NCHRP 9-49A Project
Performance of WMA Technologies: Stage II – Long-term Field Performance

FHWA Mix ETG

Oklahoma City, OK
September 17, 2015

Project Background

- Duration: 04/2011-07/2016
- Team Members
  - Haifang Wen - Washington State University (Prime)
  - Louay Mohammad - Louisiana State University
  - Shihui Shen - Penn State University at Altoona
  - Braun Intertech
  - Bloom Companies

Outline

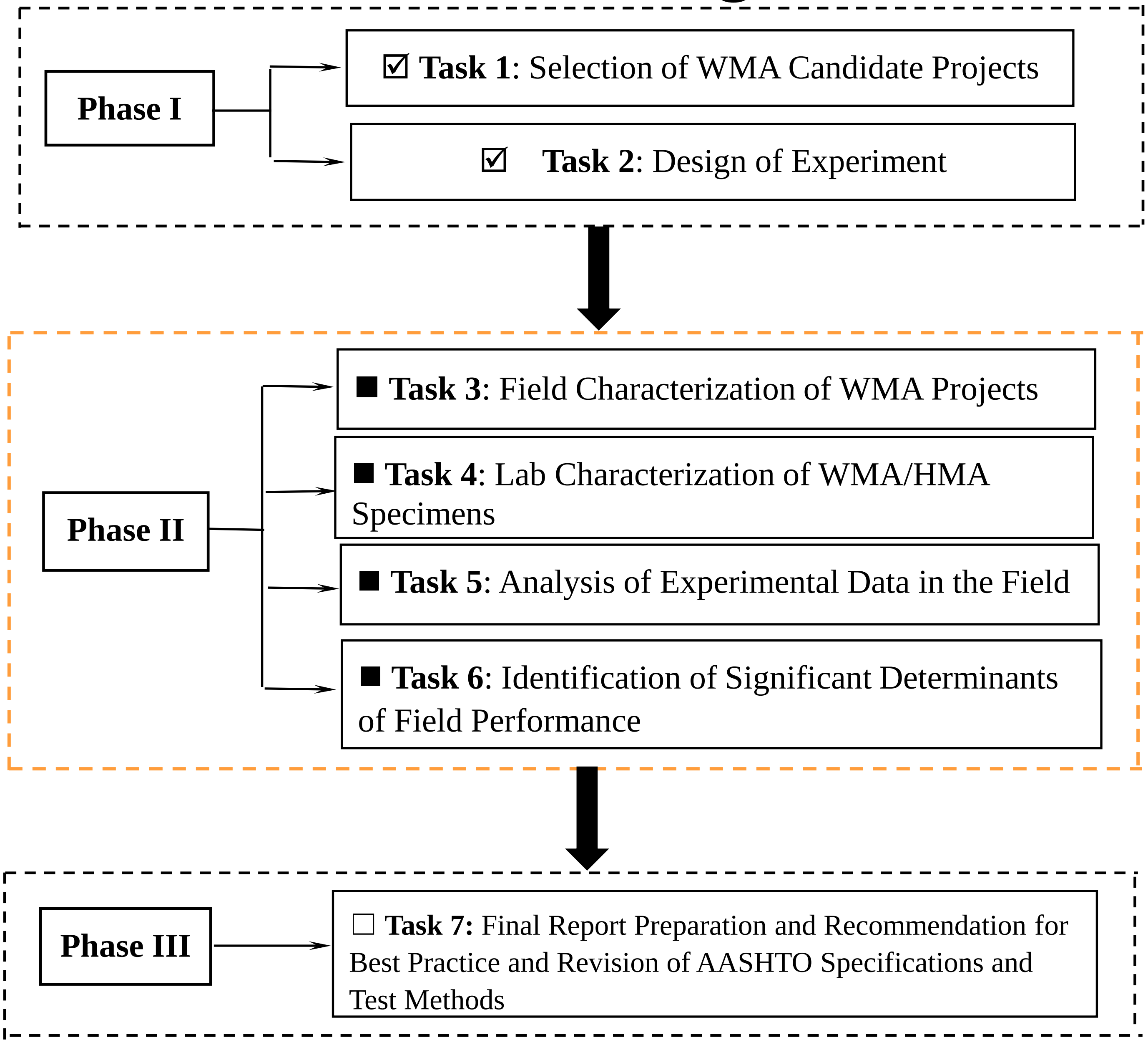
- Objectives & Research Progress
- Preliminary Findings
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Property Changes Over Time
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- Summary and Future Work

Research Objectives

- To identify the material and engineering properties of WMA pavements that are *significant determinants* of their long-term field performance, and

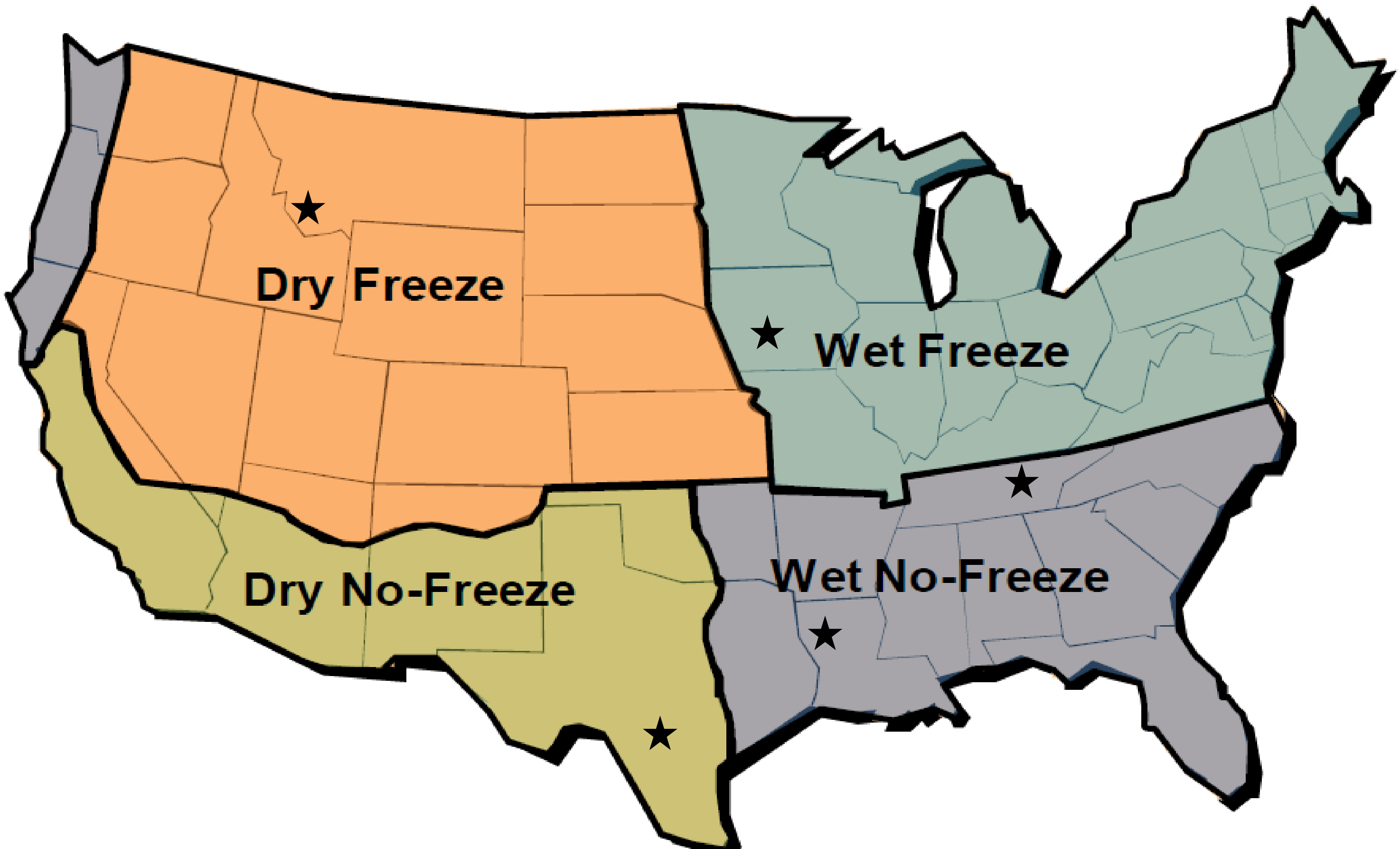
- To recommend *best practices* for the use of WMA technologies.

Research Progress



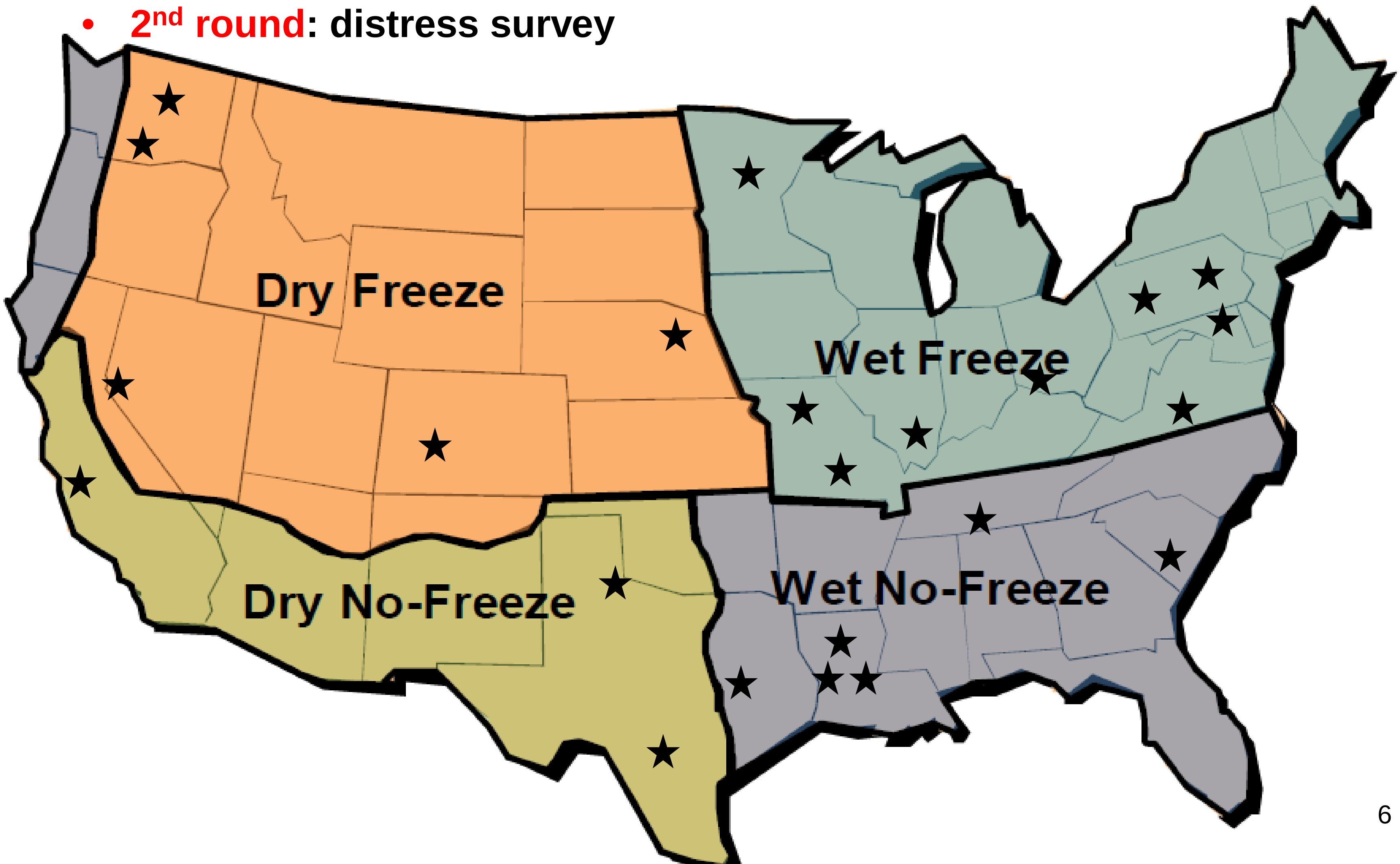
New (2011 Construction) Pavement Projects

- **5 Projects = 10 HMA-WMA pairs**
- **1st round: pre-overlay distress survey, construction monitoring, on-site sample compaction, field cores, and falling weight deflectometer tests**
- **2nd round: field cores and distress survey**

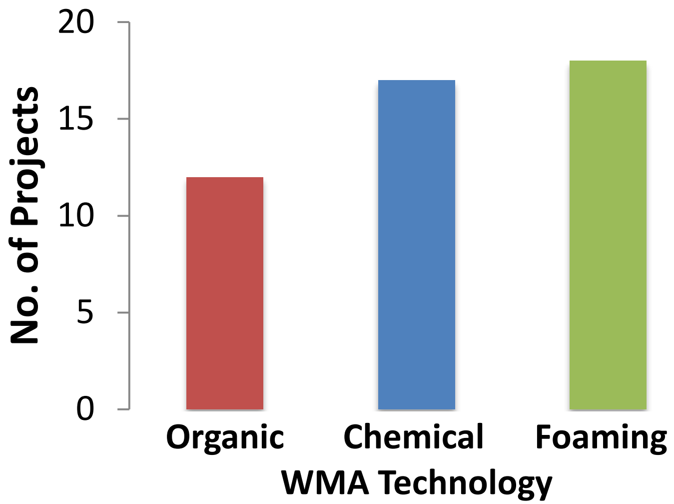


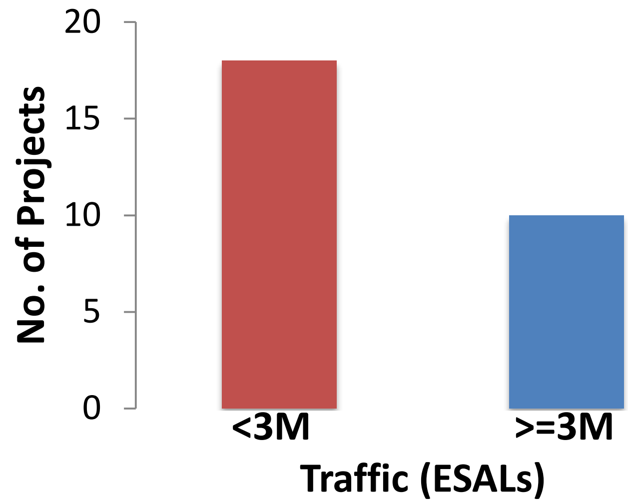
In-service (as of 2011) Pavement Projects

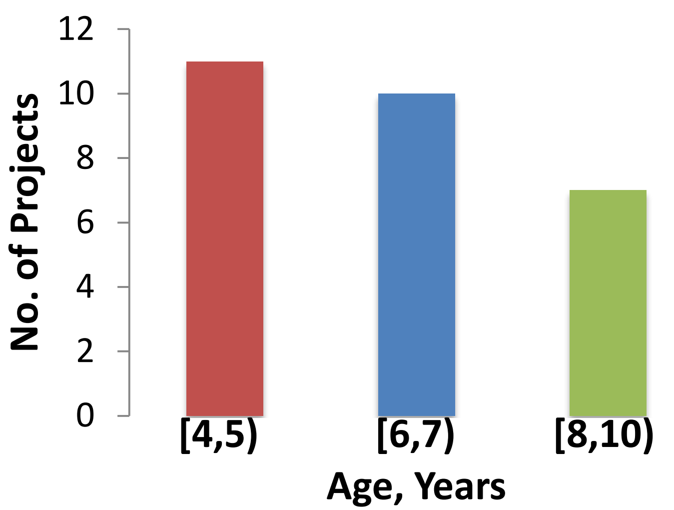
- 22 field projects + 1 HVS = 40 HMA-WMA pairs
- 1st round: distress survey, field cores and falling weight deflectometer tests
- 2nd round: distress survey

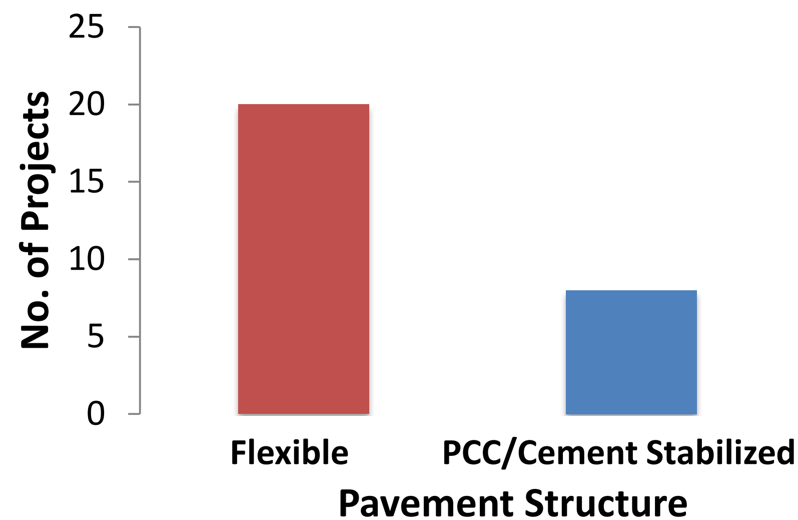


Projects Distribution









Project	MT I-15	TN SR 125	IA US 34	TX FM 973	LA US 61
Construction Year	2011	2011	2011	2011	2012
Warm Mix	Sasobit, Evotherm DAT, Foaming	Evotherm 3G	Sasobit, Evotherm 3G	Evotherm 3G, Foaming	Sasobit, Evotherm 3G
Mixing Temp., °F	H (315-320) W (283-300)	H (320-350) W (290-320)	H (330-340) W (265-280)	H (310-340) W (249-290)	H (325) W (295)
Compaction Temp., °F	H (290-300) W (269-285)	H (311-335) W (275-290)	H (253-265) W (220-239)	H (268-291) W (221-268)	H (277-316) W (245-250)
Design Thickness, in.	2.5	1.25	1.5	2.0	2.0
Traffic	3 million (3,170 AADT, 26.3% truck)	0.39 million (3,470 AADT, 13% truck)	3 million (6,450 AADT, 10.9% truck)	3 million (11,300 AADT, 4.3% truck)	9 million (34,138 ADT, 14% truck)
Aggregate	Siliceous	Gravel & Sand	Limestone, Quartzite & Sand	Gravel, Limestone & Dolomite	Granite & Limestone
NMAS, in.	3/4	1/2	1/2	3/4	1/2
Asphalt Binder	PG 70-28	PG 70-22	PG 58-28	PG 70-22	PG 76-22
Anti-stripping Agent	Hydrated Lime, 1.4%	AZZ-MAZ, 0.3%	None	None	0.6%
Polymer-modified	SBS	Yes	None	N/A	SBS
Asphalt Content, %	4.6	6.0	5.44	5.2	4.7
G_{mm}	HMA (2.458) Sas (2.466) Evo (2.459) Foam (2.453)	HMA (2.352) Evotherm (2.355)	HMA (2.423) Sasobit (2.428) Evotherm (2.429)	HMA(2.406) Evotherm (2.405) Foaming (2.420)	HMA (2.464) Sasobit (2.468) Evotherm(2.464)
Sampling Date	Sep. 15-17, 2011	Oct. 24-31, 2011	Sep. 6, 2011	Dec. 1, 2011	May 16-June 6, 2012
RAP or RAS	None	10% RAP	17% RAP	None	15% RAP
Structure	2.5" overlay + 7" existing HMA + 16.2" base (non-stabilized) + infinite subgrade	1.25" overlay + 8" bituminous base + 6" min. aggregate base + infinite subgrade	HMA & Sasobit: 1.5"overlay + 5" existing HMA + 7" PCC + subgrade Evotherm: 1.5" overlay + 3" existing HMA + 9" PCC + subgrade	2" overlay + 8" existing HMA + 10" base + 141.1" subgrade (lean clay)	2" overlay + 8" existing HMA + 8" PCC + 6" cement treated soil subgrade

