Performance Impacts of Recycling and WMA Production and on Asphalt Fatigue Cracking

Objectives of this Experiment

- ***Establish realistic boundaries*** **for high-RAP mixes employing WMA technologies and RAS mixes based on** ***percent binder replacement*** **and** ***binder grade changes*** **when combined together.**

ALF Experimental Design

HMA / WMA Production Temperature Warm Mix Technology Recycle Content	300ºF - 320ºF		240ºF - 270ºF	
	-		Foam	Chem.
0%	✔ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✔ PG64-22		✔ PG64-22	✔ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✔ PG64-22	✔ PG58-28		
40% ABR RAP ≈ 44% by weight	✔ PG64-22	✔ PG58-28	✔ PG58-28	✔ PG58-28

Testing Progress & Sequence

(ALF 1) Lane 9 WMA-F 20% ABR — Complete

(ALF 2) Lane 11 WMA-C 40% ABR 58-28

-move-

(ALF1) Lane 1 0% Control — Oct/Nov 2014

(ALF2) Lane 5 HMA 40% ABR

-move-

(ALF1) Lane 4 WMA-C 20% ABR — Nov 2014 / Jan 2015

(ALF2) Lane 7 HMA 20% ABR RAS 58-28

-move-

(ALF1) Lane 2 WMA-F 40% ABR 58-28 — Feb/Mar 2015

(ALF2) Lane 8 HMA 40% ABR 58-28

-move-

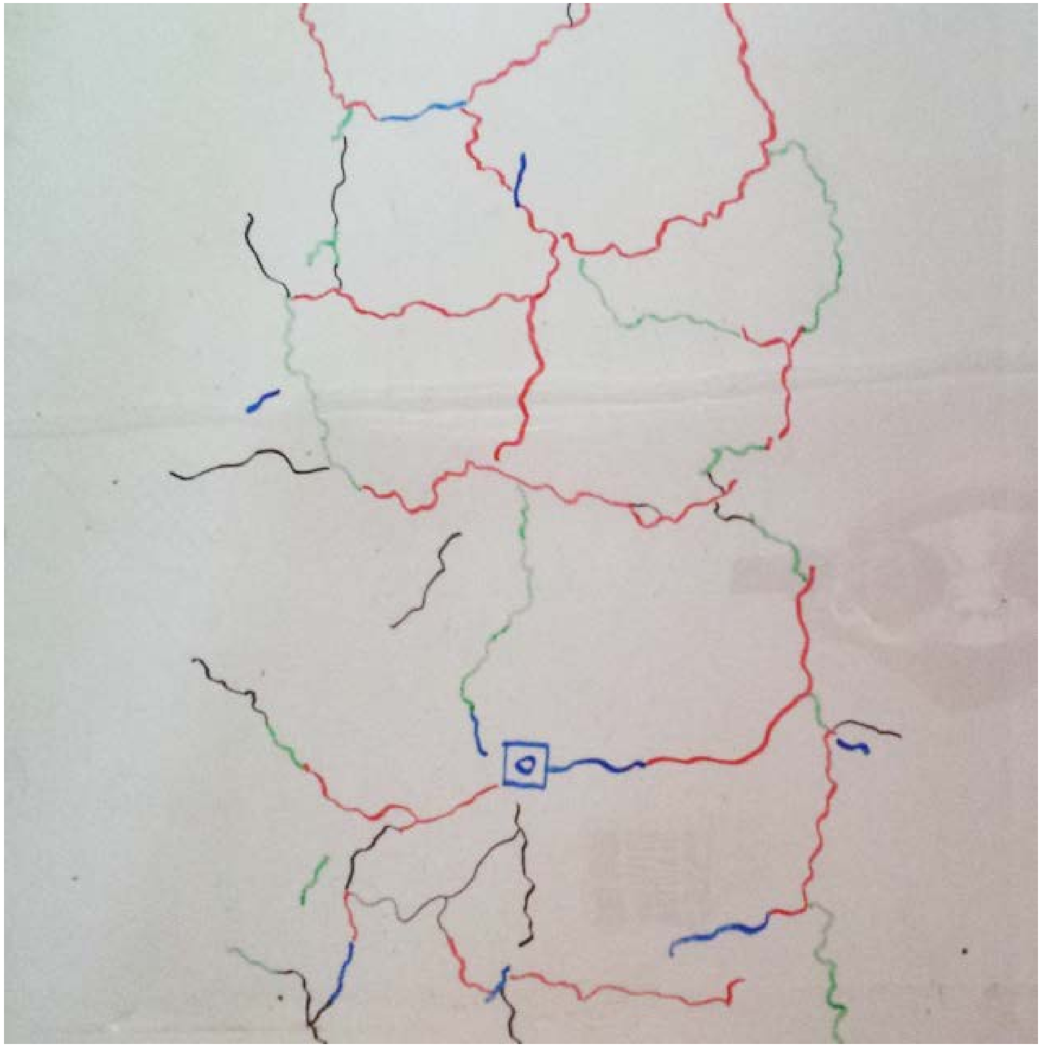
Before Summer 2015 ??

