring at Jt.
2008	43	94.1	**88.9**	method spec
2009	29	94.1	**89.2**	method spec
2010	No data, transition to PWL spec			
2011	137	94.1	**91.0**	PWL, LSL 89%
2012	162	94.0	**91.6**	PWL, LSL 89%
2013	167	93.9	**91.4**	PWL, LSL 89%
2014	316	94.1	**92.3**	PWL, LSL 90%
2015	493		**92.6**	PWL, LSL 90%

PA: Increased Projected Life of Joints Due to Improved Joint Density



PA: Annual Statewide Totals on Incentives/Disincentives for Joint Density

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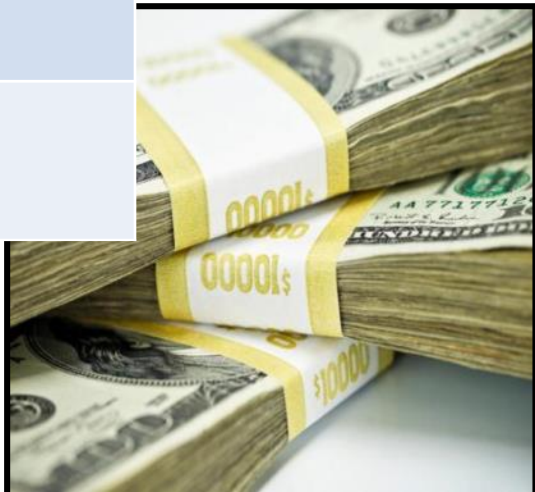
Year	Incentive Payments	Disincentive Payments
2011	$268K	$99K
2012	$489K	$63K
2013	$588K	$25K
2014	$1,002K	$127K



Note: MI and CT have averaged over 91.5%, and AK over 92.0% density at the joint over recent construction seasons

Constructing a Quality Longitudinal Joint

- Types of LJs
- Planning for the Joint
- Placement and Rolling

Use best practices for paving previously discussed!

The Best Longitudinal Joint: *Echelon Paving*


But, the need to maintain traffic limits the opportunities to pave in echelon
Consequently, most longitudinal joints are built with a cold joint.

Preferred Joint Type? Experts Evenly Divided.

Wedge Joints and Compaction

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Vibratory Wedge Compactor

Average Joint Densities from PA DOT for Entire Paving Season

	2011	2012	2013
Notched Wedge	91.7%	91.7%	"mostly notched wedge joints"
Butt (vertical)	90.3%	90.7%	

Plate Compactor

Plan for Longitudinal Joints…

(i.e. Discuss During Pre-Con Meeting)

- Joint Type
- Layout Plan of Final Lift showing joints (DelDOT)
  - Recognize need to offset joints between layers
  - Avoid wheel paths, RPMs, striping (if possible)
- Testing of Joint
  - Type, location, schedule, by whom
- Joint Construction Practices
  - Paving, rolling, materials
- Pave low to high when possible for *shingle effect*
  - Avoids holding rain water at joint by hot side being slightly higher (recommendation later)

Poor planning –
joint in wheelpath

First Pass Must Be Straight!

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string-line should be used to assure first pass is straight

Stringline for reference, and/or Skip Paint, Guide for following

Great Results

Tough to get proper overlap (1”) with next pass

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Best Way to Roll an Asphalt Joint