Wet Freeze Zone	MD 925	MO Hall St.	MO Rte. CC	MN TH 169	OH SR 541	PA SR 2012	VA I-66	IL 147	PA SR 2006
Construction Year	9/2005	5/2006	2007	7/2010	9/2006	5-6/2009	7/2010	6/2010	5/2009
Warm Mix (content, %, by weight of binder)	Sasobit	Sasobit (1.5%); Evo ET; Asph (0.3%)	Evotherm DAT	Evotherm 3G	Sasobit (1.5%), Evo ET (5.3%), Asp (0.3%)	LEA, Gencor (0.5%)	Astec DBG	Astec DBG	Sasobit, Advera
Production Temp., °F	HMA (310-350); Sasobit (270-310)	HMA (320), Sas (240); Evo (225); Aspha (275)	HMA (320); Evo (280-290)	HMA (300); Evotherm (265)	HMA (320), Sas (260); Evo (235); Asp (245)	H (290-310); Gen (250-265); LEA (240-260)	HMA (317); Astec DBG (288)	HMA (300);, Astec DBG (270)	HMA (310), Sas (265); Adv (260)
Traffic (AADT)	10,480	21,000	8618	12,600	650	254	57,000	775	523
Aggregate	N/A	Limestone Steel Slag	Limestone	N/A	Limestone	Limestone	N/A	Limestone	Limestone
NMAS, in.	3/8	1/2	1/2	3/4	3/8	3/8	1/2	1/2	3/8
Asphalt Binder	64-22	70-22	64-22	58-28	70-22	64-22	76-22	64-22	64-22
Anti-stripping Agent	None	ARR MAZ, 0.25%	Pave Bond Lite, 0.25%	None	None	None	Pave Bond Lite, 0.5%	None	None
Asphalt Content, %	5.0	5.3	5.4	4.2	6.1	5.9	H (5.0); W (5.4)	5.0	6.0
G_{mm}	2.519	2.451	2.469	2.549	2.429	2.476	H (2.62); W (2.605)	H (2.450); W (2.47)	H(2.467); Sas (2.462); Adv (2.469)
Sampling Date	6/28/12	7/16-18/12	7/17/12	8/28/12	6/18/12	6/26/12	6/26/12	7/19/12	6/21/12
RAP	15%	10%	20%	N/A	15%	None	N/A	10%	None
Structure	2"+ 5" HMA + 8"Macadam stone	1.75"+ 12" PCC + 0-3" base	3.75"+ 7" PCC + 6" base	2"+ 8" HMA + 6" base	1.25"+6.75" HMA+ 9" Granular Base	1.5"+ 5" HMA+4"Aggregate Base	1.5"+ 5" HMA+ 9"+ 10" base	1.5"+ 9" HMA	1.5"+ 5" HMA + 4" stone base

Wet No-Freeze	SC US 178	TN SR 46	TX FM 324	LA 116	LA 3191	LA 3121
Construction Year	9/2007	10/2007	2-3/2008	3/2010	11/2008	3/2009
Warm Mix	Evotherm DAT	Sasobit, Evotherm DAT, Astec DBG, and Advera	Sasobit, Evotherm DAT, Rediset, Advera	Foam	Astec Foam	Evotherm 3G
Production Temp., °F	HMA (295), Evotherm (240)	HMA Danley (320-350); HMA Franklin (320-350), Sasobit (250); Evotherm DAT (240); Advera (250); DBG (260)	H (330) W (240)	N/A	N/A	N/A
Traffic (AADT)	3880	4440	1450	2600	ADT 200	ADT 400
Aggregate	N/A	Limestone	Limestone	N/A	N/A	N/A
NMAS, in.	3/8	1/2	3/8	1/2	1/2	1/2
Asphalt Binder	64-22	70-22	64-22	70-22	70-22	70-22
Anti-stripping Agent	N/A	Franklin (AD-Here 77-00, 0.3%); Astec DBG (Pavegrip 650, 0.3%)	1% Lime	N/A	N/A	N/A
Asphalt Content, %	H (5.3), W (5.4)	5.3	4.6	4.4	5.2	5.1
G_{mm}	H (2.460), W (2.463)	HMA Danley (2.428), Sasobit (2.411), Evotherm (2.410), Astec DBG (2.444), Advera (2.422) HMA Franklin (2.425)	HMA, Sas, Evo (2.508) Adv, Rediset (2.498)	H (2.525) W (2.541)	H (2.453) W (2.486)	H (2.507) W (2.490)
Sampling Date	07/27/12	07/24/12	2/6-8/13	05/21/13	05/21/13	05/20/13
RAP	N/A	None	None	15	15	15, 30
Structure	2" overlay + 5.7" HMA + 7.1" PCC + Sand Clay Base	1.25" Overlay + 4.26" HMA + 6" crushed stone	1.5" Overlay + 5.7" HMA + 10" base	1.5" Overlay + 5" HMA +8.5" Base	2" HMA + 6" HMA+ 7" PCCP	2" Overlay + 12" Cement-treated Base

Dry- Freeze	WA I-90	WA SR 12	CO IH 70	NE US 14	NV
Construction Year	6/2008	4/2010	7-8/2007	2008	8/2010
Warm Mix	Sasobit	Aquablack	Sasobit (1.5%); Evotherm DAT (0.5%); Advera (0.3% of mix)	Advera, Evotherm DAT	Ultrafoam
Production Temp., °F	HMA (330), Sasobit (276)	HMA (325), Aquablack (275)	HMA (mixing 310, compaction 280); Sasobit (255, 235); Evotherm (250, 230); Advera (255, 235)	H (330), W (275)	H (330), W (275)
Traffic (AADT)	13,000	6,550	30,000	2,140	5,000
Aggregate	Basalt	Basalt	Crushed River Rock	Limestone, Gravel	N/A
NMAS, in.	1/2	1/2	1/2	1/2	1/2
Asphalt Binder	76-28	64-28	58-28	64-28	64-28
Anti-stripping Agent	None	Superbond (0.25%)	Hydrated Lime (1% by mass of aggregate blend)	None	Hydrated Lime, 1.5%
Asphalt Content, %	5.5	5.2	6.3	5.0	4.6
G_{mm}	2.601	2.596	2.45	H-Adv (2.439), H-Evo (2.441)	2.451
Sampling Date	8/27/12	8/28/12	10/18/12	10/14/12	10/19/12
RAP, %	15-20	20	None	<15	15
Structure	3" Overlay + 11.28" HMA + 6.5" base (HMA)/5" base (Sasobit)	3" Overlay + 7.8" HMA + 9" base	2.5" Overlay + 10-11" HMA	3" Overlay + 4" HL Slurry Stabilization + 1.5" Existing Asphalt + 4” Bit Sand Base	6" HMA + 9" Aggregate Base

Dry No-Freeze	TX SH 251	TX SH 71	CA HVS 3a	CA HVS 3b
Construction Year	8/2008	6/2008	9/2009	9/2009
Warm Mix	Astec DBG	Evotherm DAT	Gencor, Evotherm DAT, Cecabase	Sasobit, Advera, Astec DBG, Rediset
Production Temp., ° F	H (310) W (270)	H (330), W (240)	HMA (320), Gencor (284), Evotherm (248), Cecabase (266)	HMA (335, 279), Sasobit (300,279), Advera (295,266), Astec DBG (295,257), Rediset (285,258)
Traffic (AADT)	2,300	57,000	HMA (74,000), Gencor (159,000), Evotherm and Cecabase (160,000)	HMA, Sasobit, Astec DBG and Rediset (160,000), Advera (50,000)
Aggregate	Limestone	Limestone	Granite	Reed
NMAS, in.	3/8	3/8	1/2	1/2
Asphalt Binder	70-22	76-22	64-16	64-16
Anti-stripping Agent	1% Akzo	0.8% Liquid	None	None
Asphalt Content, %	5.1	4.8	7.0	8.3
G_{mm}	H (2.45), W (2.4)	2.416	H (2.503)	H (2.505)
Sampling Date	2/5/13	2013	2012	2012
RAP, %	None	N/A	Rubber (18% of binder)	Rubber (18% of binder)
Structure	2.0" Overlay + 4.3" HMA	2" Overlay + HMA	2.5" Gap-graded Rubberized HMA + 2.5" HMA + 15.6" Base	2.5" Gap-graded Rubberized HMA + 2.5" HMA + 15.6" Base

Field Work Progress

New Projects

Items	MT I-15			IA US 34			TN SR 125			TX FM 973			LA US 61		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Distress Survey	✔	✔		✔	✔		✔	✔		✔	-		✔	✔	
FWD/Coring	✔	✔		✔	✔		✔	✔		✔	-		✔	✔	

In-service Projects

Items	MD 925		MO Hall St.		MO Rte. CC		MN TH 169		OH SR 541		PA SR 2012		VA I-66		SC US 178		TN SR 46		CO IH 70		WA I-90		WA SR 12	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Distress Survey	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
FWD/Coring	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-

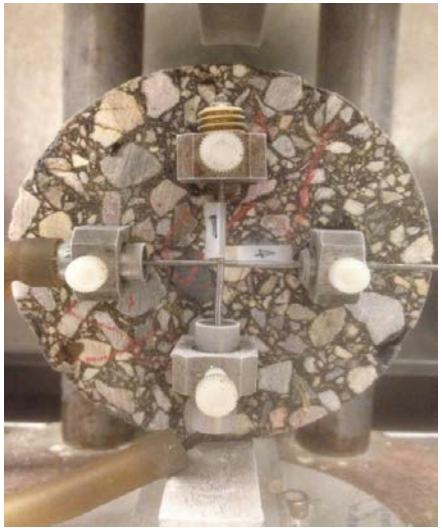
In-service Projects (continued)

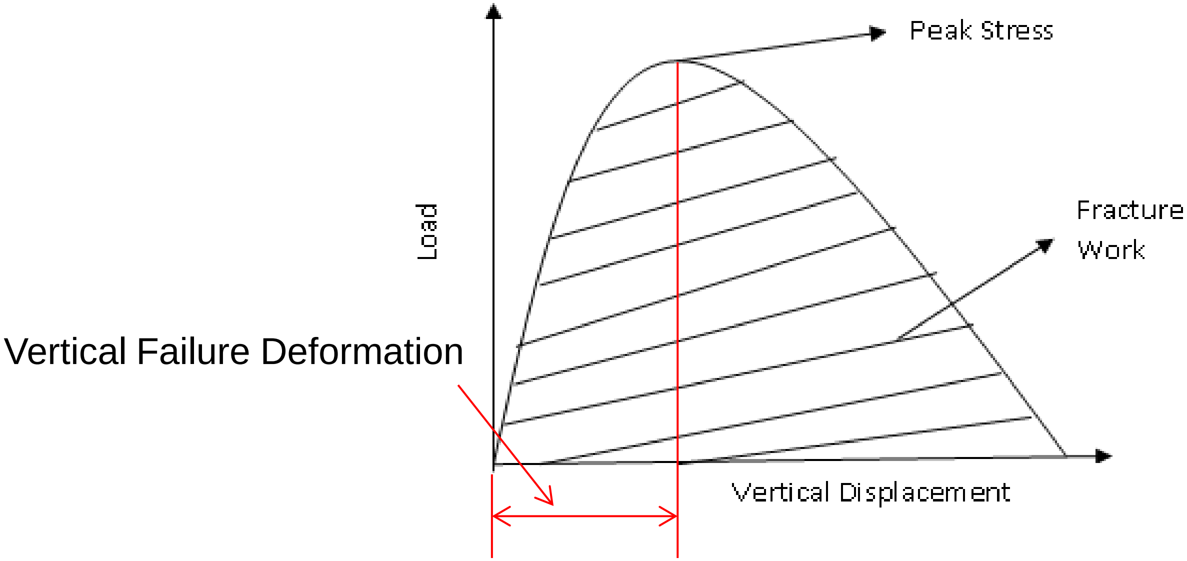
Items	TX SH 251		NE US 14		TX FM 324		LA 3121		LA 116		LA 3191		NV Bravo		IL 147		PA SR 2006		TX SH 71		CA HVS	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Distress Survey	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	-	✔	-
FWD/Coring	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-	✔	-

Notes: "✔": completed; blank cells: to be completed; "-" not planned or not available

Mixture Test Summary

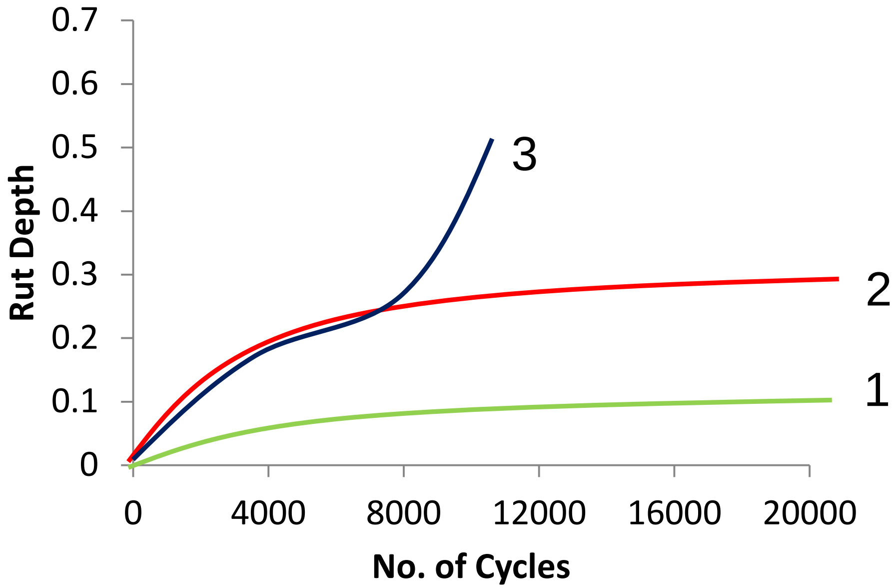
Mixture Test	IDT Dynamic Modulus/Creep Compliance	Fatigue- IDT Fracture at Room Temp	Thermal Cracking- IDT Fracture at Low Temp	Rutting/Moisture - Hamburg
Testing Conditions	Temp.: −4, 14, 32, 50, 68, 86ºF; Frequency: 20, 10, 5, 1, 0.1, 0.01 Hz Duration: 100 seconds	Temp.: 68ºF Loading rate: 2 in./min	Temp.: 14ºF Loading rate: 0.1 in./min	Temp.: 122ºF Wet condition
Material Properties	Dynamic modulus; Creep compliance	IDT strength; Fracture work density; Vertical failure deformation Horizontal failure strain	IDT strength; Fracture work density; Vertical failure deformation; Horizontal failure strain	Rut depth; Stripping inflection point (SIP); Cycles
References/ Standards	AASHTO T322 Wen et al. 2002	AASHTO T322	AASHTO T322 Wen 2012	AASHTO T324





Rutting Resistance Index (RRI)

RRI = No. of Cycles @ end of test × (1”- Rut Depth)



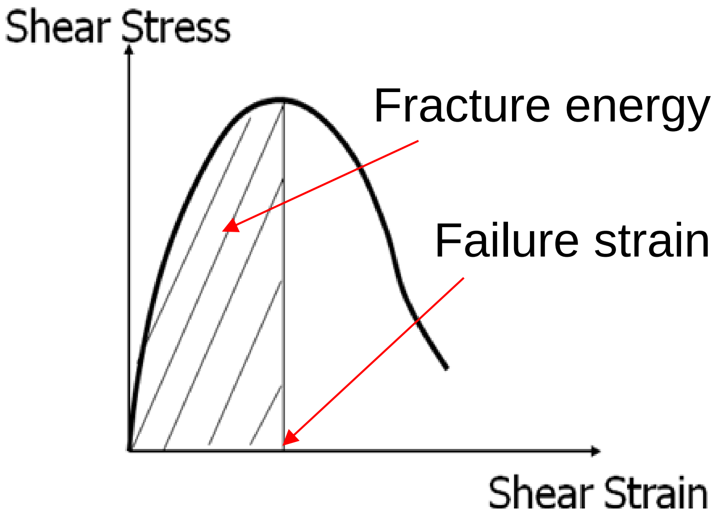
(1) Good rutting performance: 0.1 in. @ 20,000 cycles, RRI=18,000

(2) Average rutting performance: 0.3 in. @ 20,000 cycles, RRI=14,000

(3) Poor rutting performance: 0.5 in. @10,000 cycles, RRI=5,000

Binder Test Summary

Binder Test	PGs	Rutting: MSCR	Fatigue: Monotonic at Room Temp	Thermal Cracking: Monotonic at Low Temp
Testing Conditions	Different temp depending on the test (DSR, BBR)	Stress: 0.1, 3.2kPa Temp.: 98% Reliability from LTPP Bind	Temp.: 68°F Shear strain rate: 0.3 s^{-1}	Temp.: 41°F Shear strain rate: 0.01s^{-1}
Material Properties	PG; BBR stiffness; m-value	$Jnr_{0.1}$, $Jnr_{3.2}$; $R_{0.1}$, $R_{3.2}$	Maximum stress; Fracture energy; Failure strain	Maximum stress; Fracture energy; Failure strain
References/Standards	AASHTO MP1/T240/T313	AASHTO T350	Wen et al. 2010	Wen 2012



Outline

- **Objectives & Research Progress**
- **Preliminary Findings**
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- **Summary and Future Work**

Transverse Cracking

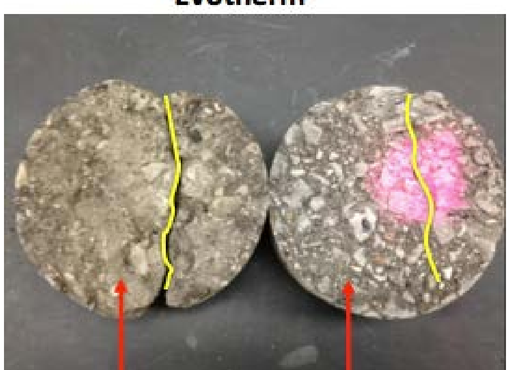
- **Field Performance Comparison between HMA and WMA**
  - 1st Round Survey
  - 2nd Round Survey
- **Significant Determinants for Transverse Cracking**
  - 1st Round Results
  - 2nd Round Results
- **Use Determinant to Compare HMA and WMA**

Transverse Cracking

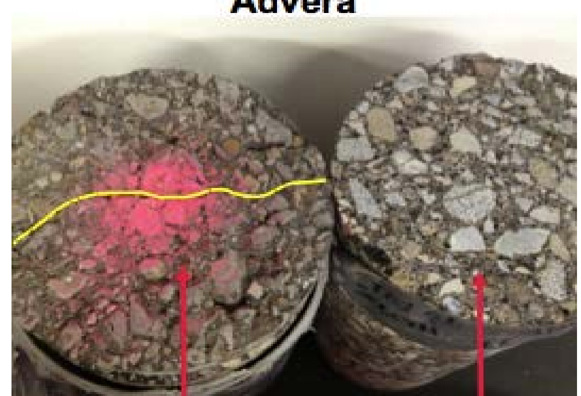
Reflective

Surface-initiated

Evotherm

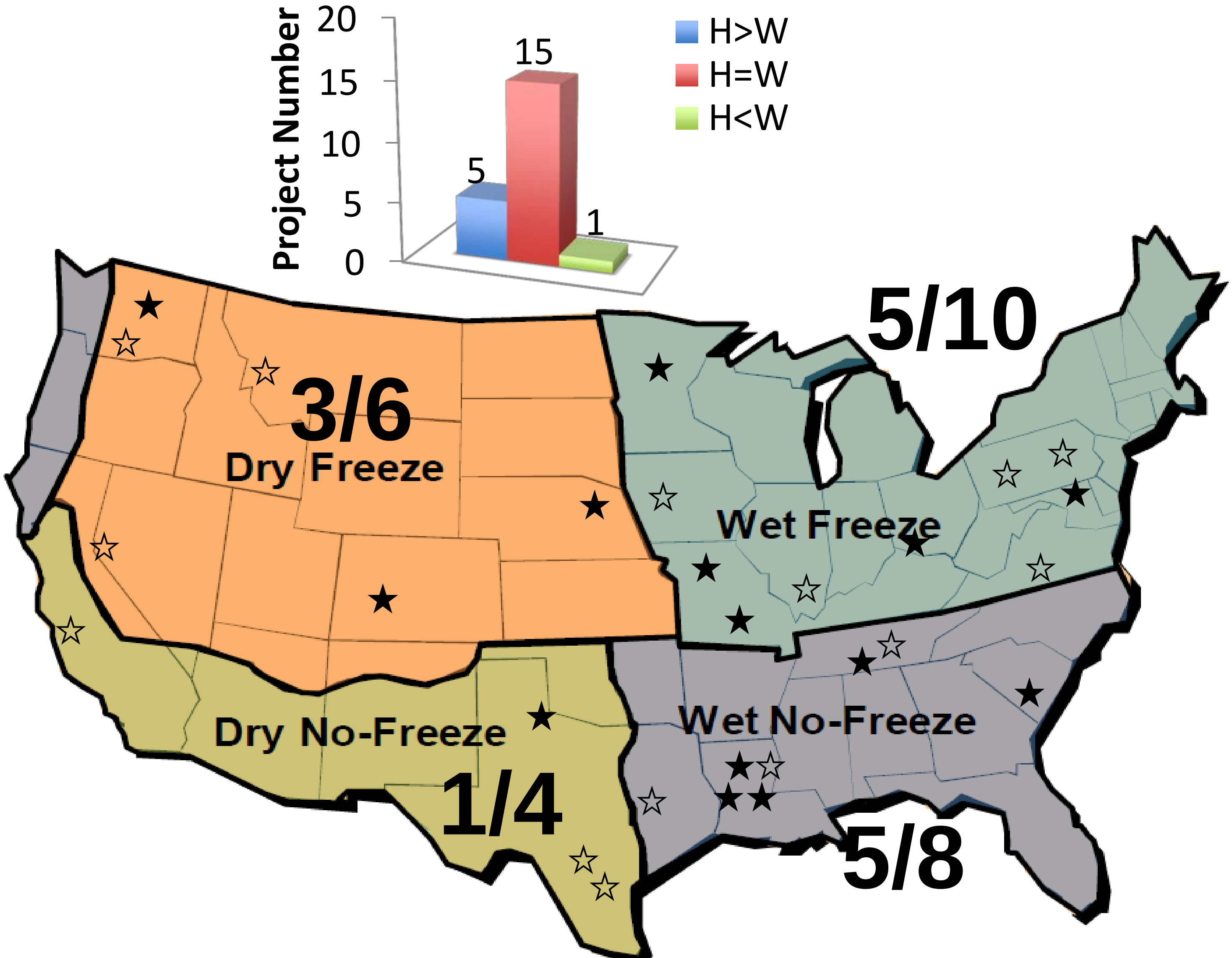


Advera



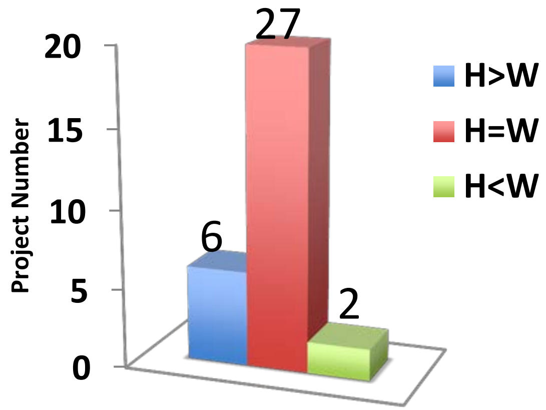
1st Round HMA/WMA Transverse Cracking Comparison