(ALF1) Lane 3 HMA 20% ABR RAS

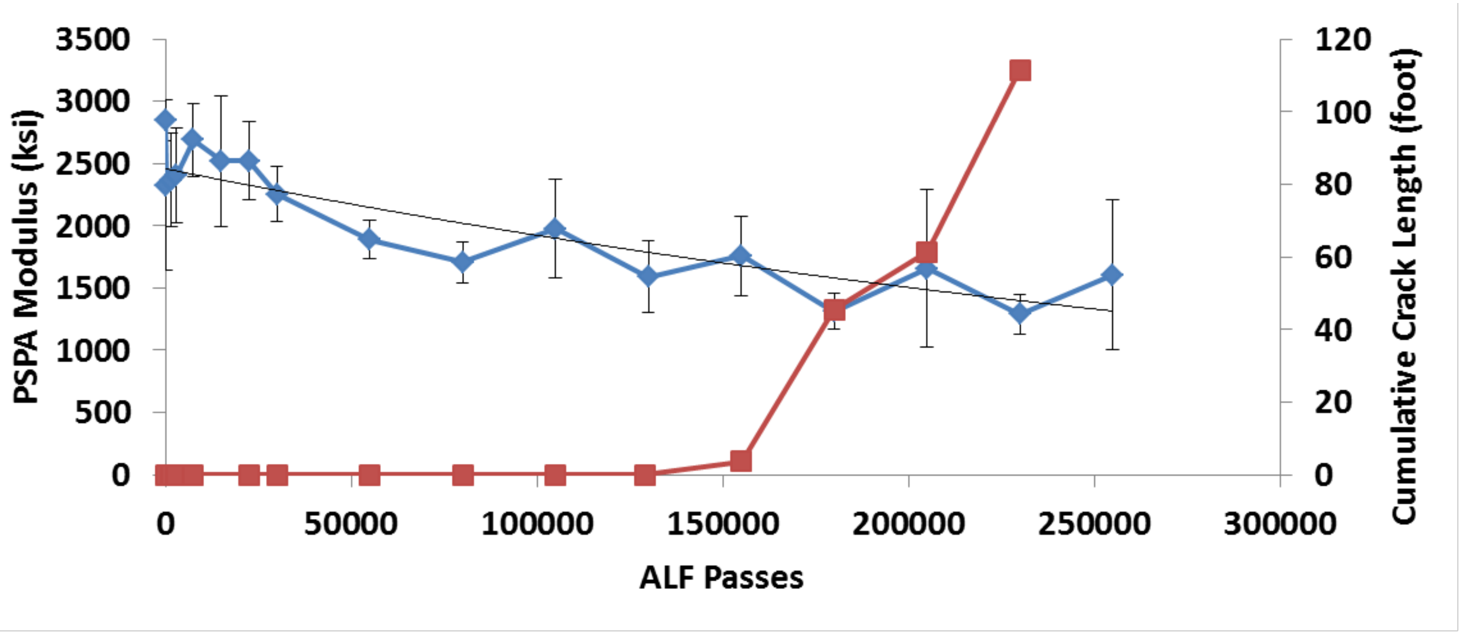
(ALF2) Lane 7 Lane 6 HMA 20% ABR

-move-

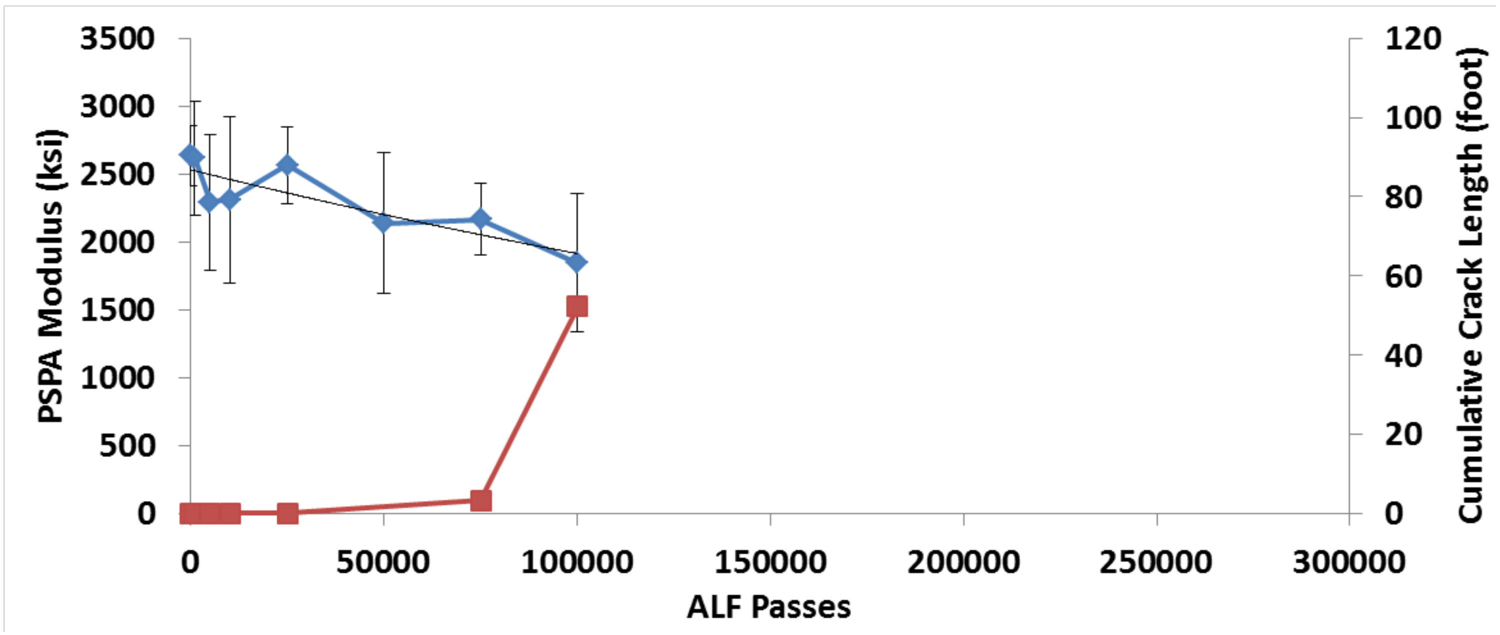
(ALF2) Lane 10 WMA-C 40% ABR 58-28



Lane 9
WMA-Foam
20% ABR
PG64-22



Lane 11
WMA-Chem
40% ABR
PG58-28



TFHRC AMPT Fatigue Experiments

		Unaged	Long Term Oven Aged	Post Construct.	6 Mo.	12 Mo.	18 Mo.	24 Mo.
SGC	Full	✔	✔					
	Small	✔	✔					
Field Cores	Small			✔	✔	…	…	…