So Our Recommendation: Option 1

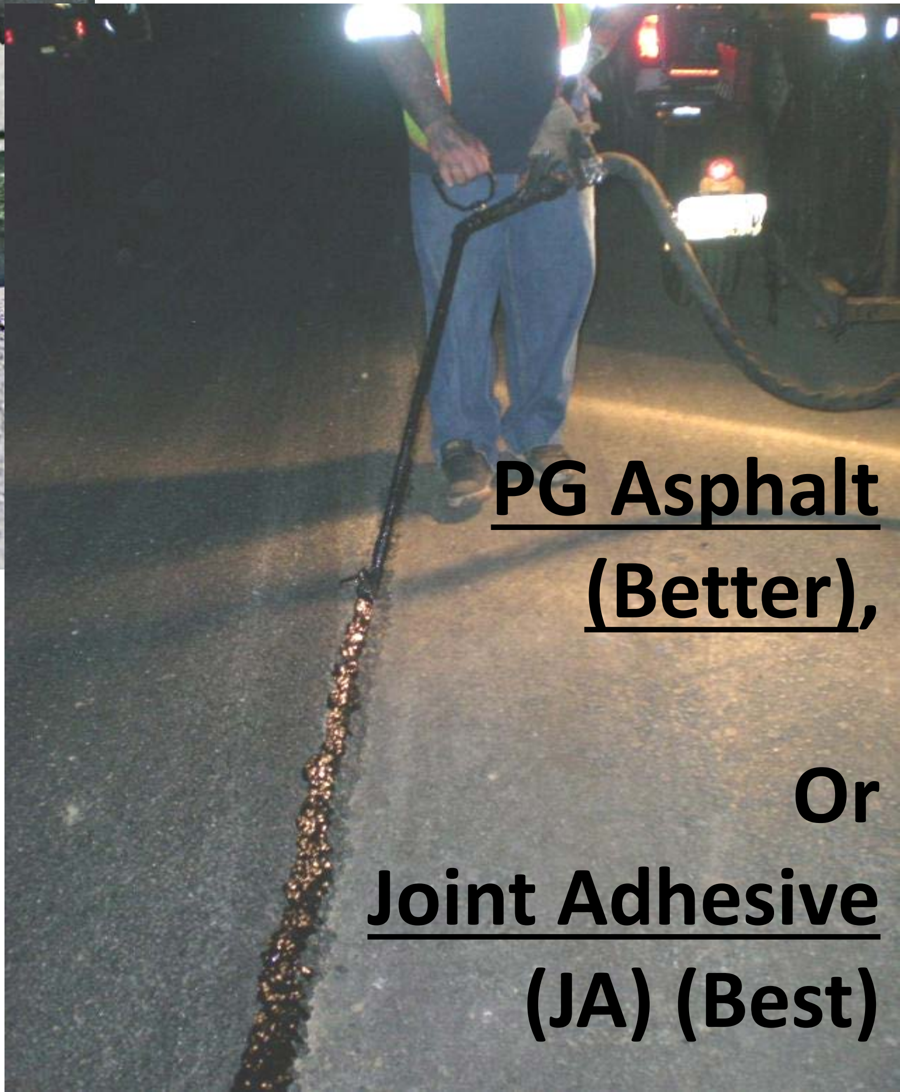
1st Roller Pass Hangs Over 4-6 inches

Compacting Notched Wedge

Vibrating wedge

Paint the Side of Joint (Butt or Wedge)

Emulsion (Good),



PG Asphalt (Better),

Or

Joint Adhesive (JA) (Best)

J-Band / VRAM

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J-Band / VRAM

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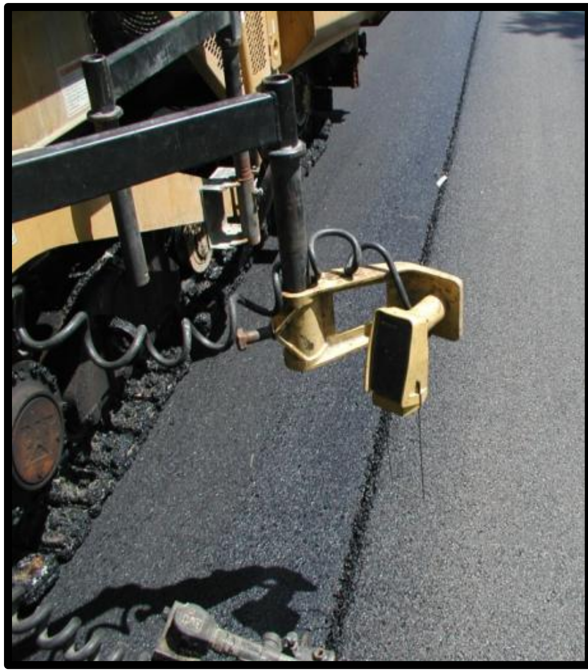
Hot Side Pass Placement

When Closing Joint, Set Paver Automation to Never Starve the Joint of Material

- Target final height difference of +0.1" on hot-side versus cold side
  - NH spec requires 1/8" higher
- Joint Matcher (versus Ski) is best option to ensure placing exact amount of material needed
- If hot-side is starved, roller drum will "bridge" onto cold mat and no further densification occurs at joint