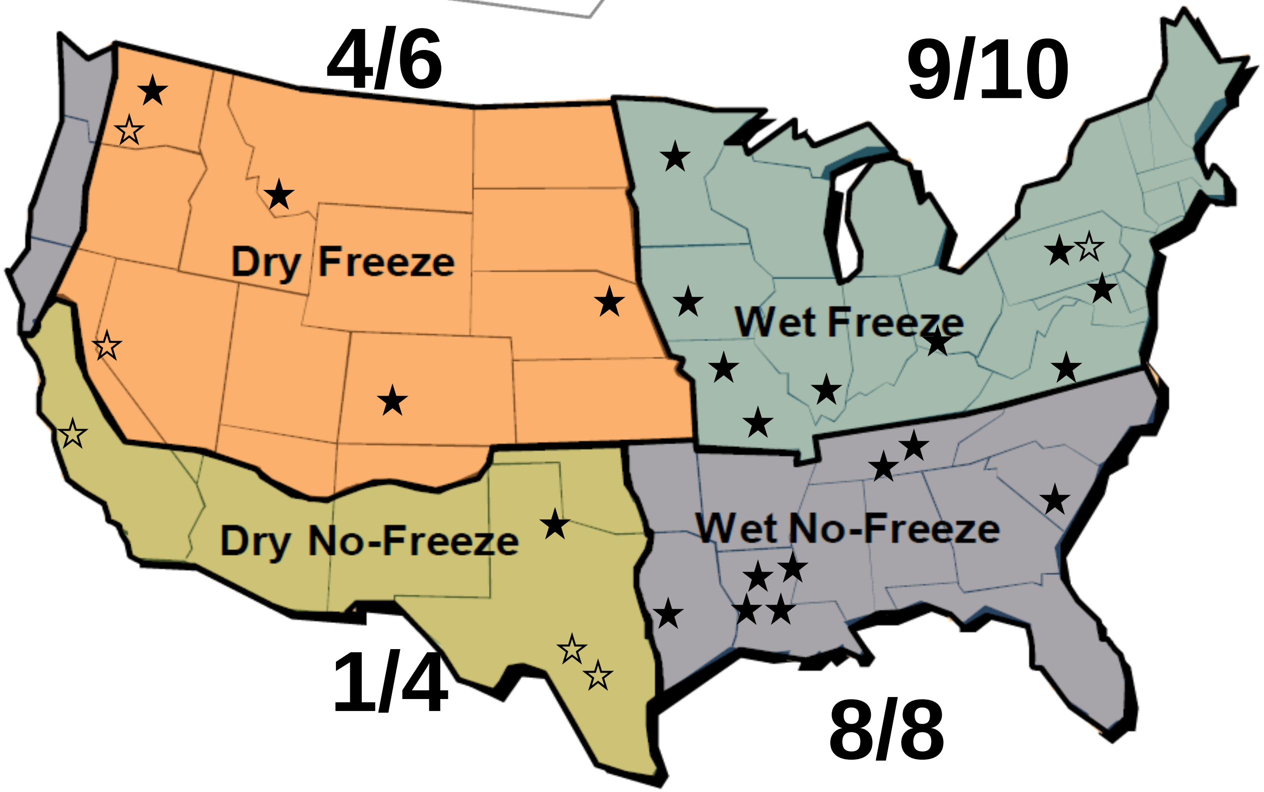
14 (21 H-W Pairs) out of 28 projects exhibited transverse cracking



2nd Round HMA/WMA Transverse Cracking Comparison

22 (35 H-W pairs) out of 28 projects exhibited transverse cracking





Significant Determinants of Transverse Cracking

Compare Material Properties

- **H>W, H=W, H<W (t-test)**

Compare Field Performance

- **H>W, H=W, H<W (t-test)**

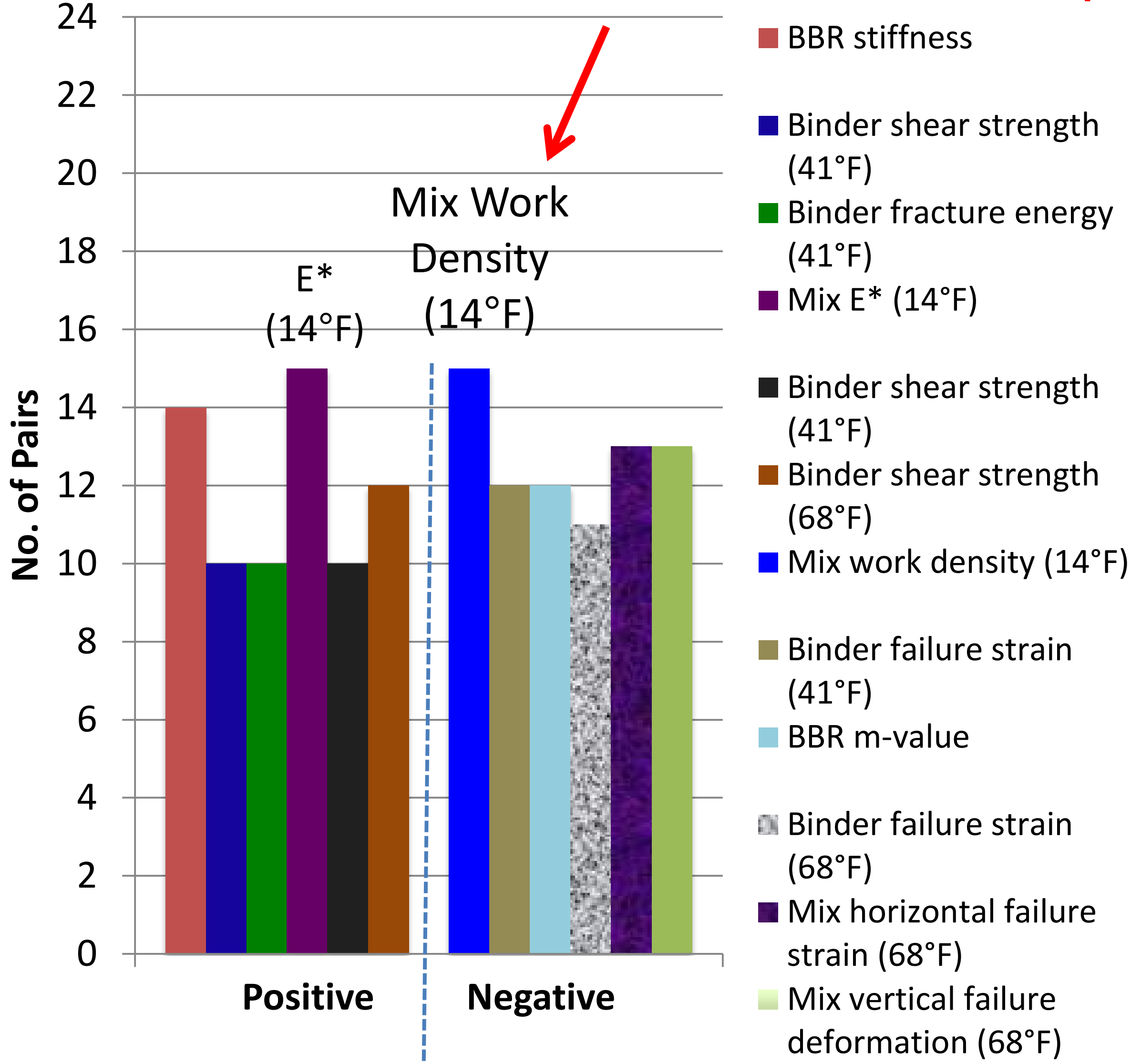
Compare the two rankings

- **Consistent trend**
- **No consistent trend**

- **Summarize the number of pairs with consistent trend and determine the promising indicator**

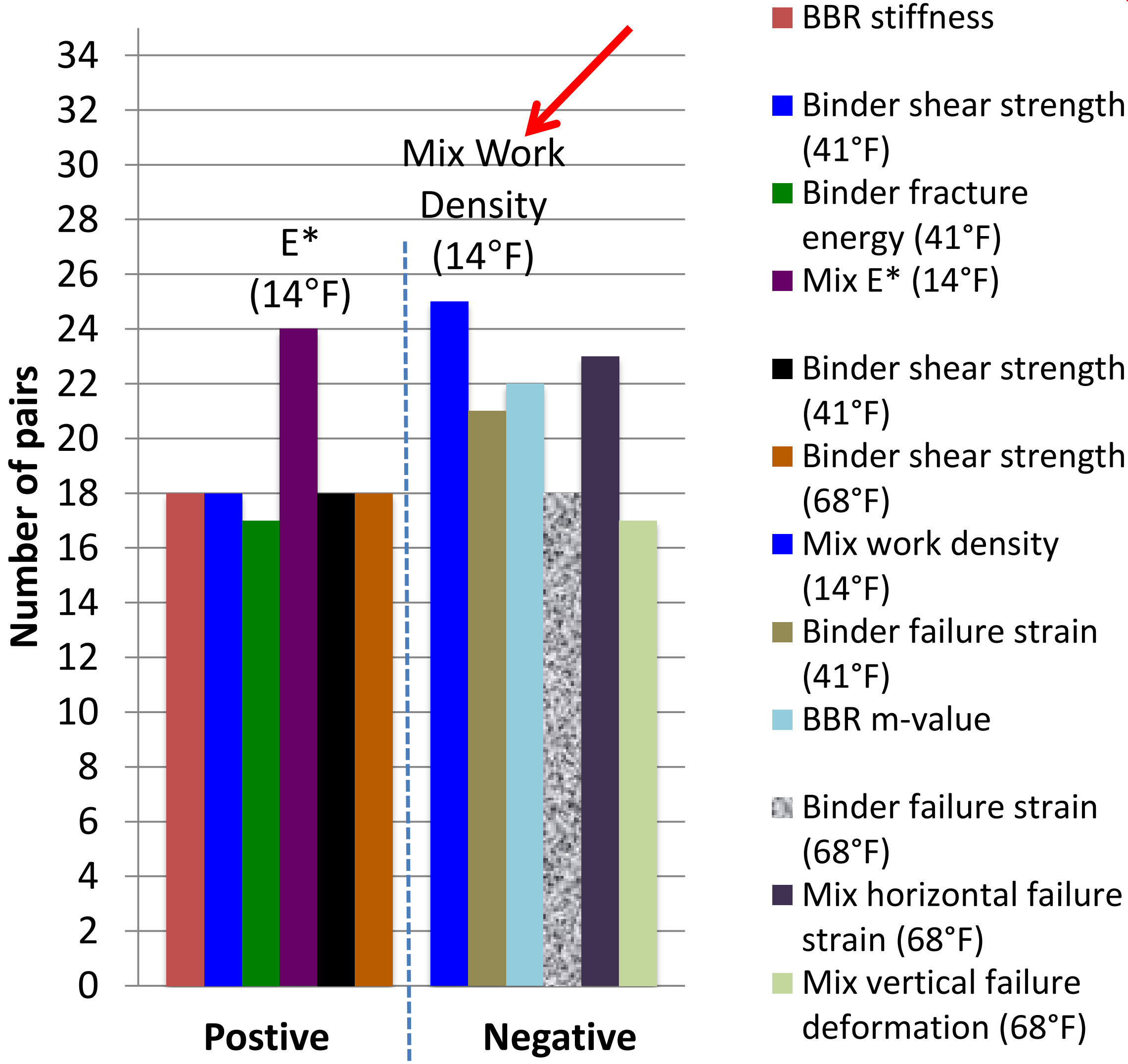
Significant Determinants for Transverse Cracking Based on 1st Round Results

15 out of 21 HMA/WMA pairs



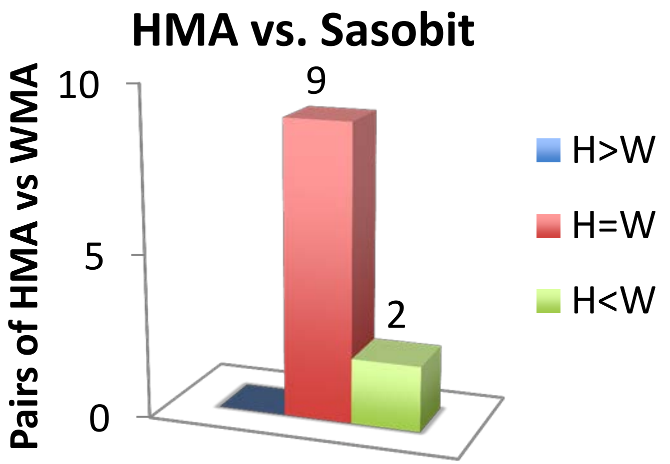
Verification: Significant Determinants for Transverse Cracking Based on 2nd Round Results

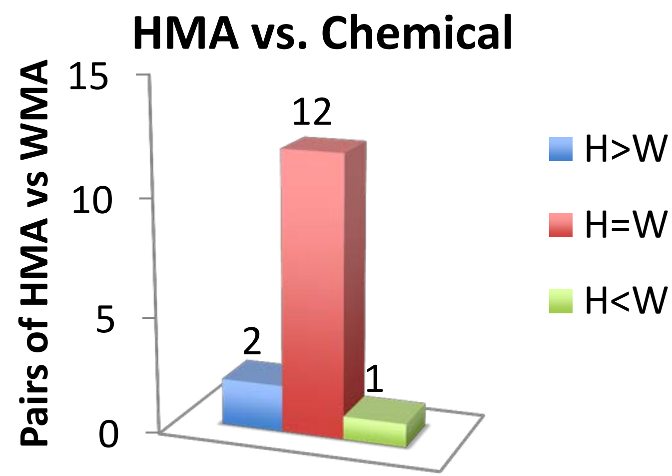
25 out of 35 HMA/WMA pairs

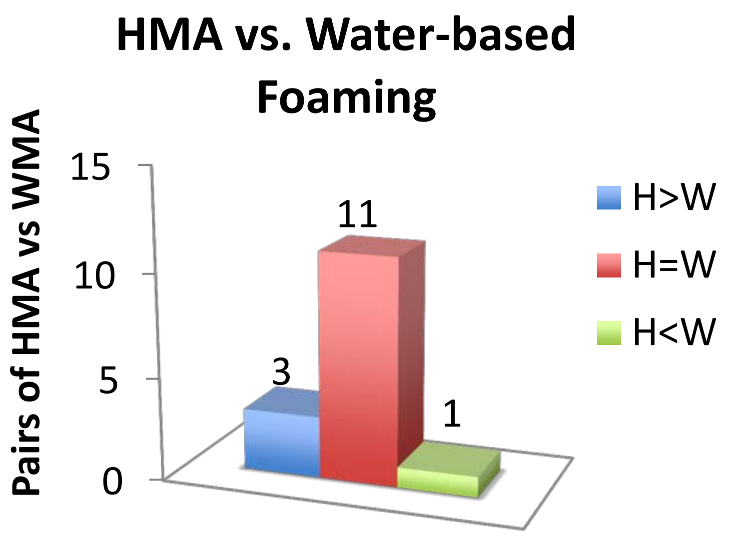


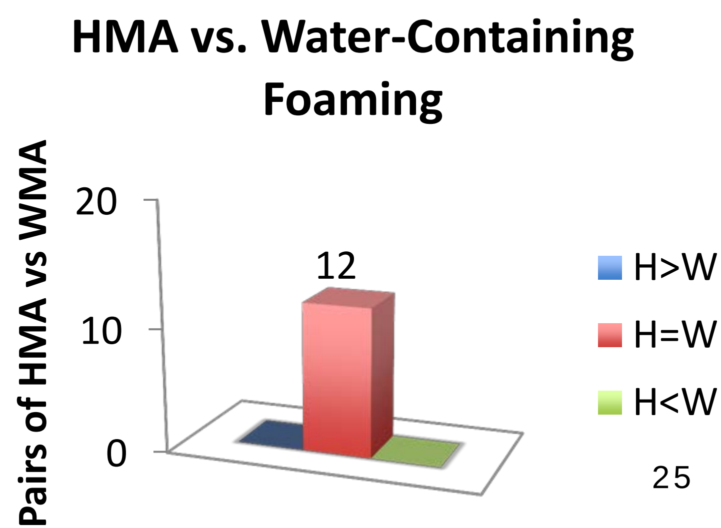
Use of Fracture Work Density as Indicator for Transverse Cracking Performance

HMA and WMA are comparable.