Post Construction, As-built |E*| and Fatigue Using Reduced-Scale Specimens

2013 **2014** **2015** 2016

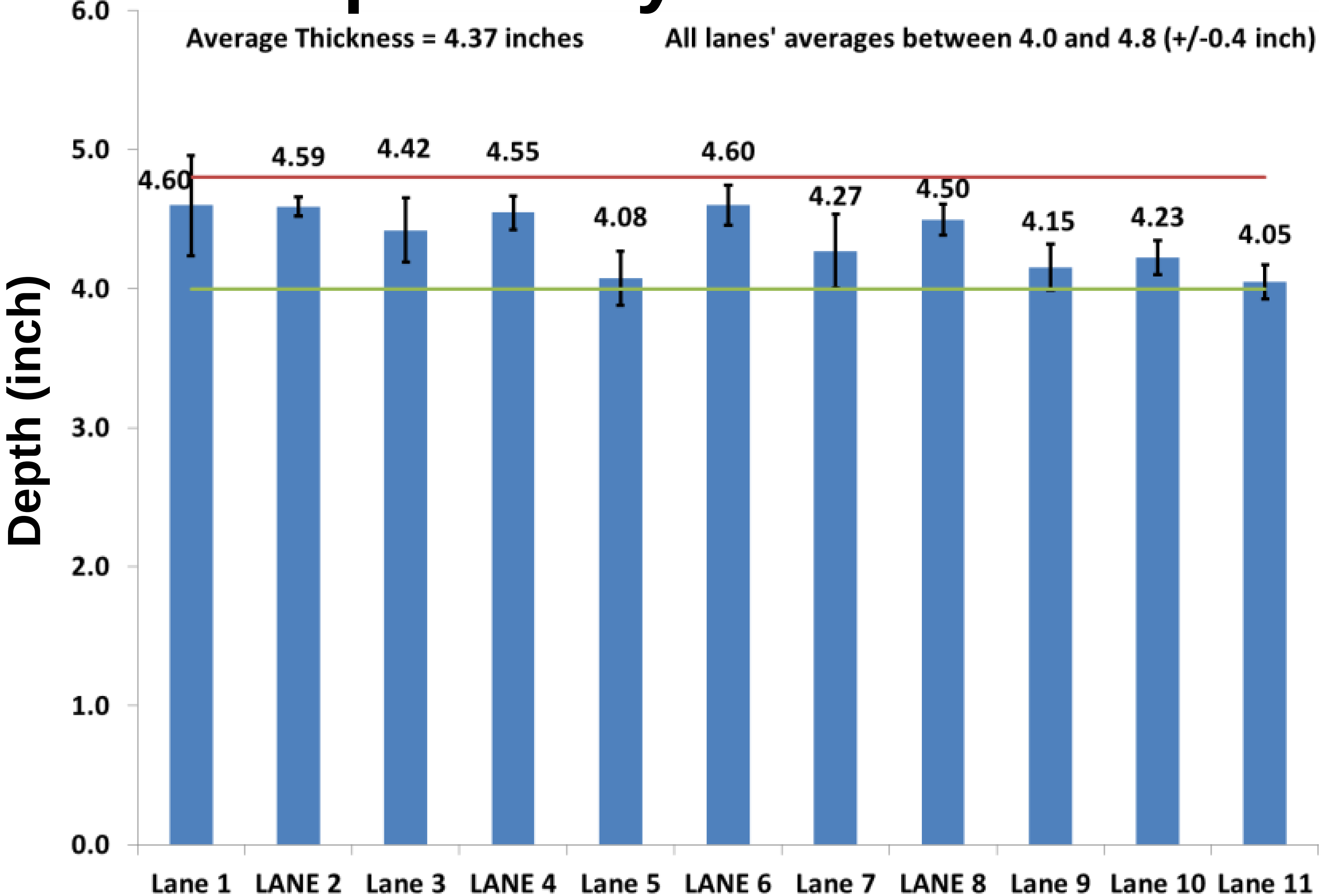
JFMAMJJASOND JFMAMJJASOND JFMAMJJASOND JFMAMJJASOND

t = 0m	t = 6m	t = 12m	t = 18m	t = 24m	t = 30m	t = 36m
Top Bottom	Top	Top Bottom	Top	Top Bottom	Top	Top Bottom

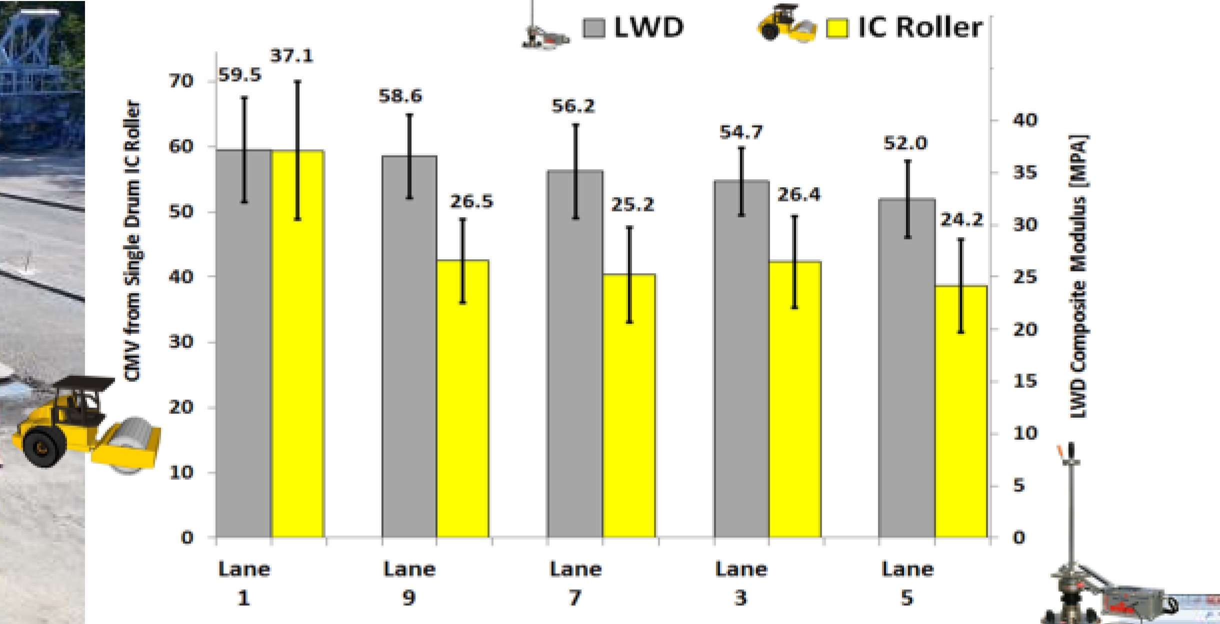
Cores Taken ✓ (t = 0m) ✓ (t = 6m)