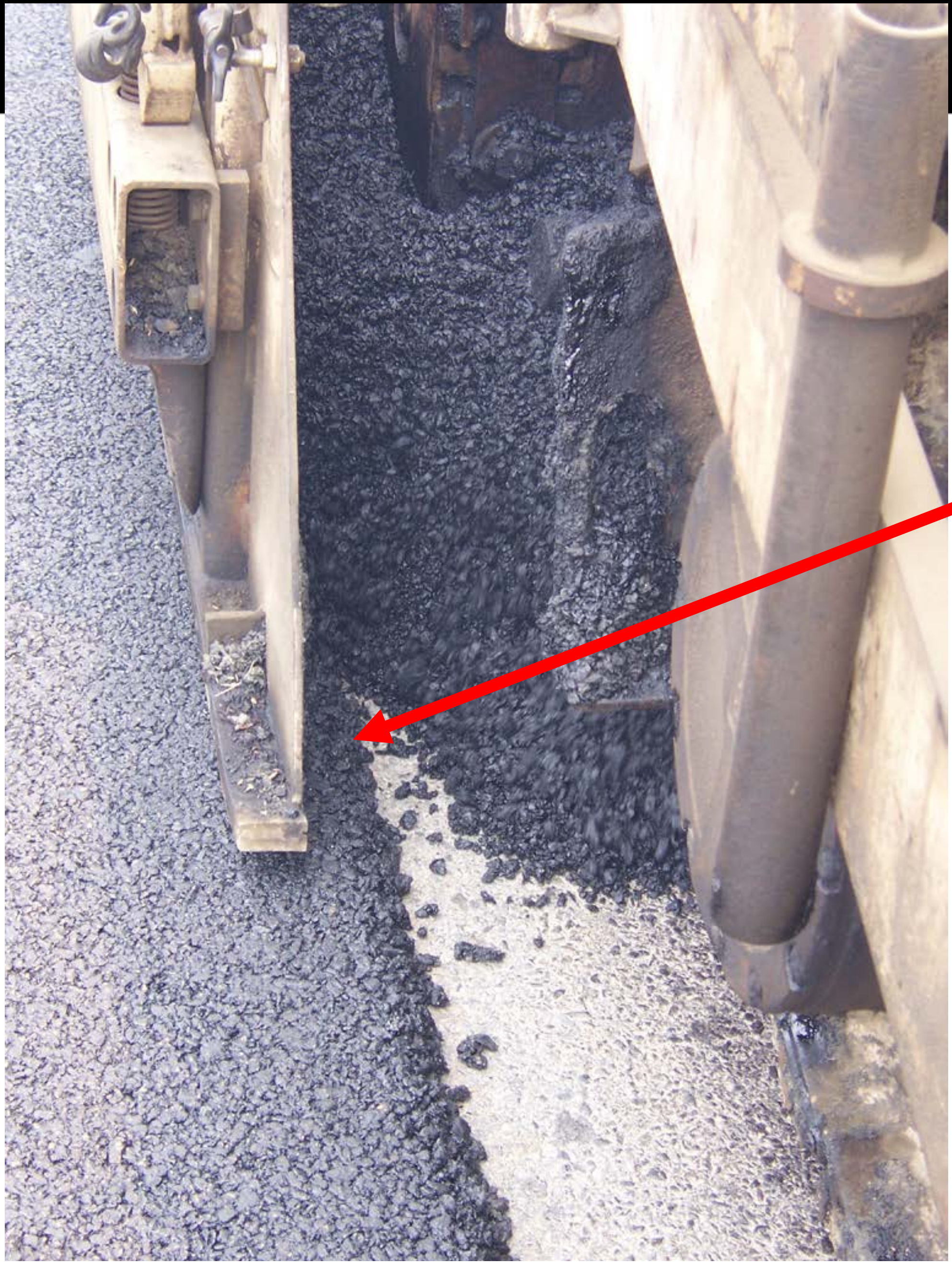
Ski Best for Smoothness

(reference is average over length of ski)

Versus Joint Matcher, which is best for joint (reference is exact location just in front of auger)

Destined for Failure

Likely that the hot side of joint was starved of material at these locations and bridging occurred.