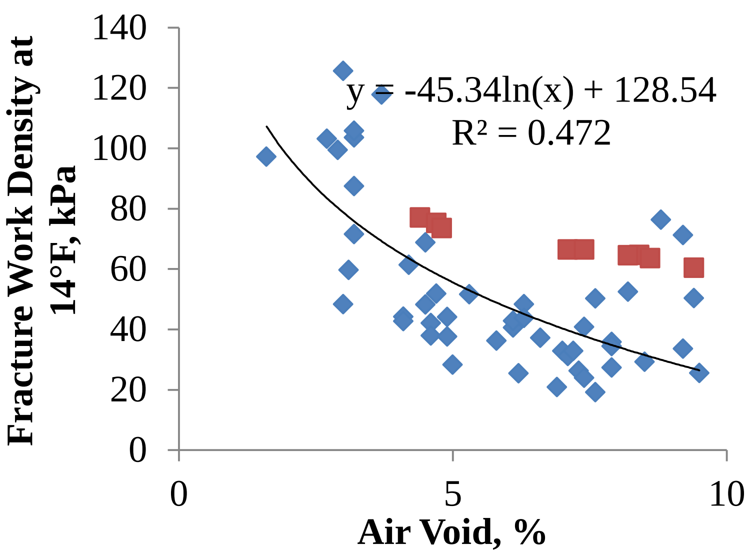


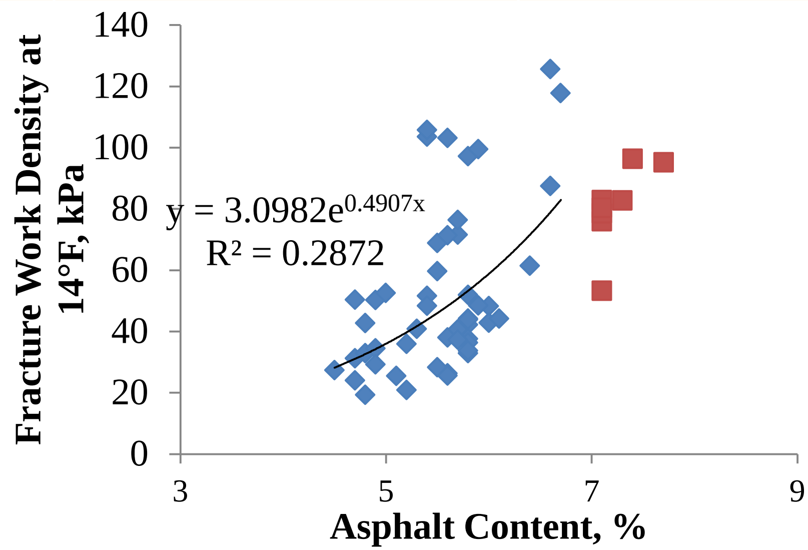




Pairs of HMA and WMA Whose FWD are not comparable

WMA	Project	FWD	Air Void	Asphalt Content
Sasobit	MT I-15	H < W	H (2.7%) = W (3.0%)	H (5.0%) > W (4.4%)
	CA 3b	H < W	H (9.4%) > W (7.4%)	H (6.7%) = W (6.4%)
Evotherm	CA3a	H > W	H (4.4%) < W (7.1%)	H (7.2%) = W (7.5%)
	TN SR 125	H > W	H (5.9%) < W (7.8%)	H (6.4%) > W (6.0%)
	MT I-15	H < W	H (2.7%) = W (2.0%)	H (5.0%) > W (4.6%)
Water-based Foaming	VA I66	H > W	H (4.5%) < W (5.3%)	H (5.5%) = W (5.4%)
	TN SR 46	H > W	H (5.0%) < W (6.9%)	H (5.4%) > W (5.2%)
	TX SH 71	H > W	H (6.7%) = W (7.2%)	H (4.6%) = W (4.9%)
	MT I-15	H < W	H (2.7%) = W (2.5%)	H (5.0%) >W (4.4%)





Implementation of the Use of Significant Determinants in Mix Design

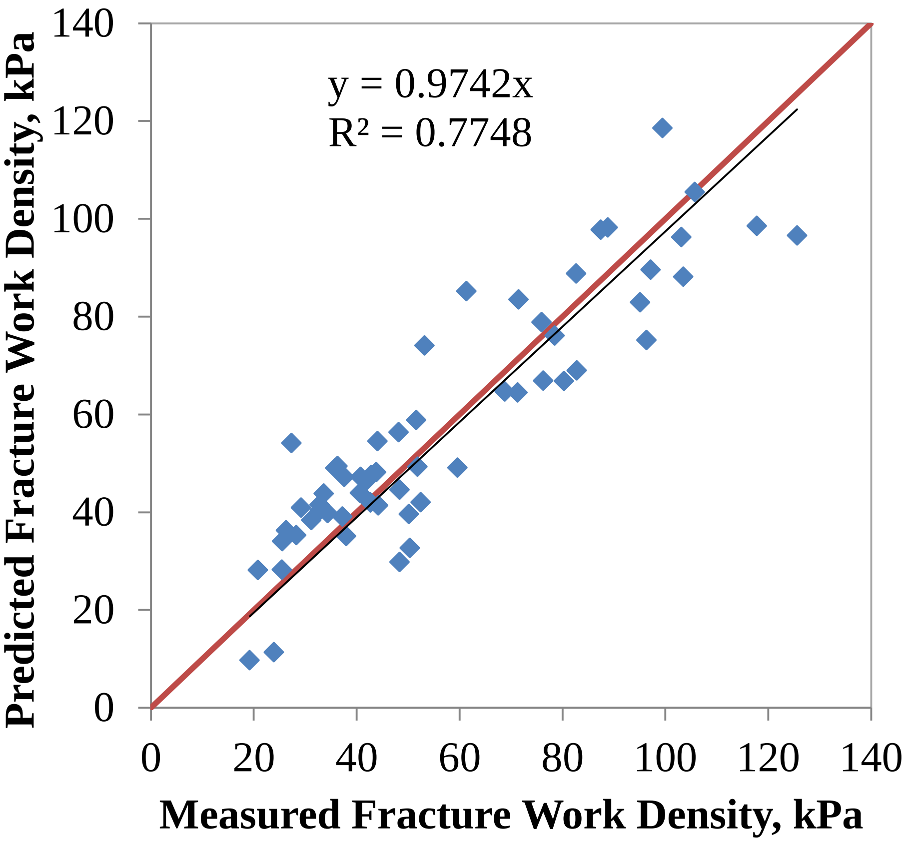
$$FWD = -91.38 + 0.387VFA + 66.74G_{se} + 8.08\varepsilon_b + 15.76P_b + 2.97P_{50}$$

Parameter		Description	P-value
FWD	=	mixture fracture work density tested at 14ºF, kPa	
G_{se}	=	aggregate effective specific gravity	0.006
VFA	=	voids filled with asphalt, %	0.006
ε_b	=	binder failure strain tested at 41°F	0.000
P_b	=	asphalt content, %	0.000
P_{50}	=	percentage passing No. 50 sieve size	0.000

Higher FWD, if

- o ductile asphalt binder (i.e., a higher level of failure strain),
- o relatively more asphalt (i.e., higher asphalt content, VFA)
- o contains more aggregate passing the No. 50 sieve,
- o contains hard aggregate (high G_{sb}).

Measured Work Density Vs Calculated Work Density



Summary of Transvers Cracking Study

- **The transverse cracking may be a combination of thermal cracking and reflective cracking.**
- **In general, HMA and WMA have comparable transverse cracking performance in the field.**
- **Fracture work density and dynamic modulus are found to be a significant determinant of transverse cracking**
- **Fracture work density is very sensitive to air void and asphalt content.**

Summary of Transvers Cracking Study

- **To achieve high fracture work density and good resistance to transverse cracking:**
  - **a high asphalt content and VFA,**
  - **a ductile asphalt binder,**
  - **hard aggregates**
  - **a fine gradation.**

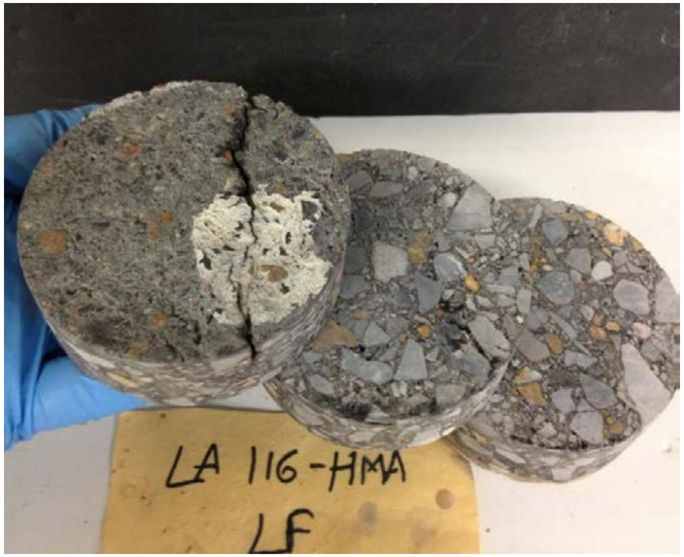
Outline

- **Objectives & Research Progress**
- **Preliminary Findings**
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- **Summary and Future Work**

Top-down Longitudinal Cracking

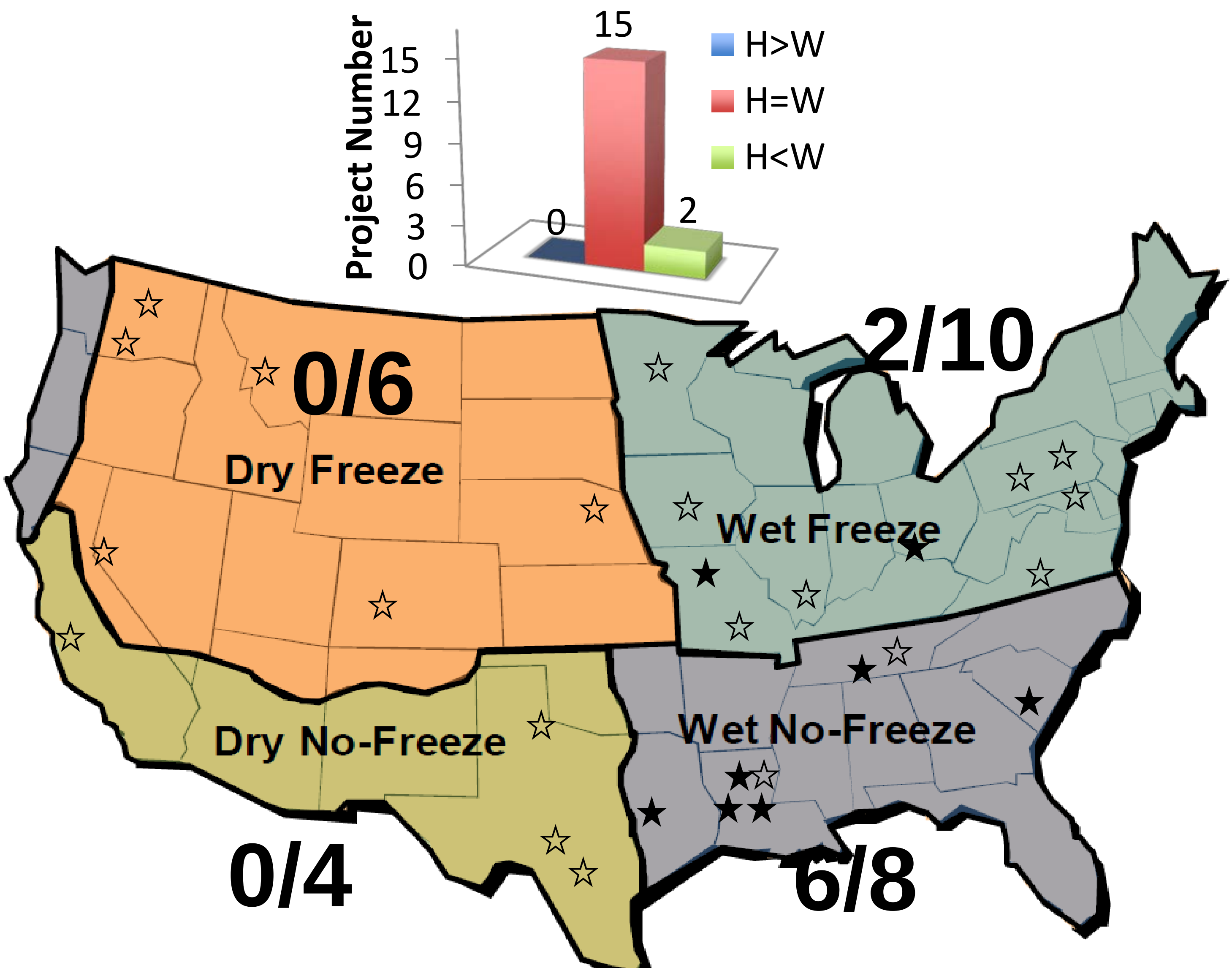
- **Field Performance Comparison between HMA and WMA**
  - 1st Round Survey
  - 2nd Round Survey
- **Significant Determinants for Top-down Cracking**
  - 1st Round Results
  - 2nd Round Results
- **Use Determinant to Compare HMA and WMA**
- **Implementation in Mix Design**

Top-down Fatigue Cracking



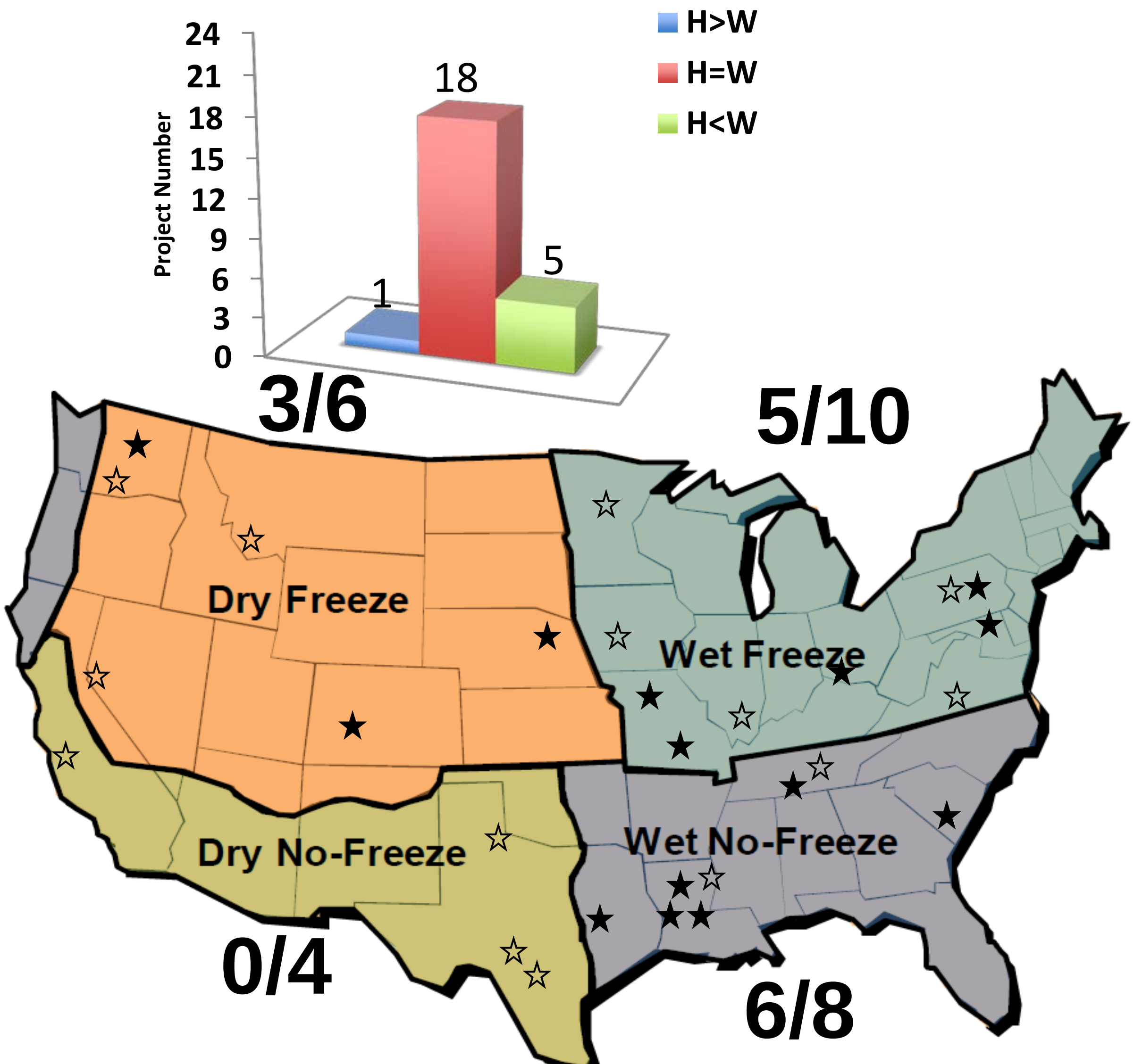
1st Round HMA/WMA Top-down Cracking Comparison

8 (17 H-W pairs) out of 24 projects exhibited top-down longitudinal cracking.

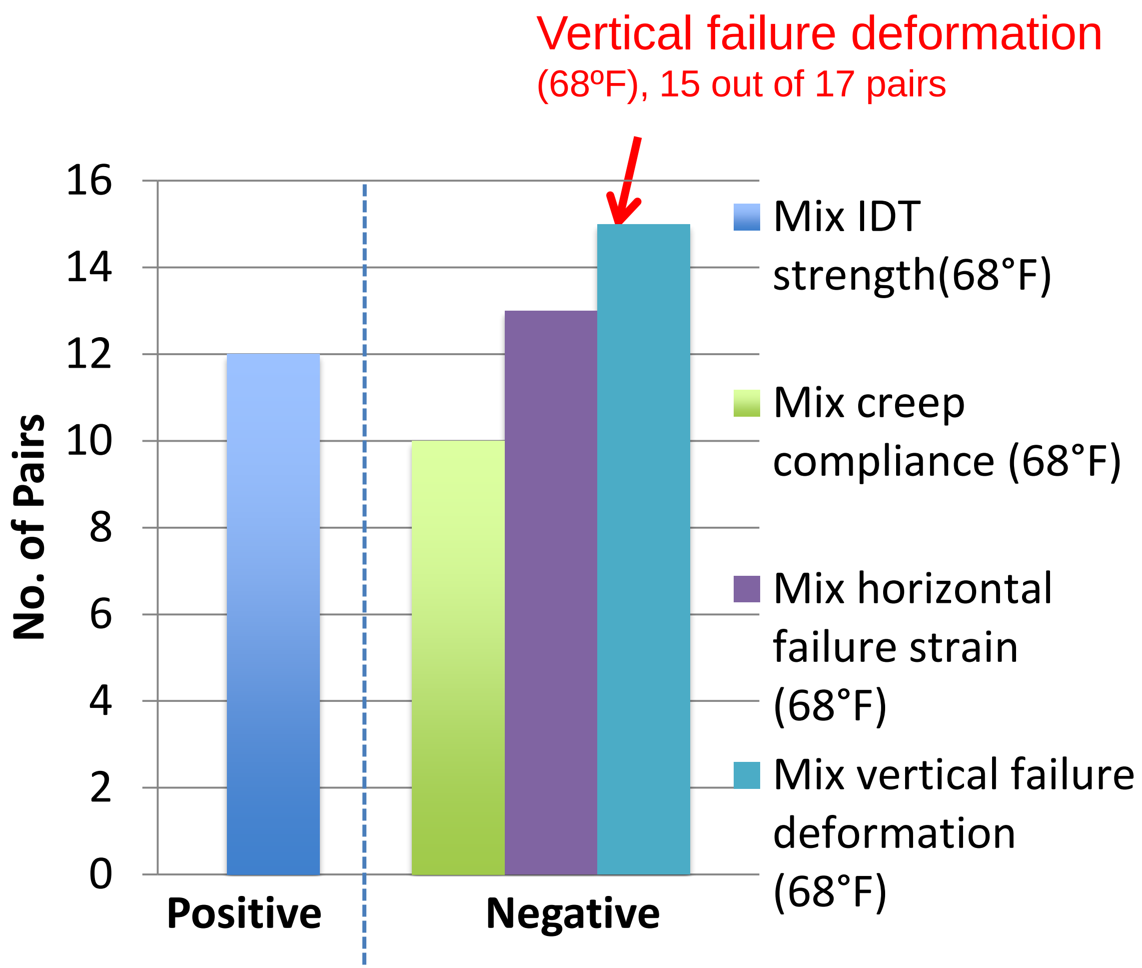


2nd Round HMA/WMA Top-down Cracking Comparison

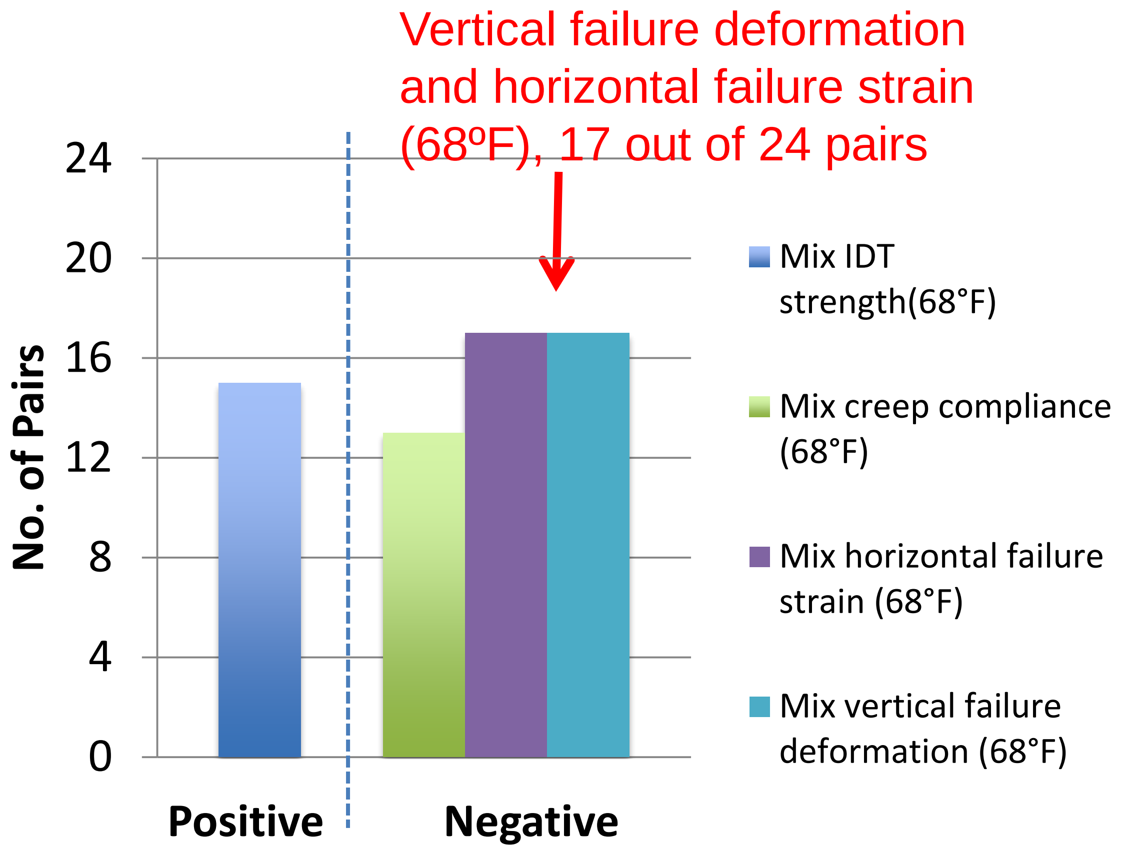
14 (24 H-W pairs) out of 28 projects exhibited top-down longitudinal cracking.