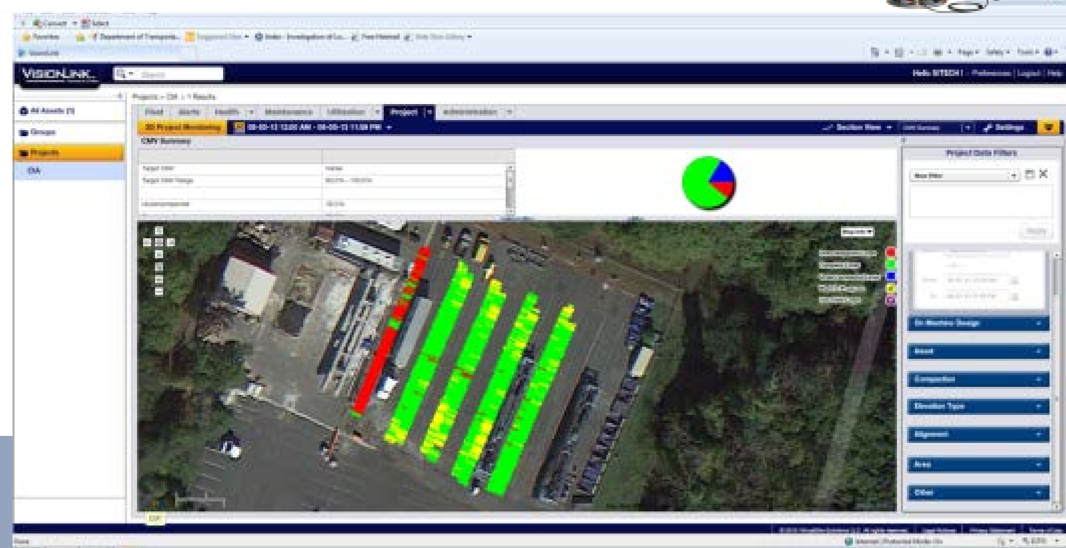
Tests Done ✓ (t = 0m) In Progress (t = 6m)

Asphalt Layer Thickness



Aggregate Base Reconditioning w/ LWD, FWD, PSPA & Caterpillar IC Retrofit





Calculated Bottom-of-AC Tensile Micro Strain

Scenario	Scenario Description	L1	L2	L3	L4	L5	L6	L7	L8	L9	L11
A	Fixed 4.5-inch HMA thickness and fixed base modulus	418	356	299	374	267	335	362	396	380	313
B	Individual Lanes' average HMA thickness and base modulus	346	308	304	337	318	288	371	396	437	401
C	Scenario B w/ thickness and modulus variability: Thick on Stiff	311	288	284	309	301	268	318	358	396	371
D	Scenario B w/ thickness and modulus variability: Thin on Soft	388	340	327	362	348	317	432	429	471	447
E	Fixed 10-inch HMA thickness & fixed base modulus	159	133	110	139	95	122	134	150	145	114

Structural and Sample Prep Effects on Lab Performance Ranking

Lane	Mixture Type		**Overall Average Rank**	Rank from Reference Condition
L2	40% RAP RBR WMA Foam	PG58-28	**2.9**	5
L6	20% RAP RBR HMA	PG64-22	**3.4**	7
L8	40% RAP RBR HMA	PG58-28	**3.7**	1
L3	20% RAS RBR HMA	PG64-22	**4.6**	3
L1	0% RBR HMA	PG64-22	**5.1**	9
L7	20% RAS RBR HMA	PG58-28	**5.1**	2
L4	20% RAP RBR HMA Chemical	PG64-22	**6.3**	8
L9	20% RAP RBR WMA Foam	PG64-22	**6.7**	4
L11	40% RAP RBR HMA	PG58-28	**8.5**	6
L5	40% RAP RBR WMA Chemical	PG64-22	**8.9**	10