Proper Overlap:

- 1.0 ± 0.5 inches
- Exception:
  Milled or sawed joint should be
  0.5 inches

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All Photos show Bottom of Lift
(Note voids in top two from no overlap)

Core #2 (No Overlap)

Core #7 (No Overlap)

Core #9 (Overlap 1 ½”)

Core #10 (Overlap 1 ½”)

Bridenbaugh & Colella

Lute the Longitudinal Joint

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Rolling the Supported Edge

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Our Recommendation:

1st pass all on hot mat with roller edge off joint approx 6-12 inches

2nd pass overlaps on cold mat 3-6 inches

Other Options / New Products

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- Mill & Pave One Lane at a Time
- Cut Back joint
- Joint Heaters
- Joint Adhesives (hot rubberized asphalt)
- Surface Sealers Over Joint
- Rubber Tire Rollers
- Warm Mix Asphalt
- Intelligent Compaction

Details provided in full workshop

GOAL
14 year old surface

- I-65 in IN: SR252 to US31
  - 12 inches HMA over Rubblized JCP
  - Warranty Project

Discuss the Importance of Tack Coats

Tack Coat's Role in Compaction

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Tack Coat Plays an Important Role in the Compaction Process

Tack Coat's Role in Compaction

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Good bond between underlying and the new layer being compacted is critical to "confine" the bottom of the new lift and keep it from sliding during rolling.

Successful Tack Coat

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The Ultimate Goal:

Uniform, complete, and adequate coverage

Importance of Tack Coats

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- **To promote the bond between pavement layers.**
  - To prevent slippage between pavement layers.
  - **Vital for structural performance of the pavement. (Durability)**
  - Resist rutting.
  - **Achieve optimum density.**