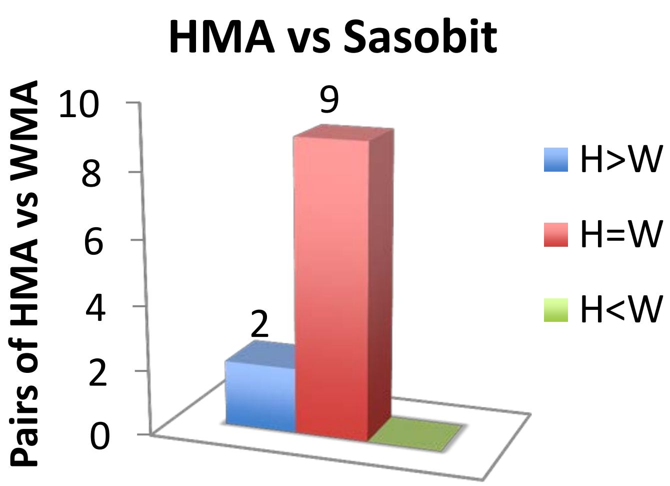
Significant Determinants for Top-down Longitudinal Cracking Based on 1st Round Results

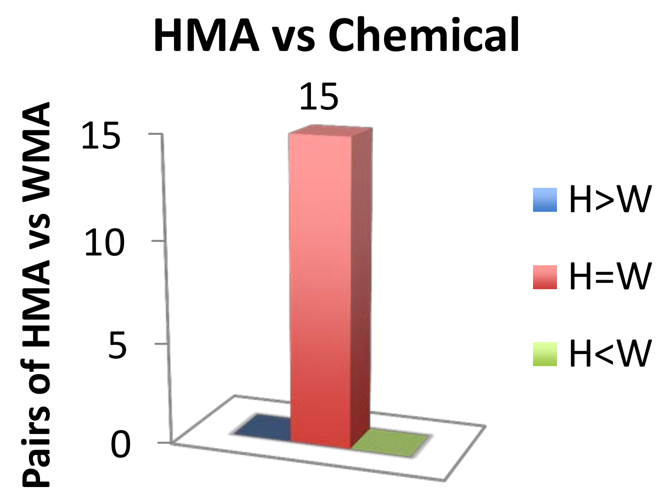


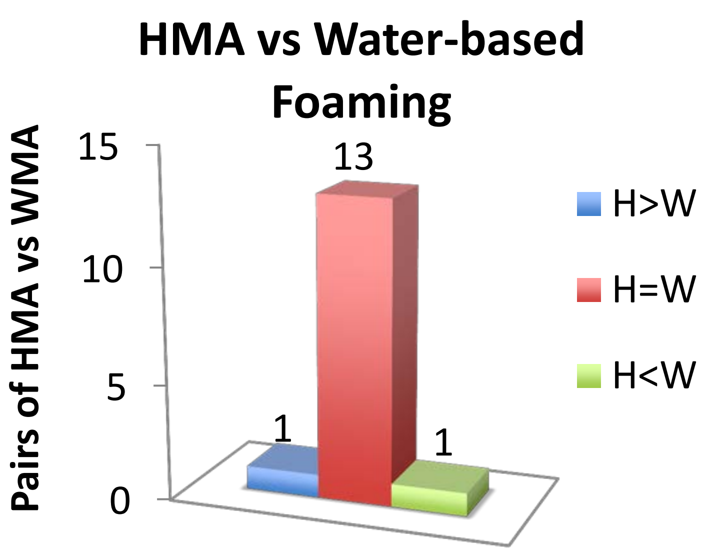
Verification: Significant Determinants for Top-down Cracking Based on 2nd Round Results

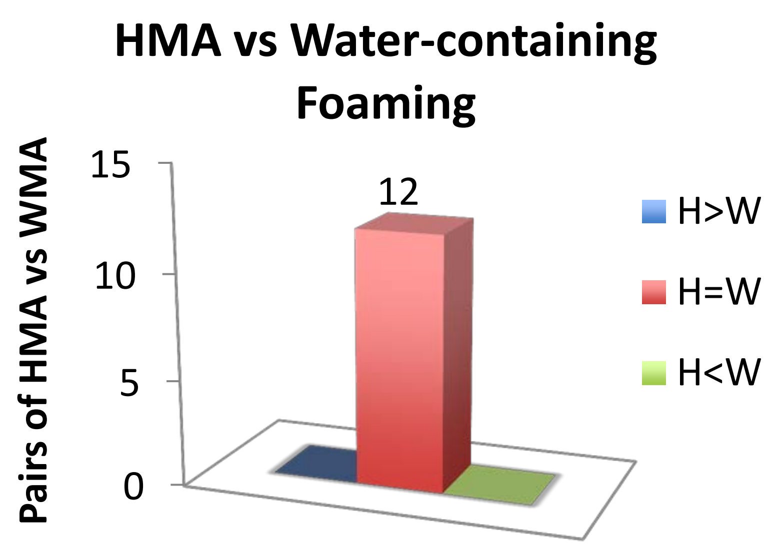


Use of Vertical Failure Deformation as Indicator for Top-down Longitudinal Cracking Resistance



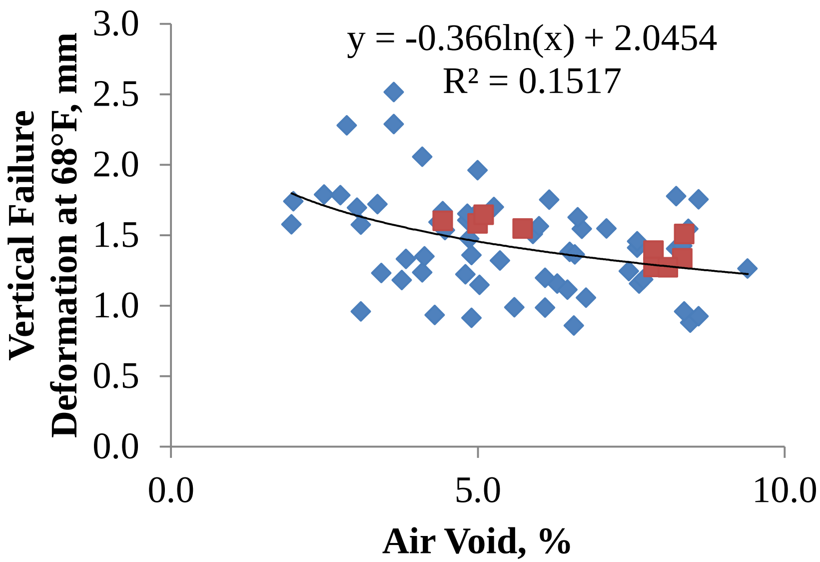


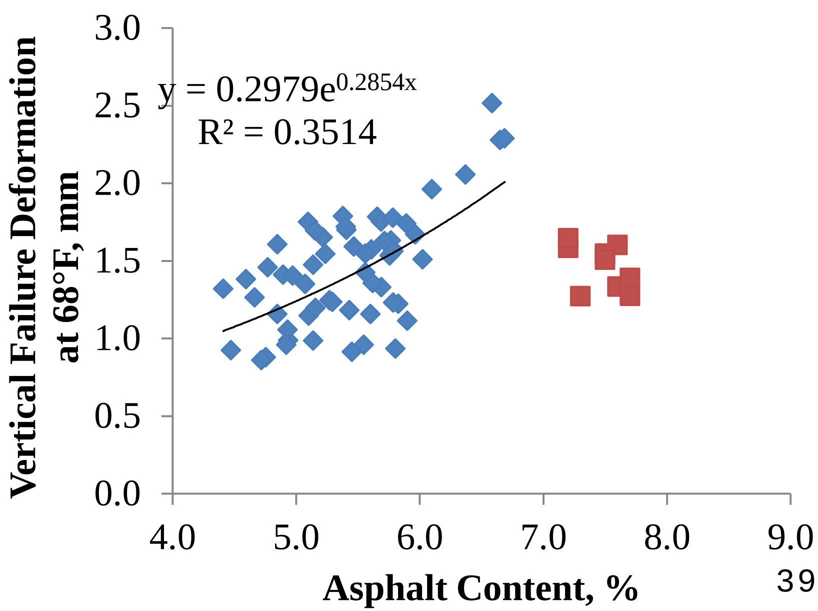




Pairs of HMA and WMA Whose VFD are not comparable

WMA	Project	VFD	Air Void	Asphalt Content
Sasobit	WA I90	H > W	H (2.5%) < W (3.1%)	H (5.4%) = W (5.6%)
	PA SR 2006	H > W	H (5.0%) < W (6.0%)	H (6.1%) = W (5.8%)
Water-based Foaming	TX SH 251	H < W	H (4.2%) = W (4.1%)	H (5.3%) = W (5.1%)
	TX SH 71	H > W	H (6.6%) < W (7.7%)	H (4.6 %) = W (4.9%)

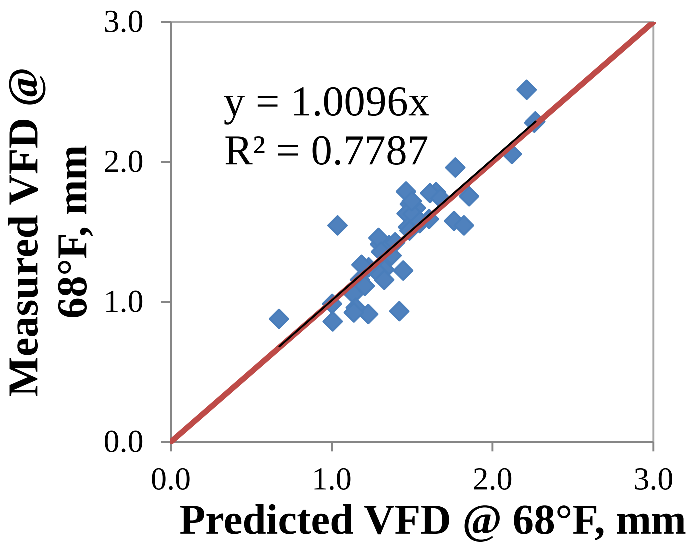




Implementation of the Use of Significant Determinants in Mix Design

$$VFD = -3.285 + 0.361P_b - 0.000152\sigma_b + 0.0172P_{30} + 0.0988G_{sb}$$

Parameter	Description	P-value
VFD =	vertical failure deformation of mix 68ºF, mm	
P_b =	binder content, %;	0.000
σ_b =	binder shear strength tested at 68°F, kPa	0.000
P_{30} =	percentage passing No. 30 sieve size	0.002
G_{sb} =	aggregate bulk specific gravity	0.012



Higher VFD, if the mix has
- o a relatively higher asphalt content,
- o lower binder shear strength,
- o finer gradation (more aggregate passing the No. 30 sieve)
- o harder aggregate (high G_{sb}).

Summary of Top-down Fatigue Cracking Study

- In general, HMA and WMA have comparable top-down fatigue cracking performance in the field, except in a few cases organic and water-containing WMA have more cracking than HMA
- The use of vertical failure deformation to represent field performance to remove the effects of other factors shows that HMA and WMA have comparable top-down fatigue cracking performance.
- Vertical failure deformation and horizontal failure strain of a mix are found to be the significant determinants of top-down fatigue cracking.

Summary of Top-down Fatigue Cracking Study

- **Vertical failure deformation is sensitive to air void and asphalt content.**
- **To achieve a high vertical failure deformation and good resistance to top-down fatigue cracking, a mix have:**
  - **a relatively high asphalt content**
  - **a soft binder**
  - **fine aggregate gradation**
  - **hard aggregates.**

Outline

- **Objectives & Research Progress**
- **Preliminary Findings**
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- **Summary and Future Work**

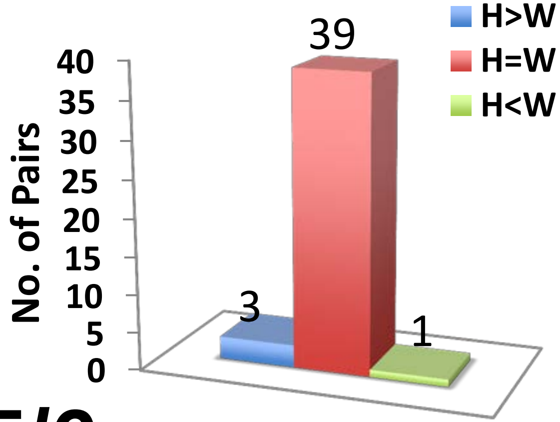
Rutting Performance

- **Field Performance Comparison between HMA and WMA**
  - 2nd Round Survey
- **Significant Determinants for Rut Depth**
  - 2nd Round Results
- **Use Determinant to Compare HMA and WMA**
- **Implementation in Mix Design**

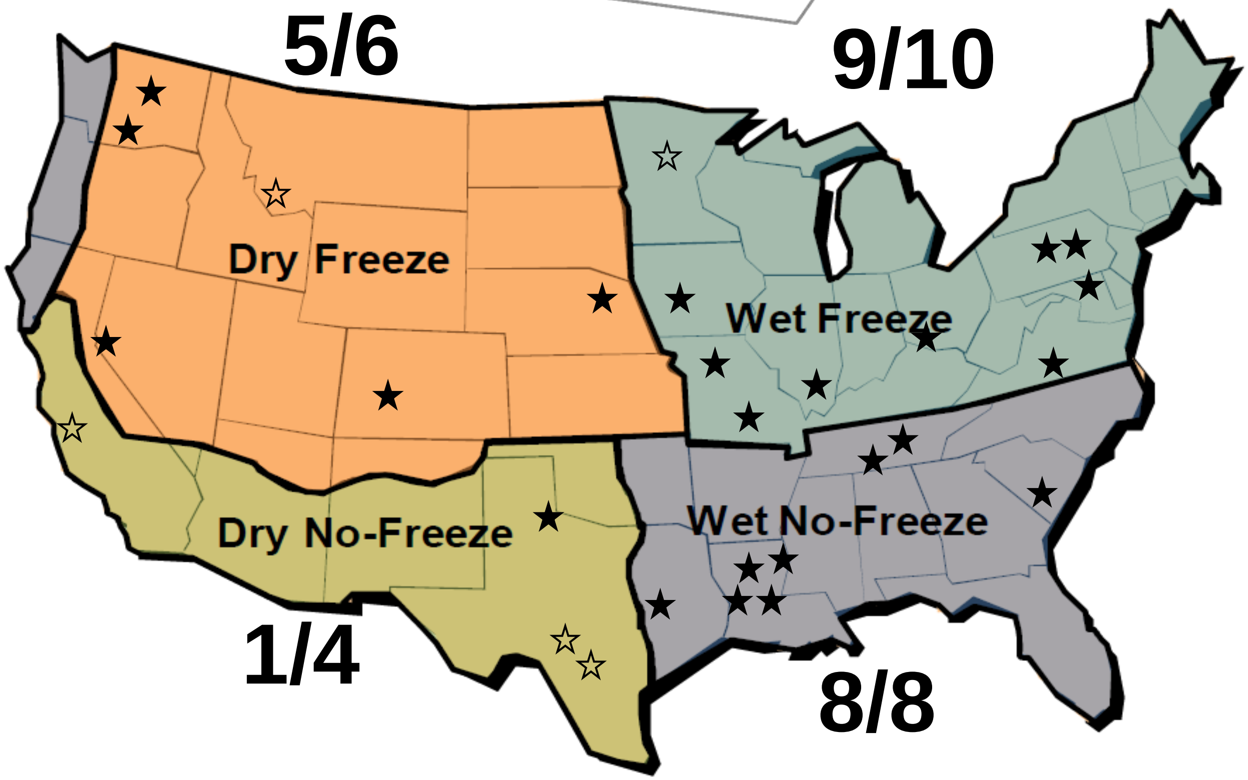
Rutting

2nd Round HMA/WMA Rutting Performance Comparison

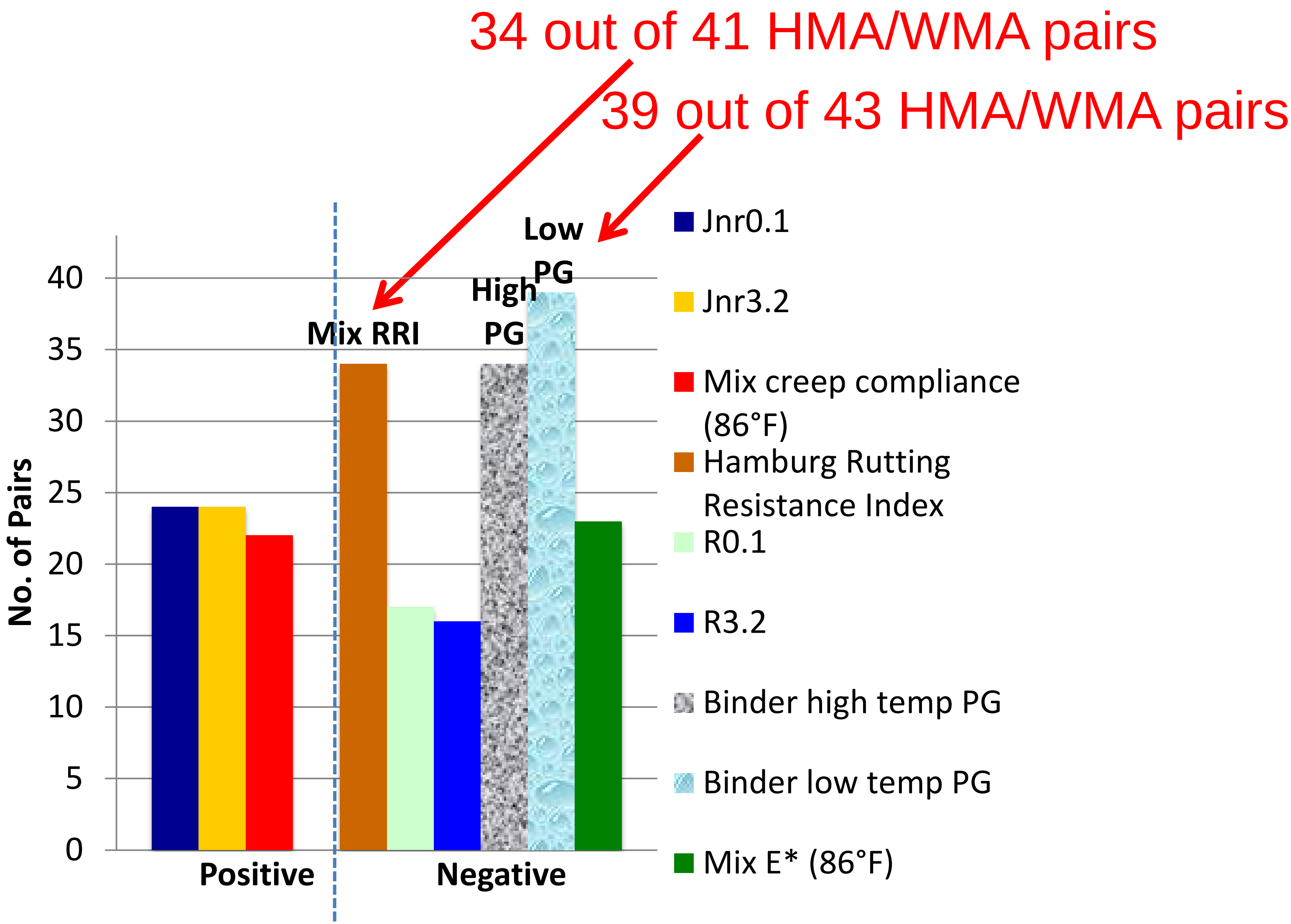
23 projects (43 H-W pairs) exhibited measurable rut depth.