Characteristics of Recycled Asphalt Materials

RAP

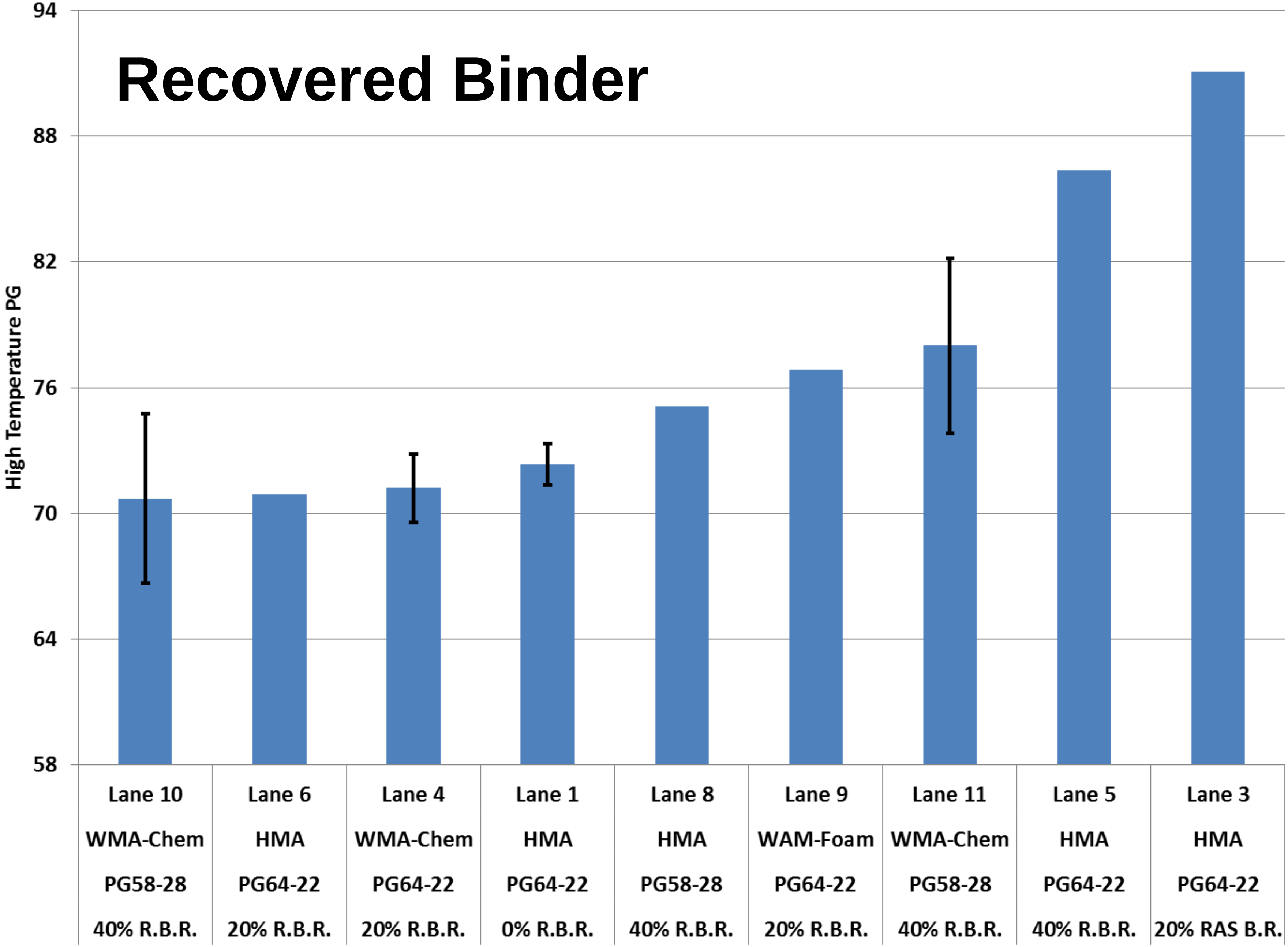
- 13 samples taken as stockpile was built
- 4.7% average AC content by solvent
  - 0.2% std. dev. AC
- TCE Recovered PG
  - PG89.4-21.7
  - ITPG 29.1C

RAS

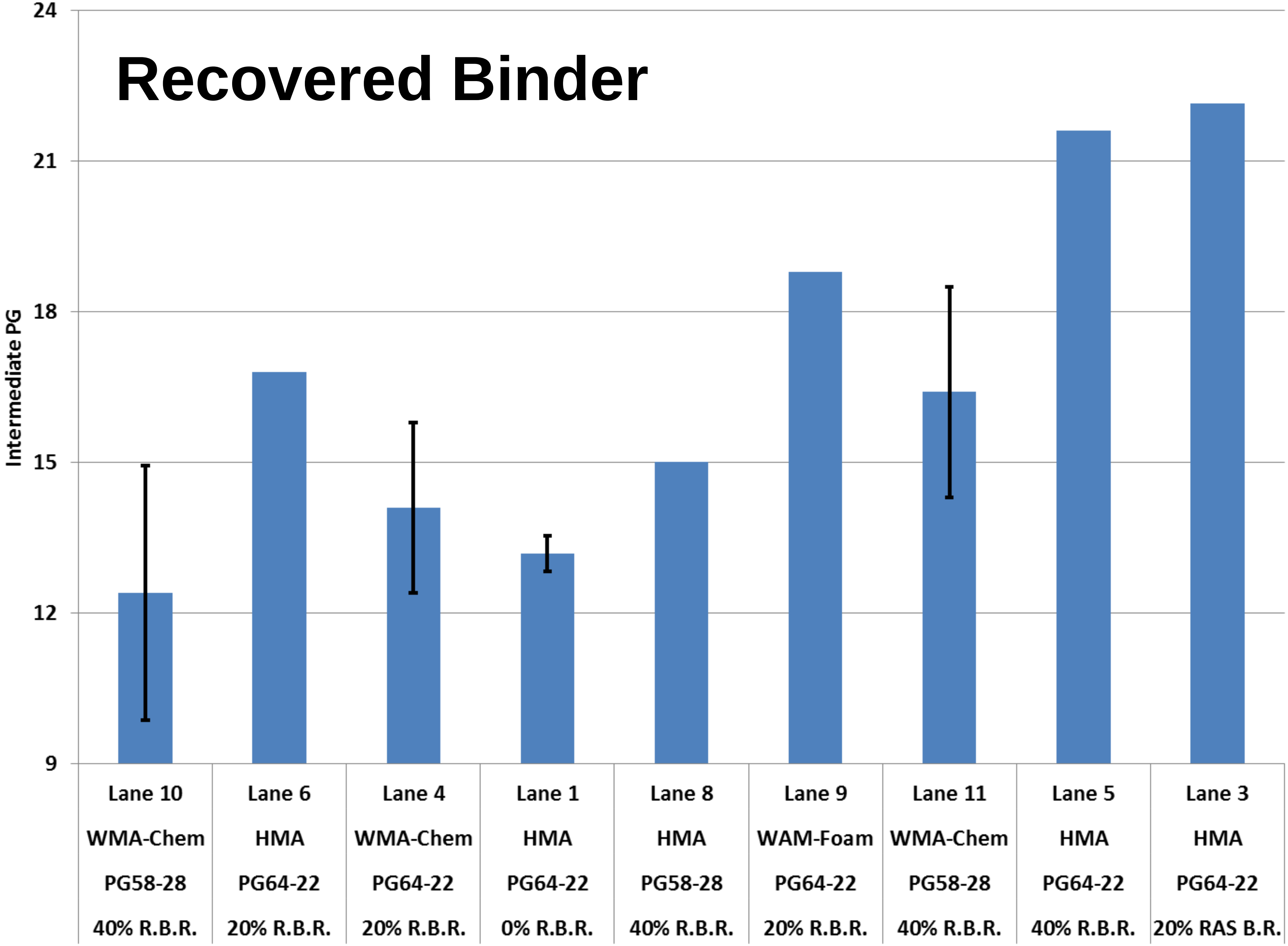
- Tear-Offs
- 99.4% Passing ½" sieve
- 85.2% Passing #4 sieve
- 20.9% AC by solvent
- High Temp >>> PG140