Loss of Fatigue Life Examples

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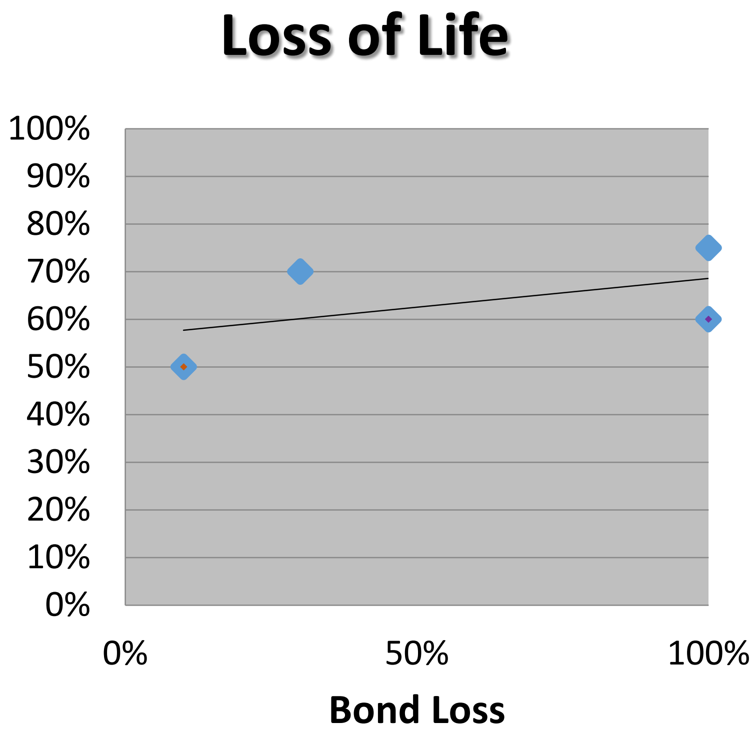
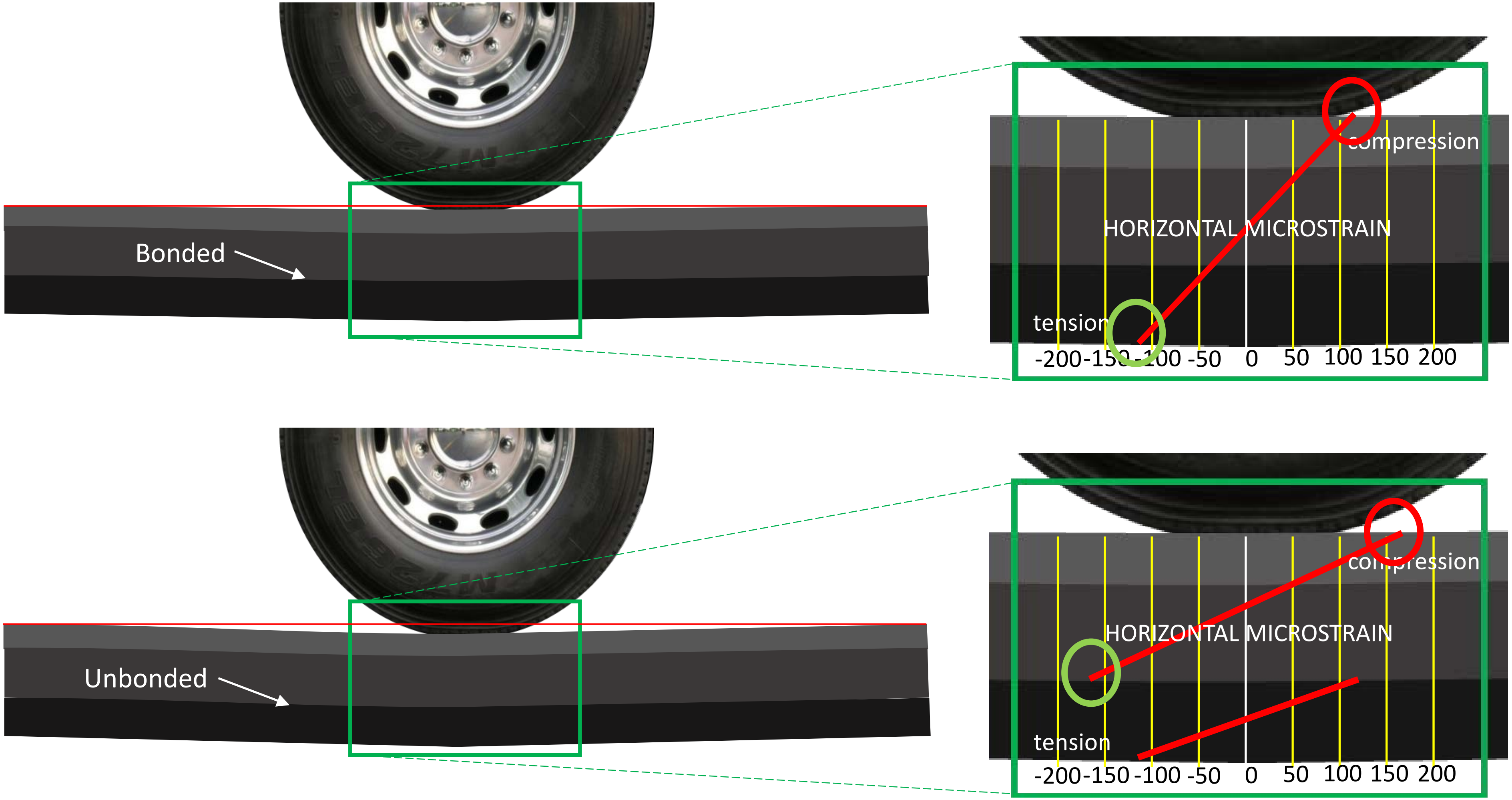
- May & King:
  - 10% bond loss = 50% less fatigue life
- Roffe & Chaignon
  - No bond = 60% loss of life
- Brown & Brunton
  - No Bond = 75% loss of life
  - 30% bond loss = 70% loss of life



Consequences of Debonding



Courtesy of NCAT

Application Rates?

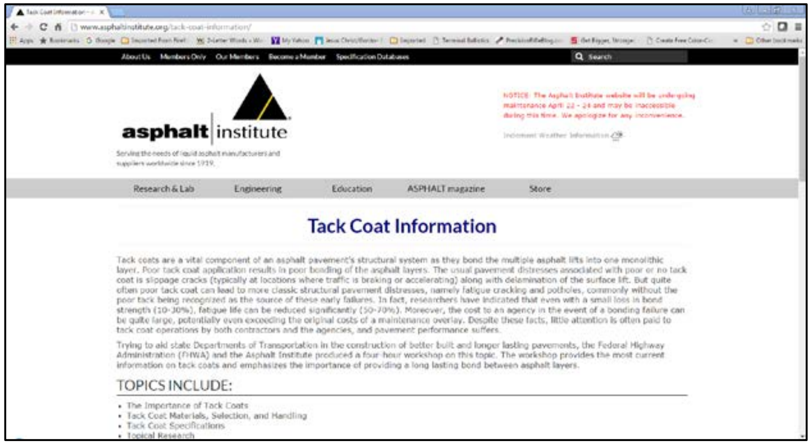
- **What is the Optimal Application Rate?**
  - Surface Type
  - Surface Condition
- **Recommended Ranges**