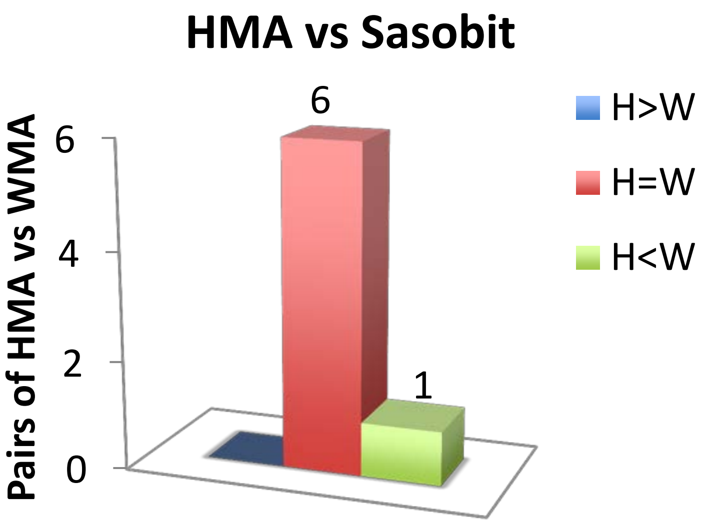
HMA and WMA are comparable in rut depth

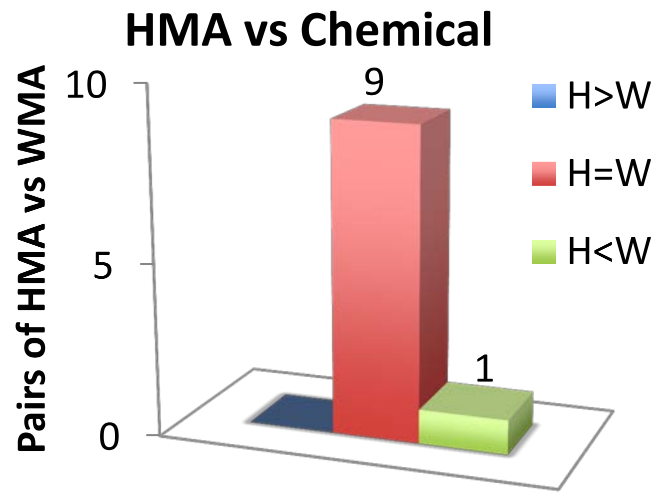


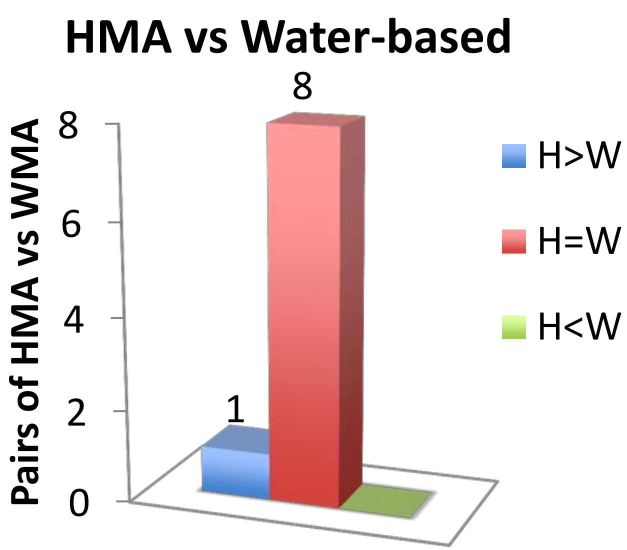
Significant Determinants for Rutting Resistance

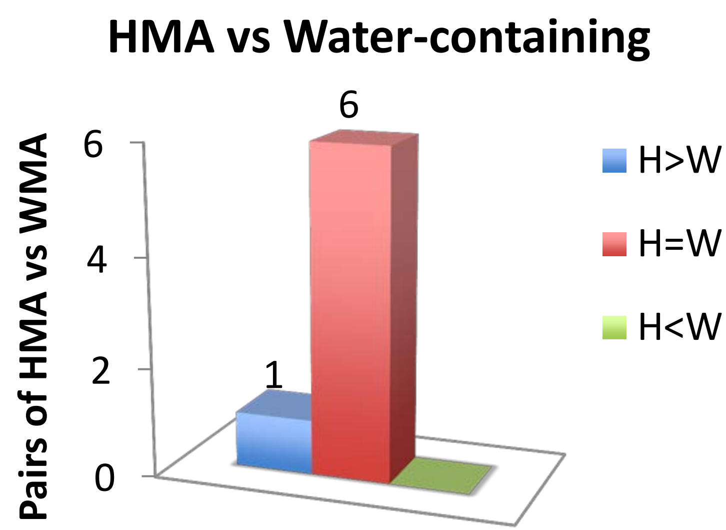


Use of RRI as Indicator of Rutting Performance



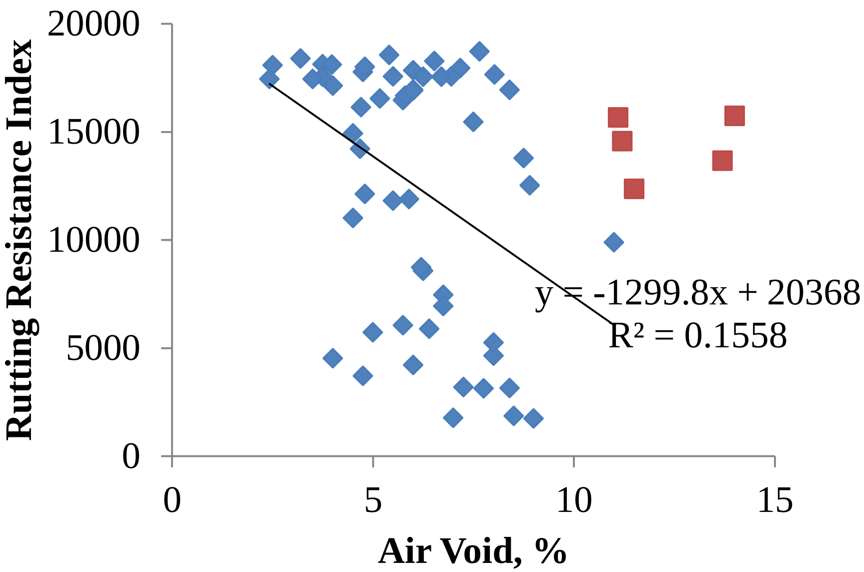


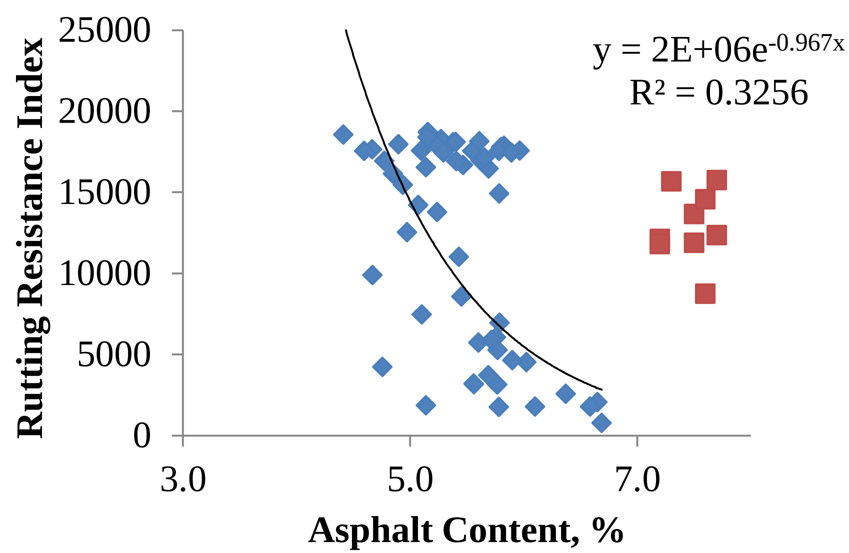




Pairs of HMA and WMA Whose RRI are not comparable

WMA	Project	RRI	Air Void	Asphalt Content
Sasobit	PA 2006	H < W	H (7.0%) = W (6.8%)	H (6.1%) = W (5.8%)
Chemical	NE US 14	H > W	H (8.0%) = W (8.4%)	H (4.7%) = W (4.8%)
Water-containing Foaming	MO Hall St.	H < W	H (6.0%) = W (6.25%)	H (5.8%) = W (5.5%)
Water-based Foaming	LA 116	H > W	H (5.4%) < W (6.7%)	H (4.4%) = W (4.6%)



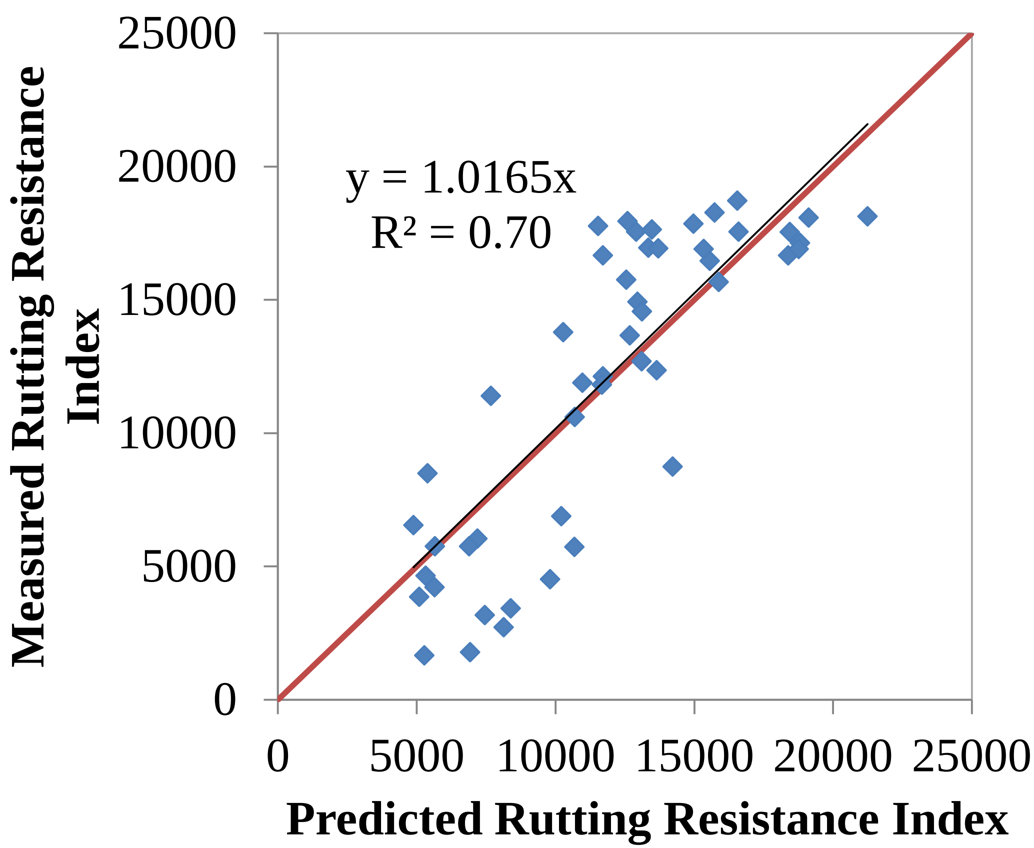


Implementation of the Use of Significant Determinants in Mix Design

$$RRI = 3700.555 + 2187.602P_{100} + 122.027R_{3.2} - 323.71P_{16} - 73.374VFA + 2054.665P_{ba}$$

Parameter		Description	P-value
RRI	=	rutting resistance index, RRI = N × (1 - RD)	
P_{100}	=	percentage passing No. 100 sieve	0.000
$R_{3.2}$	=	percentage of recovery of binder at stress level of 3.2 kPa from MSCR test	0.000
P_{16}	=	percentage passing No. 16 sieve	0.000
VFA	=	voids filled with asphalt	0.003
P_{ba}	=	asphalt binder absorption	0.013

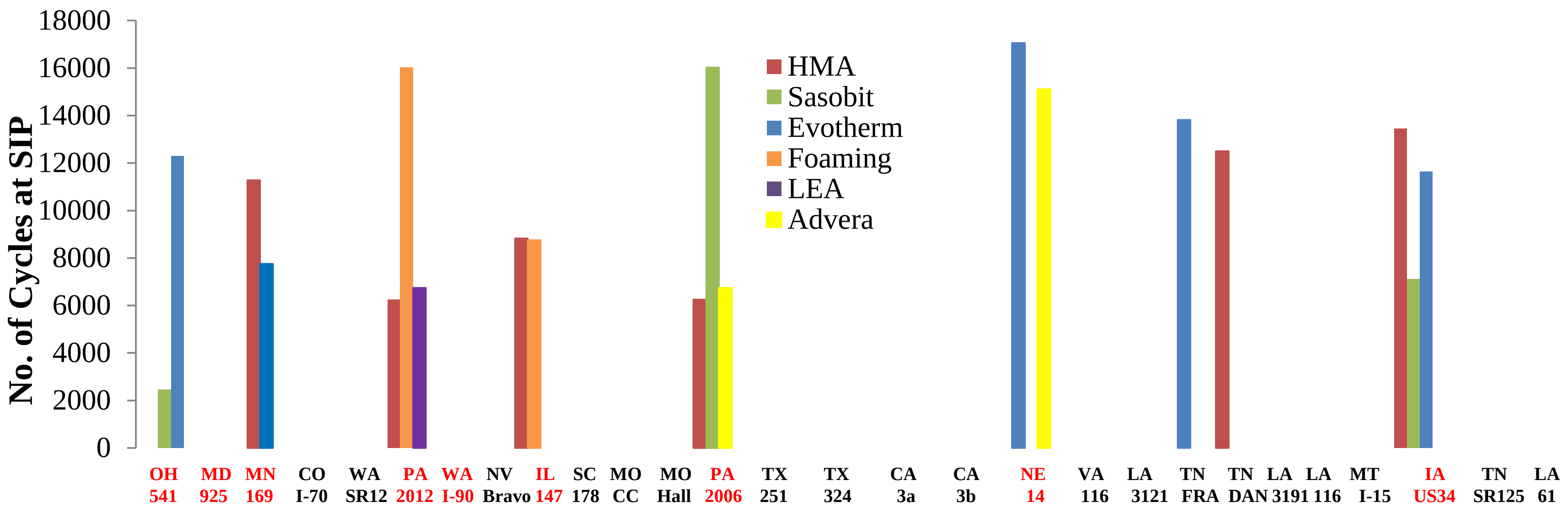
Measured RRI Vs Calculated RRI



Summary of Rutting Study

- In general, HMA and WMA have comparable rutting performance in the field.
- The mix's rutting resistance index (RRI) is recommended to be a significant determinant of rutting performance.
- To develop a rutting resistant mix, a mix has
  - a high percent recovery from MSCR test
  - a low VFA
  - a high asphalt absorption rate
  - a gap-graded aggregate.

Moisture Susceptibility



For the projects that show SIP, it is found that anti-stripping agents were not applied in most cases.

Summary of Rutting Study

- In general, HMA and WMA have comparable rutting performance in the field.
- The mix's rutting resistance index (RRI) is recommended to be a significant determinant of rutting performance.
- To develop a rutting resistant mix, a mix needs to have a high percent recovery from MSCR test, a low VFA, a high asphalt absorption rate, and a gap-graded aggregate.
- A mix without anti-stripping agent is likely to have a stripping inflection point.

Outline

- **Objectives & Research Progress**
- **Preliminary Findings**
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Effects of WMA on construction practices
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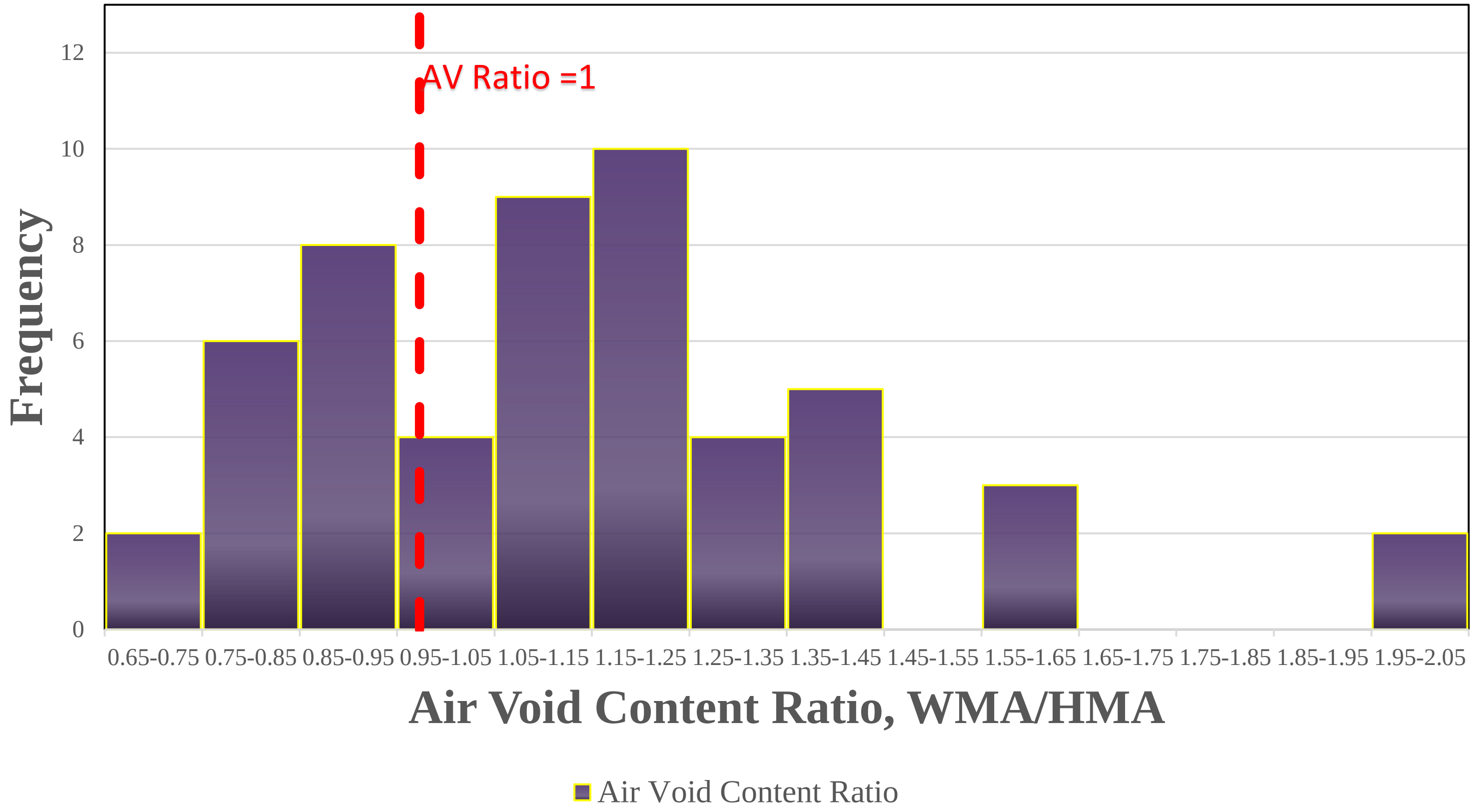
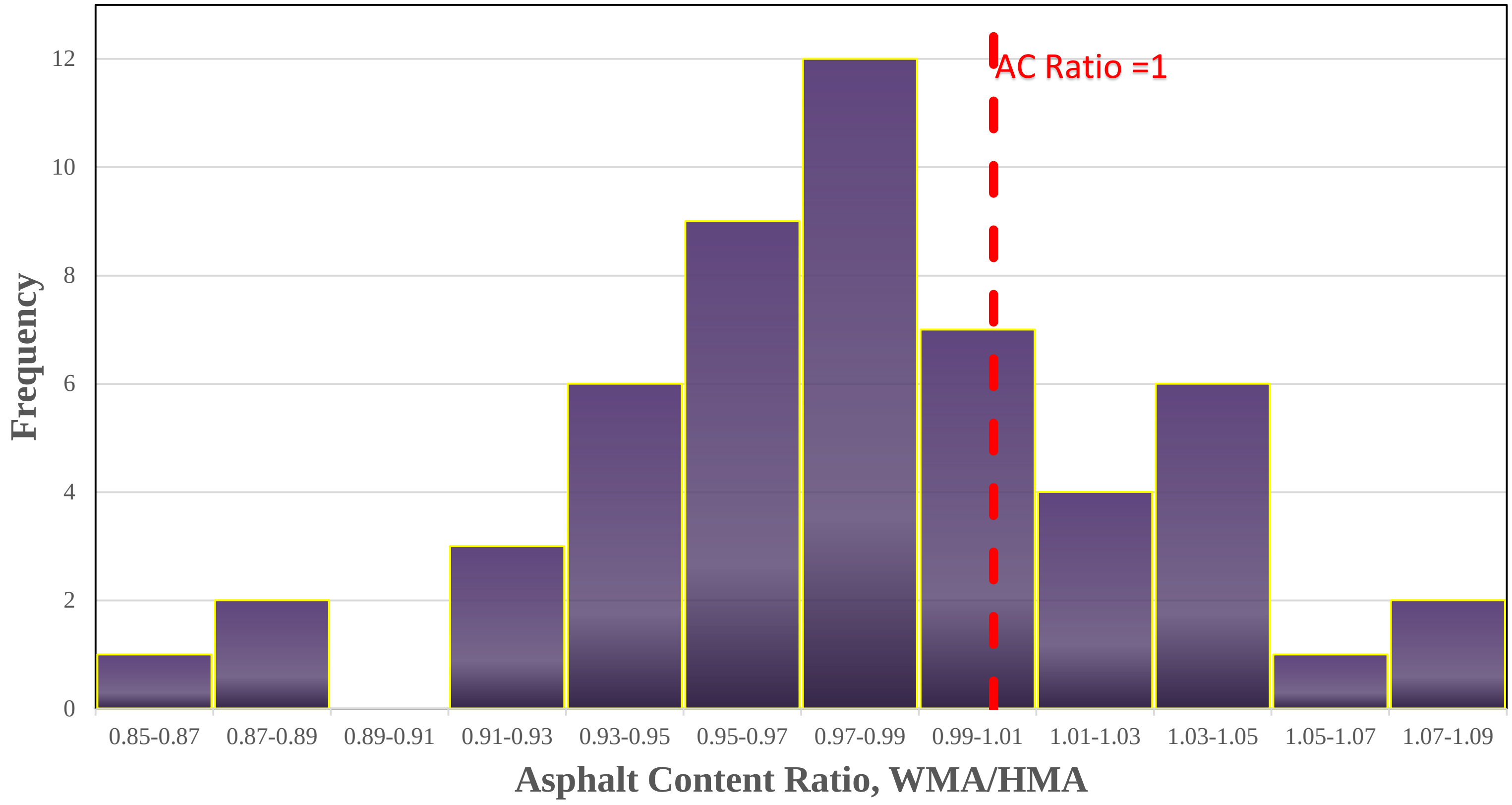
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- **Summary and Future Work**