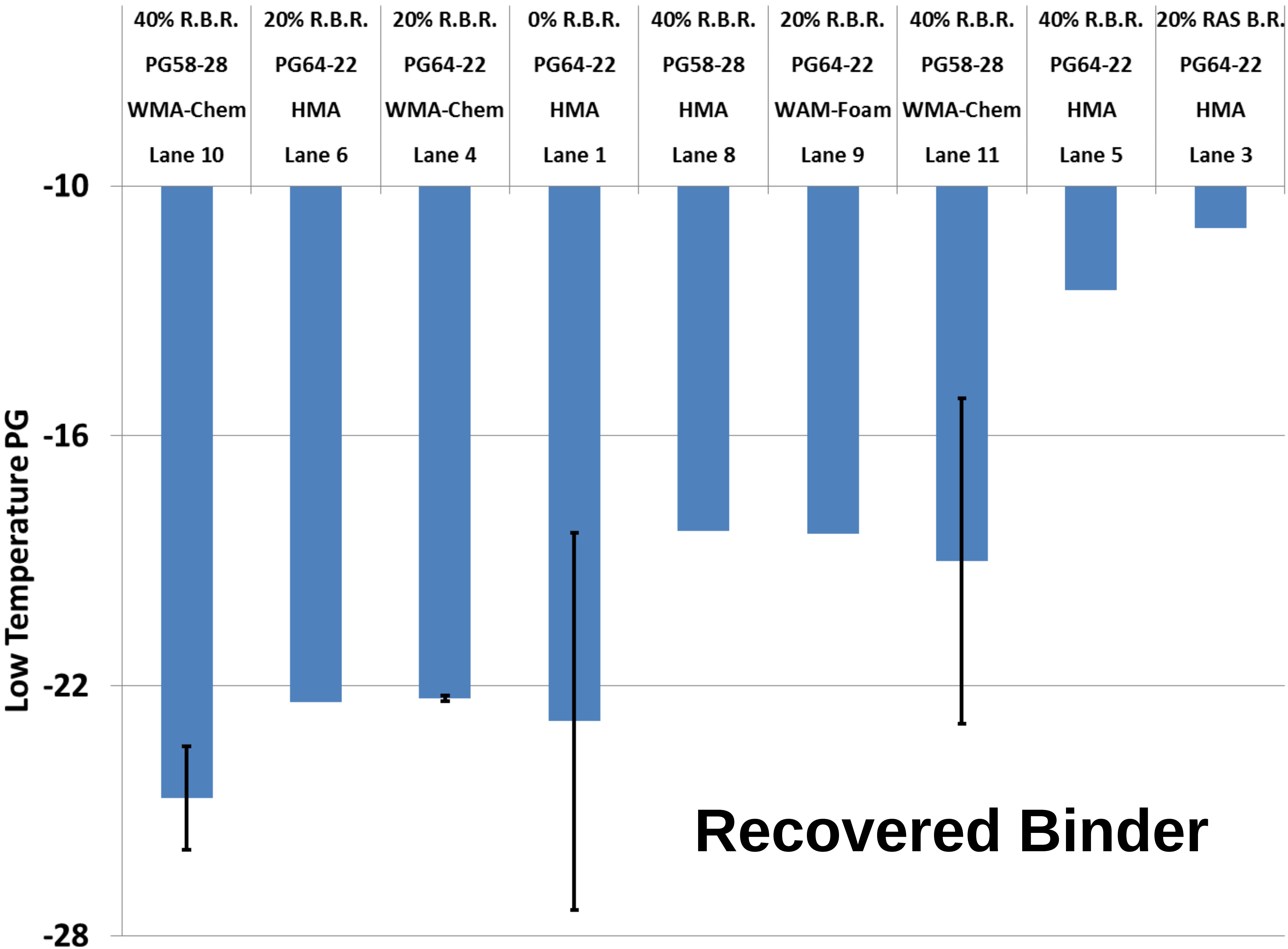
Dedicated RAP and RAS stockpiles for the Project