Surface Type	Residual Rate (gsy)	Appx. Bar Rate Undiluted* (gsy)	Appx. Bar Rate Diluted 1:1* (gsy)
New Asphalt	0.02 – 0.05	0.03 – 0.07	0.06 – 0.14
Existing Asphalt	0.04 – 0.07	0.06 – 0.11	0.12 – 0.22
Milled Surface	0.04 – 0.08	0.06 – 0.12	0.12 – 0.24
Portland Cement Concrete	0.03 – 0.05	0.05 – 0.08	0.10 – 0.16

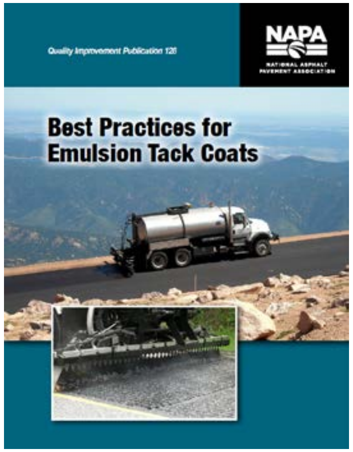
*Assume emulsion is 33% water and 67% asphalt.

Additional Resources

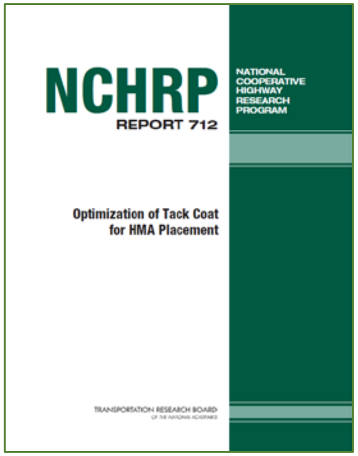
http://www.asphaltinstitute.org/tack-coat-information/