Air Void: WMA/HMA



Binder Content: WMA/HMA



Fractured Aggregate after Testing

Summary

- As a whole, WMA has a tendency to have slight higher air void and lower asphalt content.
- The mix design results in the laboratory based on gyratory compactor may not be translated into the field.
- The compaction pressure may be too high and does not distinguish different mixes.*

Outline

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  - Transverse Cracking
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- **Summary and Future Work**

TN SR 125 Project: HMA Pavement

Before Construction

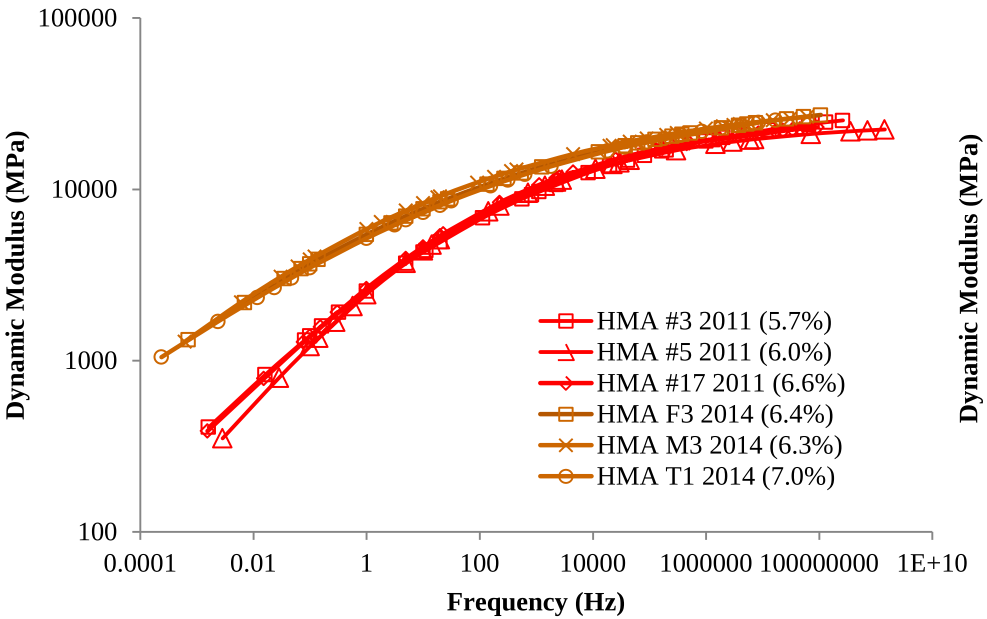
During Construction

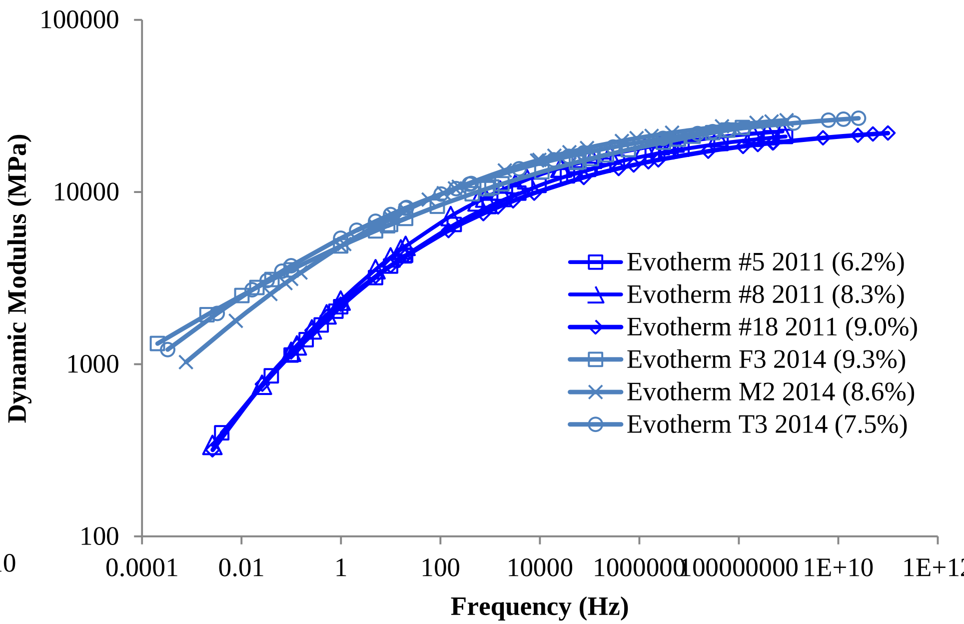
After Construction

3 years After Construction

TN SR 125 Project: 2014 Vs 2011 Field Cores

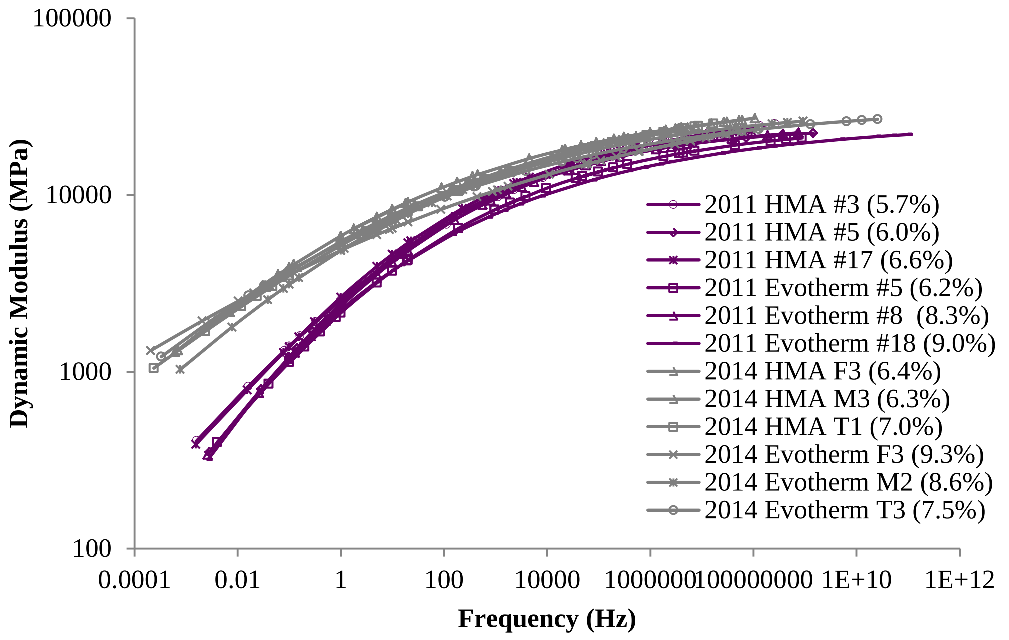
Dynamic Modulus





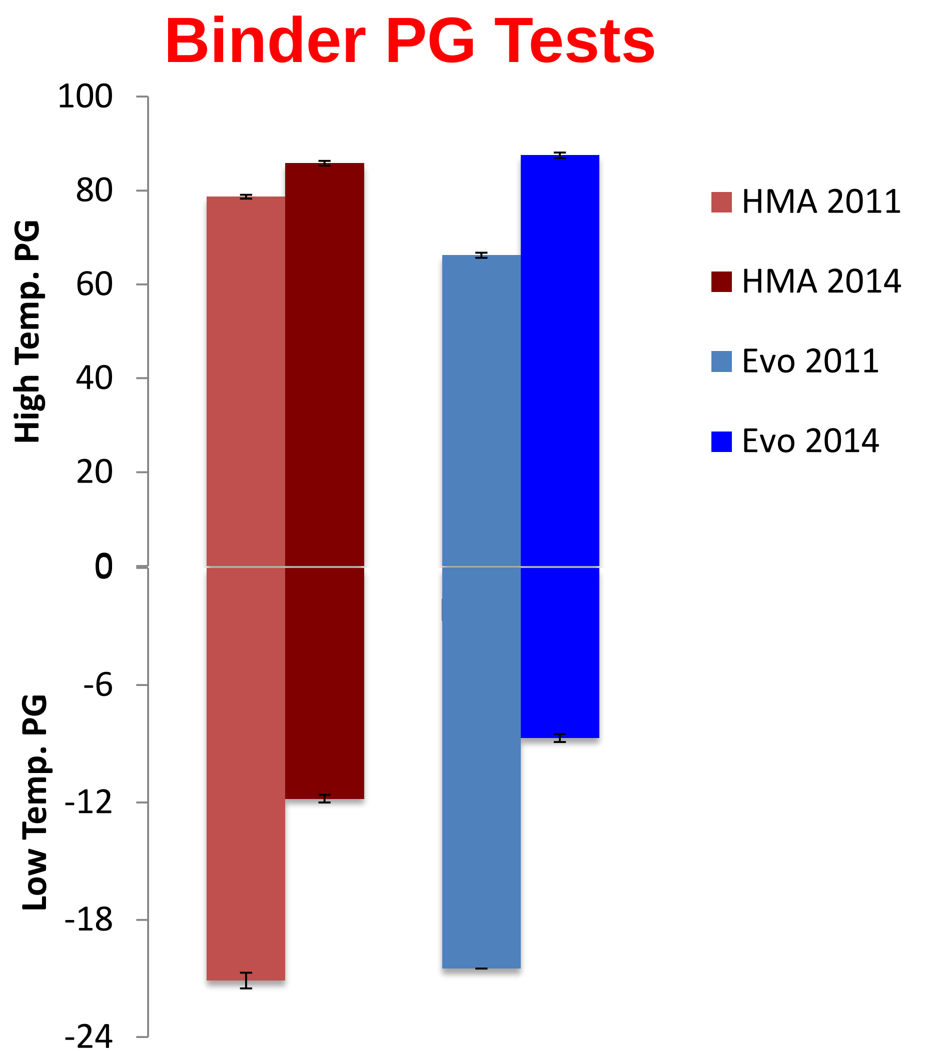
TN SR 125 Project: 2014 Vs 2011 Field Cores

Dynamic Modulus

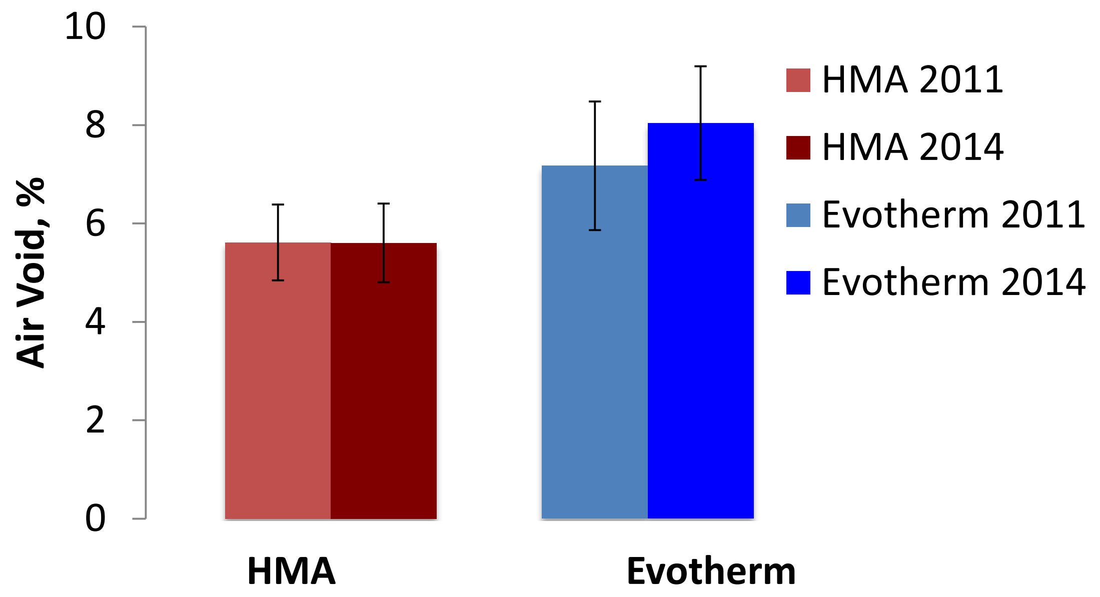


2014 field cores shows higher E* than 2011

TN SR 125 Project: 2014 Vs 2011 Field Cores

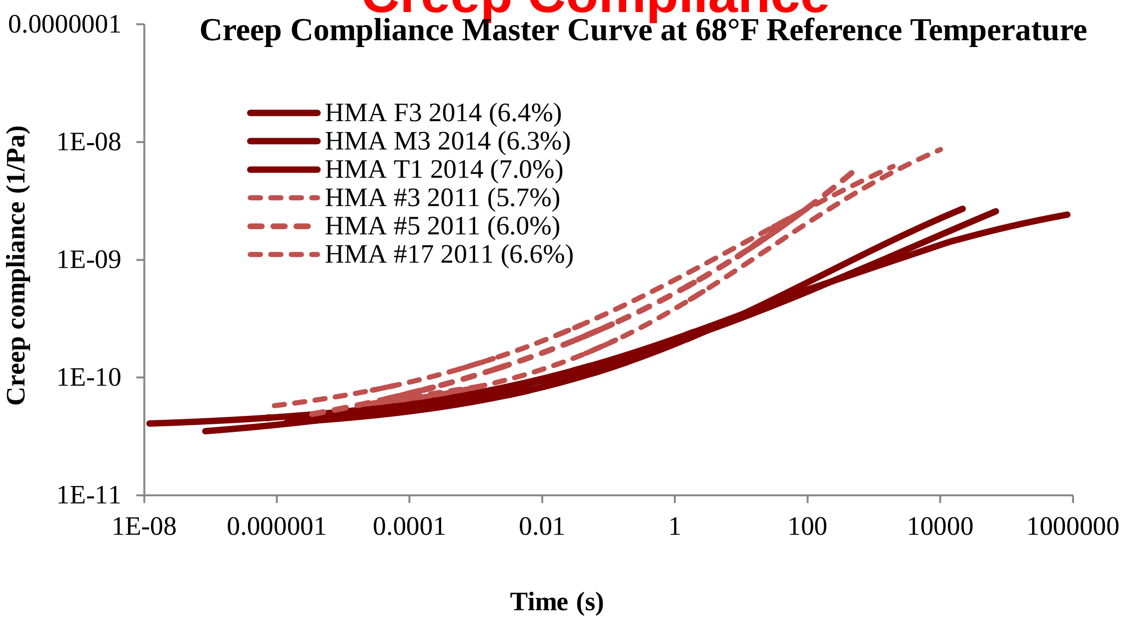


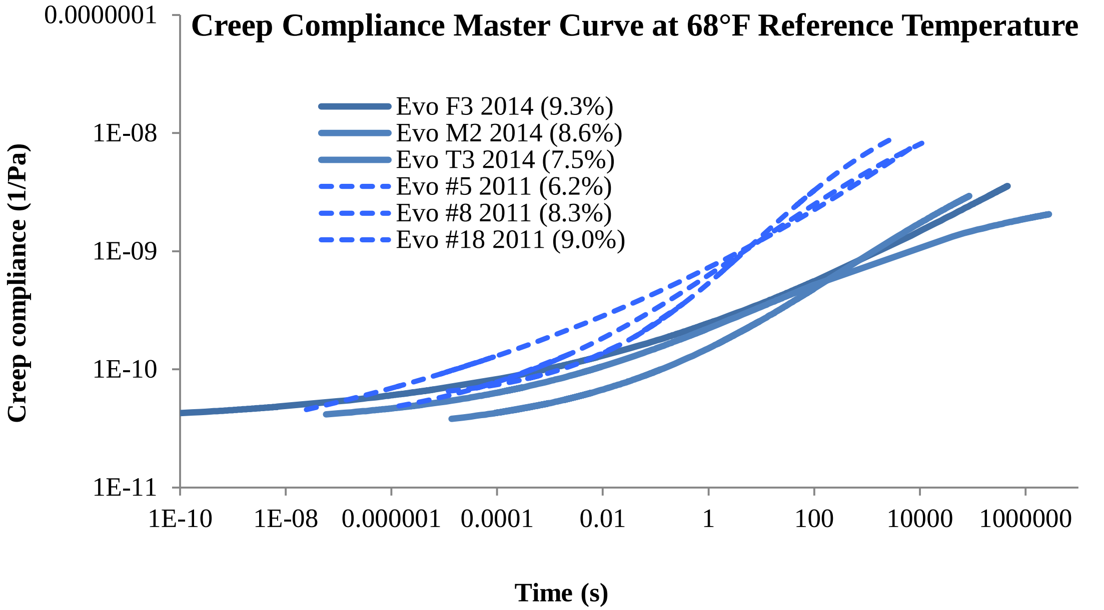
TN SR 125 Project: 2014 Vs 2011 Field Cores Air Void