Recovered Binder



Recovered Binder





40% R.B.R. PG58-28 WMA-Chem Lane 10
20% R.B.R. PG64-22 HMA Lane 6
20% R.B.R. PG64-22 WMA-Chem Lane 4
0% R.B.R. PG64-22 HMA Lane 1
40% R.B.R. PG58-28 HMA Lane 8
20% R.B.R. PG64-22 WAM-Foam Lane 9
40% R.B.R. PG58-28 WMA-Chem Lane 11
40% R.B.R. PG64-22 HMA Lane 5
20% RAS B.R. PG64-22 HMA Lane 3
-10
-16
-22
-28
Low Temperature PG
Recovered Binder

Collaboration with Other Institutions
Develop a Catalog of a Variety of Cracking Tests

- Texas Transp. Inst. — Overlay Tester
- Washington State Univ. — IDT Fracture Energy
- Louisiana State Univ. — Notched SCB
- AAT & FHWA Resource Ctr. — Bending Beam Fatigue
- NCAT / MeadeWestVaco

Cantabro

SCB*

TTI OT*

IDT

Take aways …

1. **Pavements should be between 18~24 months old when full scale ALF testing is complete**
   - **Changes will be tracked based on E* and Fatigue with small scale specimens**
   - **Cracking has been bottom-up ; initiates in the less aged layer**

2. **Terrific volunteer and collaborative effort should provide a robust variety of performance tests**

3. **We cant build real pavements well enough to reflect differences we measure in the lab???**
   - **Better Question: How different do mixes need to look in the lab before they might be different in the field?**

Take aways …

1. Pavements should be between 18~24 months old when full scale ALF testing is complete
   - Changes will be tracked based on E* and Fatigue with small scale specimens
   - Cracking has been bottom-up ; initiates in the less aged layer

2. **Terrific volunteer and collaborative effort should provide a robust variety of performance tests**

3. We cant build real pavements well enough to reflect differences we measure in the lab???
   - Better Question: How different do mixes need to look in the lab before they might be different in the field?

Take aways …

1. Pavements should be between 18~24 months old when full scale ALF testing is complete
   - Changes will be tracked based on E* and Fatigue with small scale specimens
   - Cracking has been bottom-up ; initiates in the less aged layer

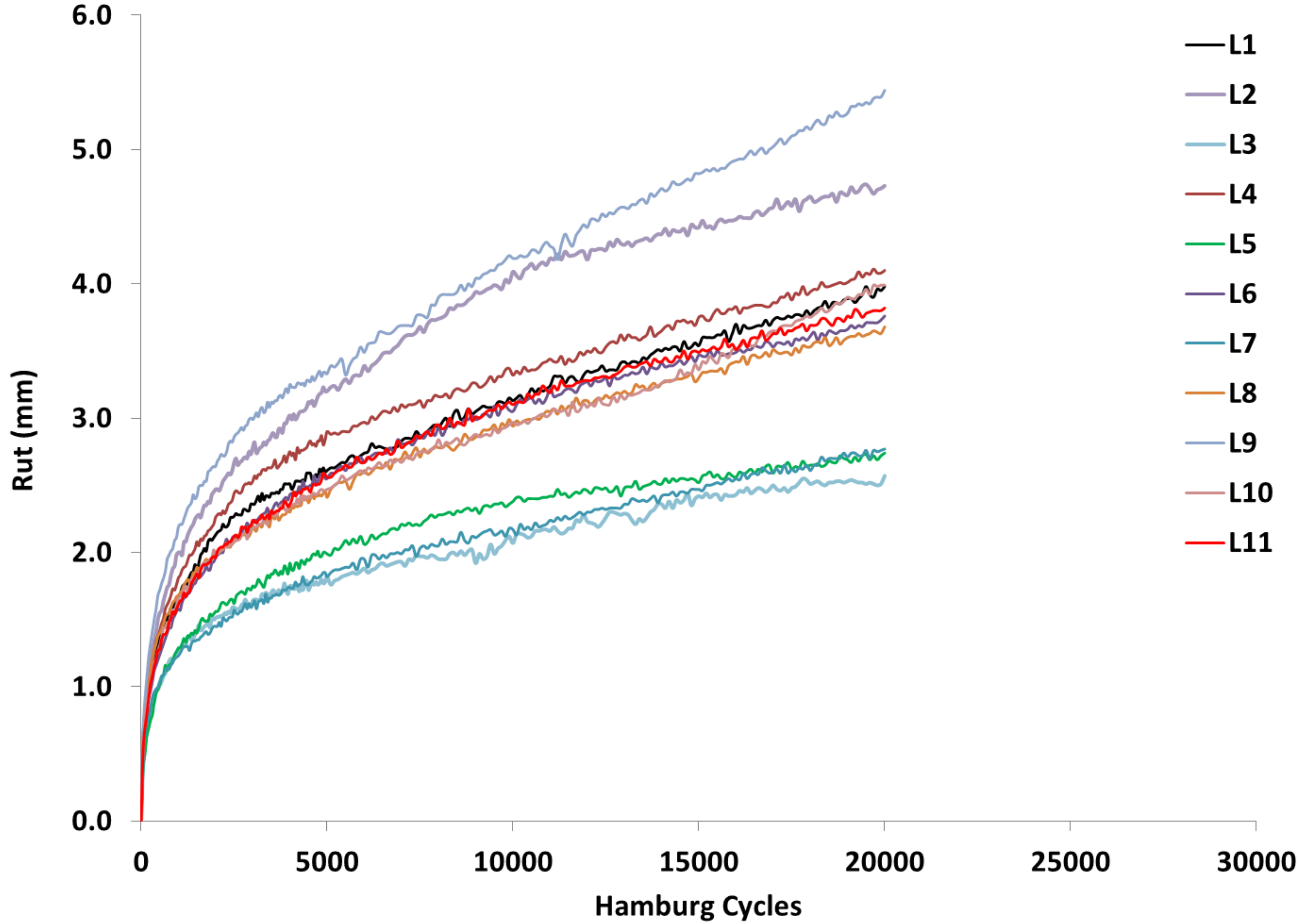
2. Terrific volunteer and collaborative effort should provide a robust variety of performance tests

3. We cant build real pavements well enough to reflect differences we measure in the lab???
   - Better Question: How different do mixes need to look in the lab before they might be different in the field?