http://www.fhwa.dot.gov/pavement/asphalt/pubs/hif16017.pdf



http://store.asphaltpavement.org/index.php?productID=786

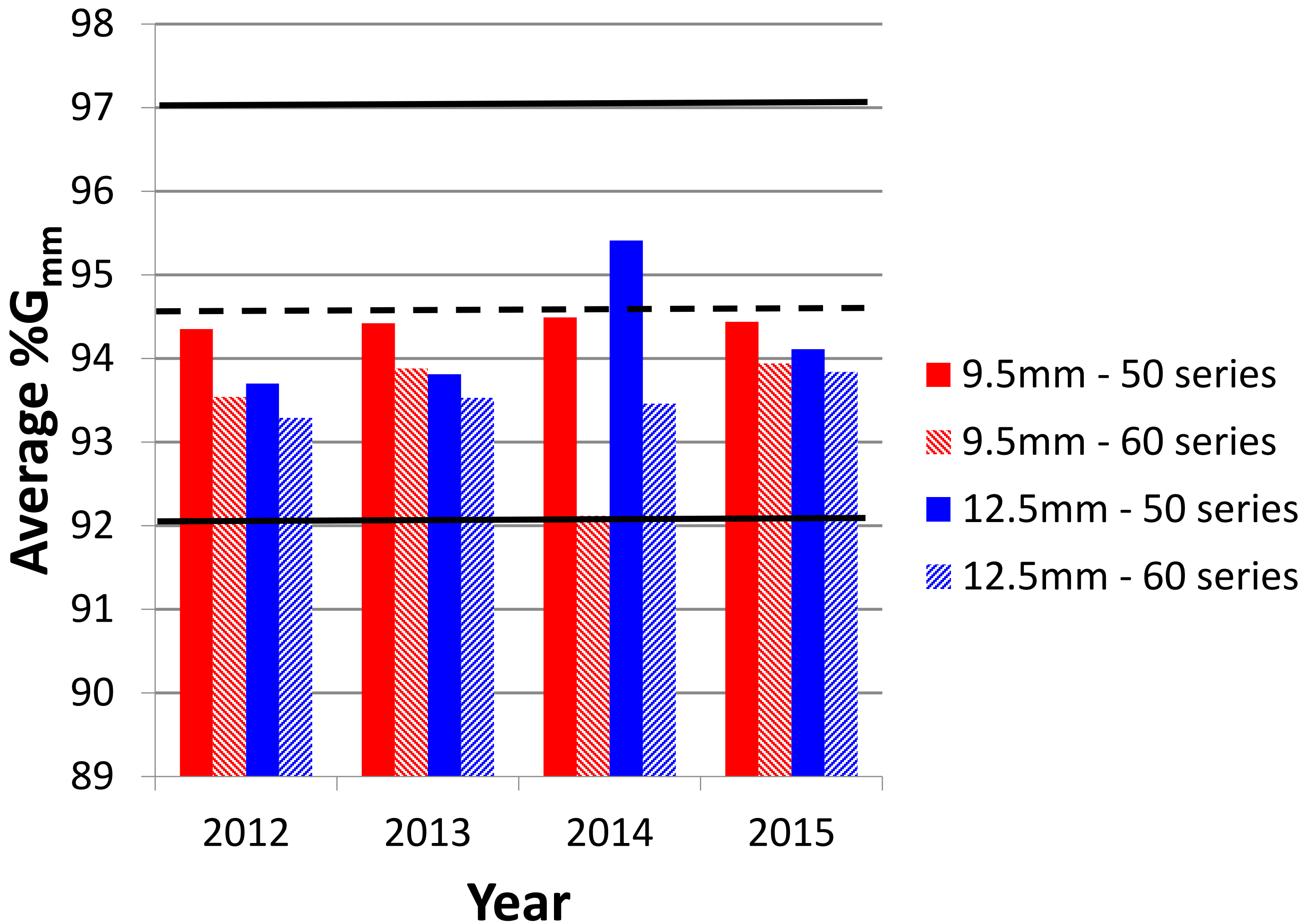


http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_712.pdf

NYSDOT - 50 vs. 60 Series

	50 Series	60 Series
Specification Type	PWL	Average
Incentives	Yes	No
Disincentives	Yes	Yes
Acceptance Measurement	Cores	Gauge Readings
Use	Interstates/Parkways	Non-interstate routes

NYSDOT – 50 vs. 60 series



Newer Technologies to Enhance Compaction

Newer Technologies to Enhance Compaction

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- Warm Mix Asphalt (WMA)
- SHRP2 Infrared (IR)
- Intelligent Compaction (IC)

Wrap Up

Maximizing Our R.O.I.

- Infrastructure loads continue to rise
- Budget availability continues to fall
- Increased pavement life can be economically achieved
- Research conservatively shows that a 10% increase in pavement life can be achieved by increasing compaction by 1%.

What would a 3% increase in compaction do for our industry?

Reduce Permeability

- Finer aggregate gradations are less permeable
  - May require higher level consensus properties
  - May require higher binder contents

- Design to a **minimum** lift thickness
  - ≥ 3X NMAS on fine graded mixtures
  - ≥ 4X NMAS on coarse graded mixtures

- Do not neglect future pavement preservation

Proper Tack Coat Application

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- Specify and monitor adequate tack coat application
  - Allow the use of alternate materials
    - Low Tracking tack
    - Modified materials
    - Paving grade binders

A well compacted pavement section will not perform if it is not properly bonded!!

Improve Longitudinal Joints

Permeable Longitudinal Joints will:

- Cause safety concerns
- Necessitate premature maintenance
- Contribute to delamination
- Severely impact the life cycle performance
- Joint density no less than 2% mat density requirement

Specify Increased Compaction

- Shoot for 94% TMD
  - Regularly achieved on airfields throughout the country.
- Use Percent Within Limit specifications
  - A 92% LSL demands 93 – 94% compaction target
  - Use a one sided test – LSL only
  - Consider high side outlier testing
- Assure Density is achieved on the road
  - Consider Cores for acceptance
  - Require adequate gauge calibration
  - Regularly determine G_{mm} on plant produced mix
- Pay for increased compaction – 5% Bonus

Use Best Construction Practices

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Uniform Paving Train Operation

- Determine plant production rate
- Plan for sufficient, timed mix delivery
- Establish a constant paver speed
- Assure ample rollers are available
    - Keep water trucks up to the rollers

Use Best Construction Practices

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Promote Innovation

- Encourage / require Intelligent Compaction
- Use WMA – compaction aid
- SHRP2 – IR
- Consider alternative rollers
  - Pneumatic
  - Vibratory Pneumatic
  - Oscillatory
  - ?

Bottom Line

Increased compaction = Increased Performance

And a Better R.O.I. for the taxpayers

Global, International, Regular, Associate and Canadian members

Affiliate and Commercial members

Thank You for Your Time !!