TN SR 125 Project: 2014 Vs 2011 Field Cores

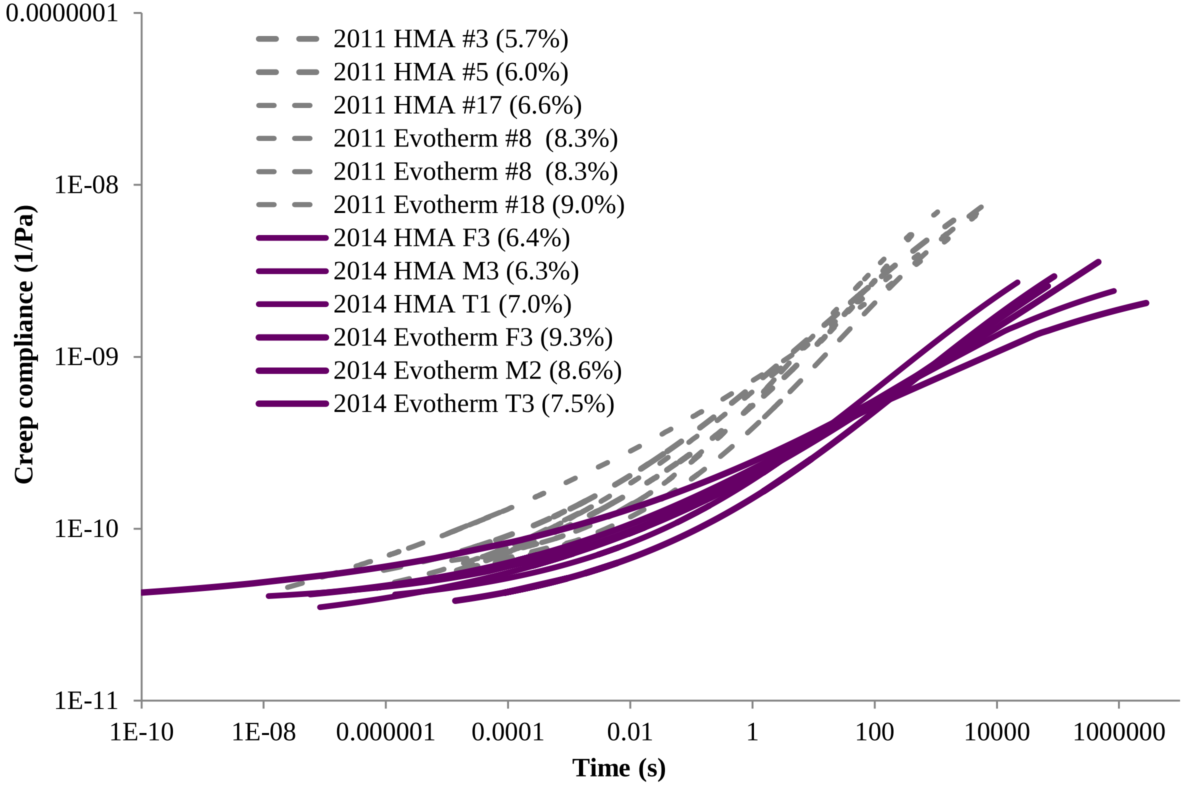
Creep Compliance





TN SR 125 Project: 2014 Vs 2011 Field Cores

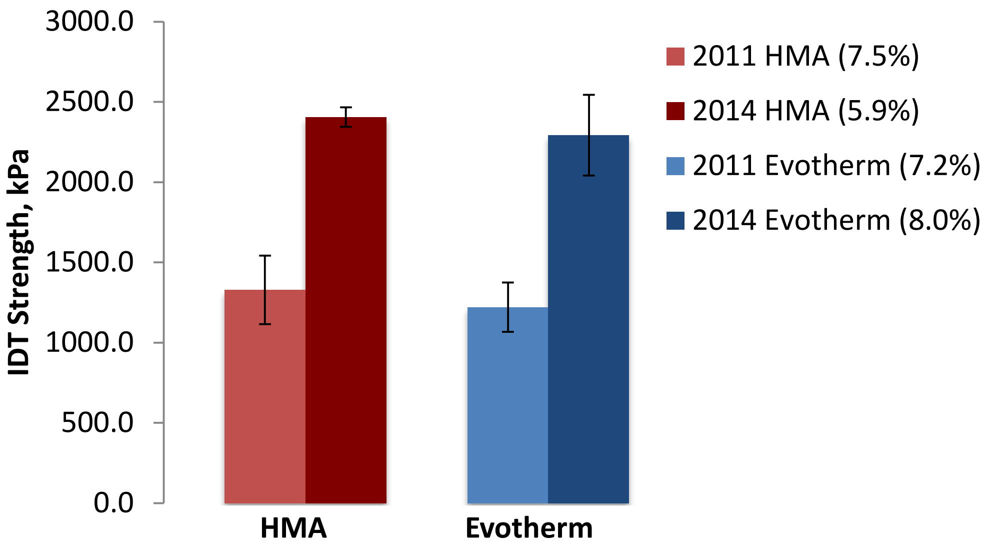
Creep Compliance

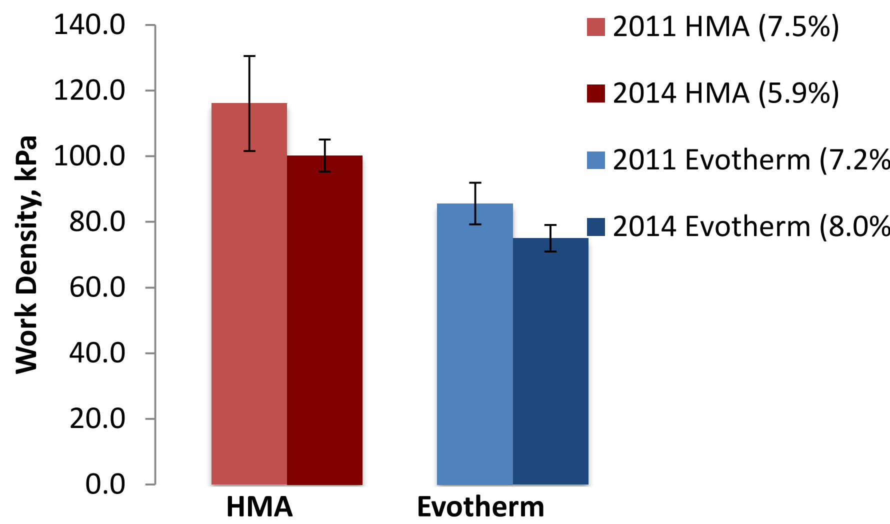


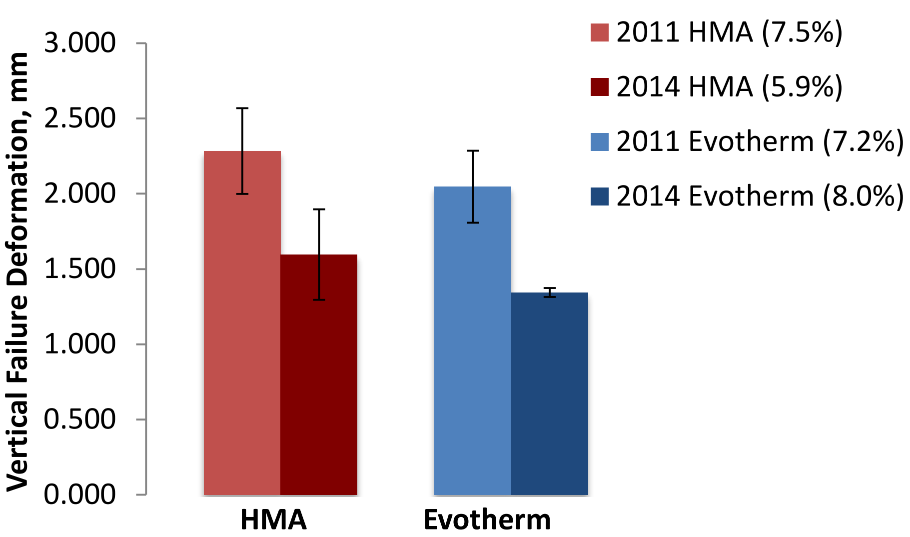
2014 field cores shows lower creep compliance than 2011

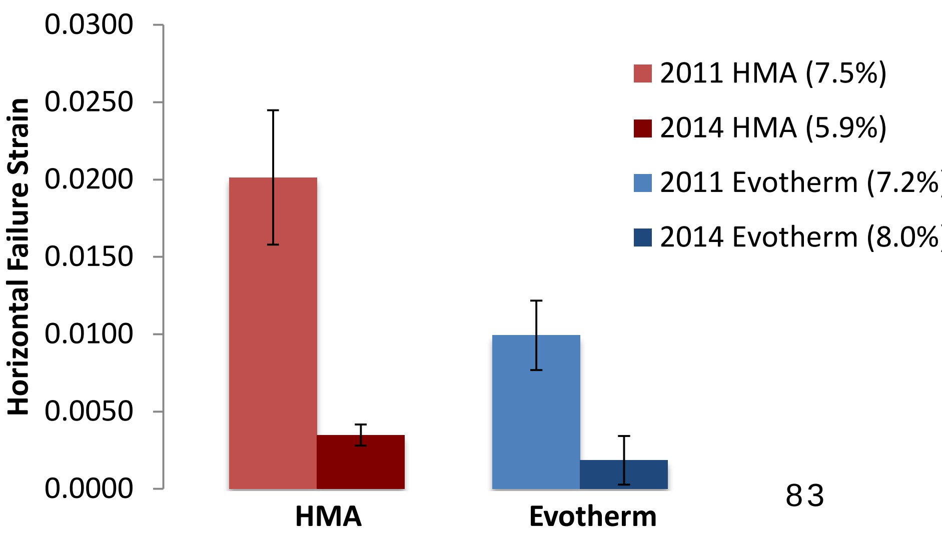
TN SR 125 Project: 2014 Vs 2011 Field Cores

IDT Test at Intermediate Temperature



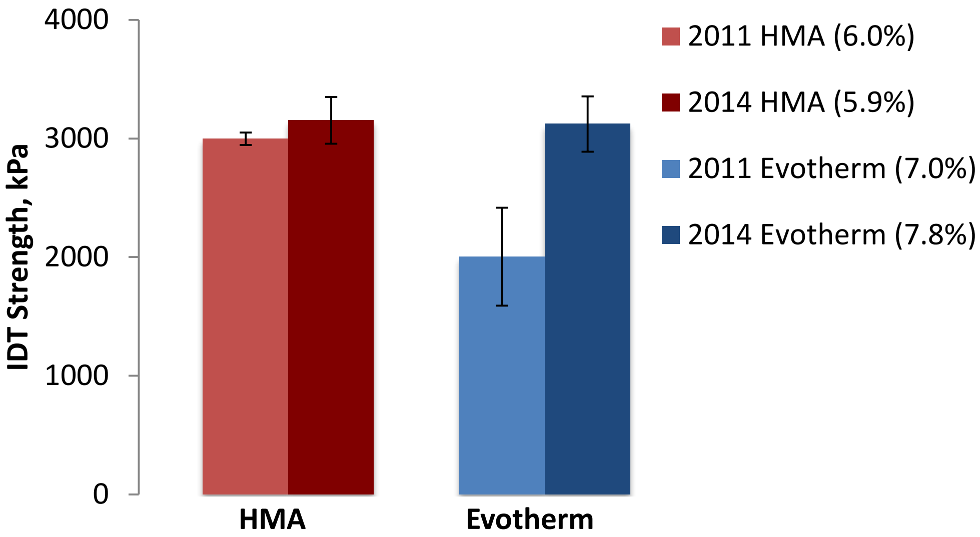


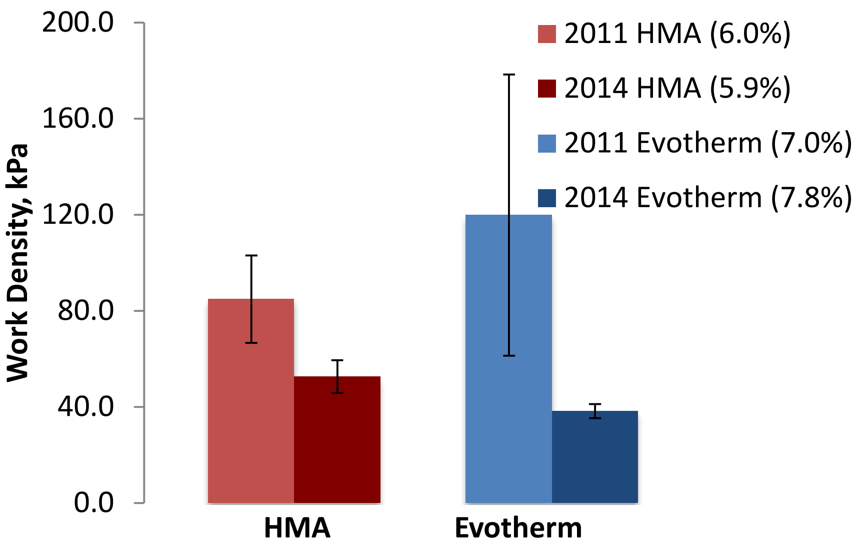




TN SR 125 Project: 2014 Vs 2011 Field Cores

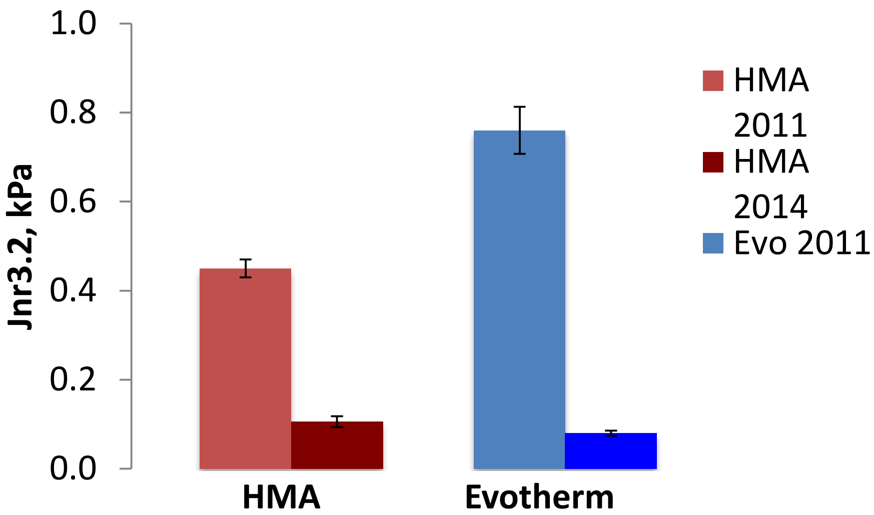
IDT Test at Low Temperature

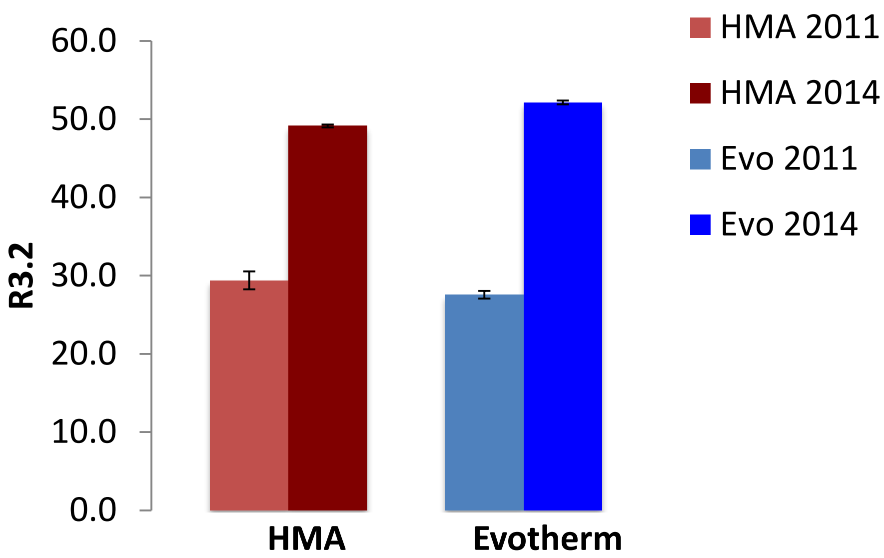




TN SR 125 Project: 2014 Vs 2011 Field Cores

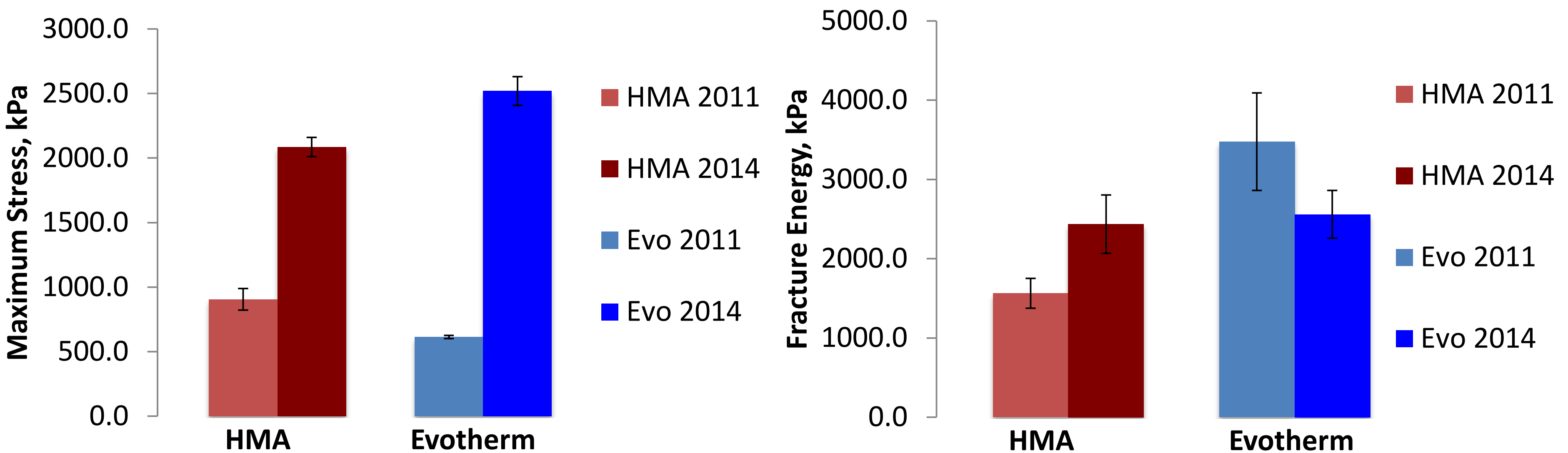
Binder MSCR Tests





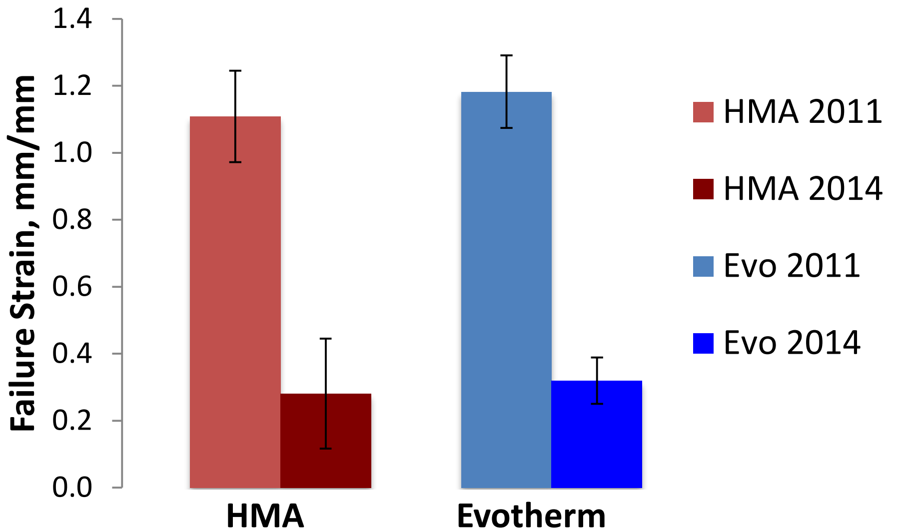
TN SR 125 Project: 2014 Vs 2011 Field Cores

Binder Fracture Tests at Intermediate Temperature



TN SR 125 Project: 2014 Vs 2011 Field Cores

Binder Fracture Tests at Low Temperature



Summary of Material Properties between HMA and WMA (TN SR125 Project)

Material	Material Property	HMA Vs. WMA	2011			2014		
			14°F	68°F	86°F	14°F	68°F	86°F
Mix	Dynamic Modulus	Evotherm	=	>	=	=	=	=
	Creep Compliance	Evotherm	=	=	=	=	>	=
	Vertical Failure Deformation (68° F)	Evotherm	=			=		
	Fracture Work Density (14° F)	Evotherm	=			>		
Binder	PGs	Evotherm	<			=		
	MSCR-R$_{3.2}$	Evotherm	=			=		
	Fracture Energy (68° F)	Evotherm	<			=		
	Failure Strain (41° F)	Evotherm	=			=		

Summary of Change of Material Properties

- **The oxidation leads to higher modulus, smaller creep compliance and slopes, higher PG, compromised cracking resistance and improved rutting resistance.**
- **The application of chip seal significantly slowed down the oxidation.**
- **There is no clear trend of significant change of ranking between HMA and WMA after 2 or 3 years in service.**

Outline

- **Objectives & Research Progress**
- **Preliminary Findings**
  - Transverse Cracking
  - Top-down Longitudinal Cracking
  - Rutting & Moisture Susceptibility
  - Material Properties Changes
    - MT I-15 Project
    - TN SR 125 Project
    - IA US 34 Project
- **Summary and Future Work**

Summary:

- In general, there is no significant difference of field performance between HMA and WMA pavements.
- Fracture work density, vertical failure deformation (and/or dynamic modulus), and rutting resistance index are recommended to be the significant determinants of transverse cracking, top-down fatigue cracking and rutting, respectively.
- Reducing the asphalt content based on laboratory compaction may compromise the cracking performance of a mix and should be discouraged.

Summary:

- A mix is more resistant to transverse cracking if it has a relatively high binder content and VFA, a ductile binder, hard aggregates and a fine aggregate gradation.
- A mix is more resistant to top-down cracking if it has a relatively high binder content, a soft binder, hard aggregates and a fine aggregate gradation.
- A mix is more resistant to rutting if it has a binder with high percent recovery, a low VFA, a gap-graded aggregate gradation, and a high asphalt absorption rate.
- Use of anti-stripping agent may be beneficial to avoid the moisture damage.

Summary:

- The aging of HMA and WMA does not significantly affect the property ranking.

Recommendations for implementations

- Implementation of findings
  - Develop mix design criteria based on significant determinants
    - Fracture work density for transverse cracking
    - Vertical failure deformation or horizontal failure strain for top-down cracking
    - Rutting resistance index for rutting
  - Use of anti-stripping agent
    - How much?
  - Procedure to ensure WMA has sufficient asphalt content
  - Adjustment of laboratory compaction
    - Compaction pressure, etc.
  - Use the material and field data to calibrate the Pavement ME models for rutting, top-down cracking, etc.
  - Develop binder specifications based on binder, mix and field data.

Thank You!

Any questions?