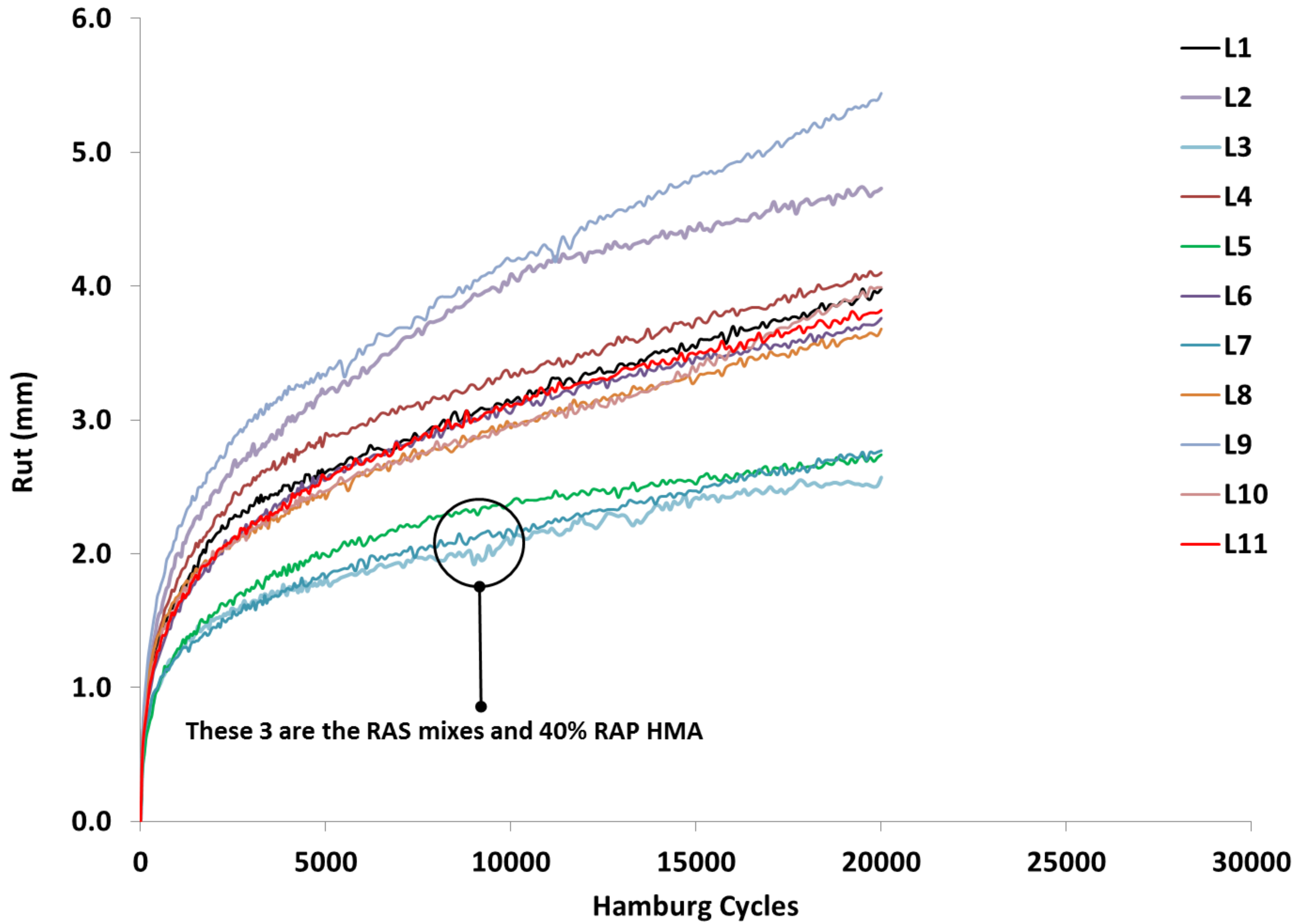
Questions? Comments?

Test	Scenario	L1	L2	L3	L4	L5	L6	L7	L8	L9	L11	τ_k	% sig
Field Core	A	5	8	4	1	9	3	2	7	6	10	0.11	28%
	C	2	5	8	1	6	3	4	7	9	10	-0.11	28%
	B	3	4	6	1	9	2	5	7	8	10	-0.16	40%
	D	3	4	5	1	9	2	7	6	8	10	-0.16	40%
Unaged Full-size	***A**	**9**	**5**	**3**	**8**	**10**	**7**	**2**	**1**	**4**	**6**	***1**	***100%**
	C	5	3	6	7	10	4	1	2	8	9	0.47	92%
	B	5	3	6	7	10	4	2	1	8	9	0.47	92%
	D	6	2	5	7	10	3	4	1	8	9	0.47	92%
Unaged Small-size	A	9	2	1	8	10	4	6	5	7	3	0.51	96%
	C	4	1	2	7	10	3	5	6	9	8	0.16	40%
	B	4	1	3	6	10	2	7	5	9	8	011	28%
	D	4	1	3	5	10	2	7	6	9	8	0.11	28%
Aged Full-size	A	9	2	5	10	8	6	7	3	1	4	0.38	84%
	C	3	1	7	8	9	2	5	4	6	10	0.20	52%
	B	3	1	5	8	9	2	7	4	5	10	0.11	14%
	D	3	1	7	6	9	2	8	4	5	10	0.02	0%
Aged Small-size	A	9	7	2	10	4	8	6	1	3	5	0.51	96%
	C	6	2	5	8	9	3	4	1	7	10	0.47	92%
	B	5	2	4	9	8	3	6	1	7	10	0.33	78%
	D	5	2	4	8	9	3	7	1	6	10	0.33	78%

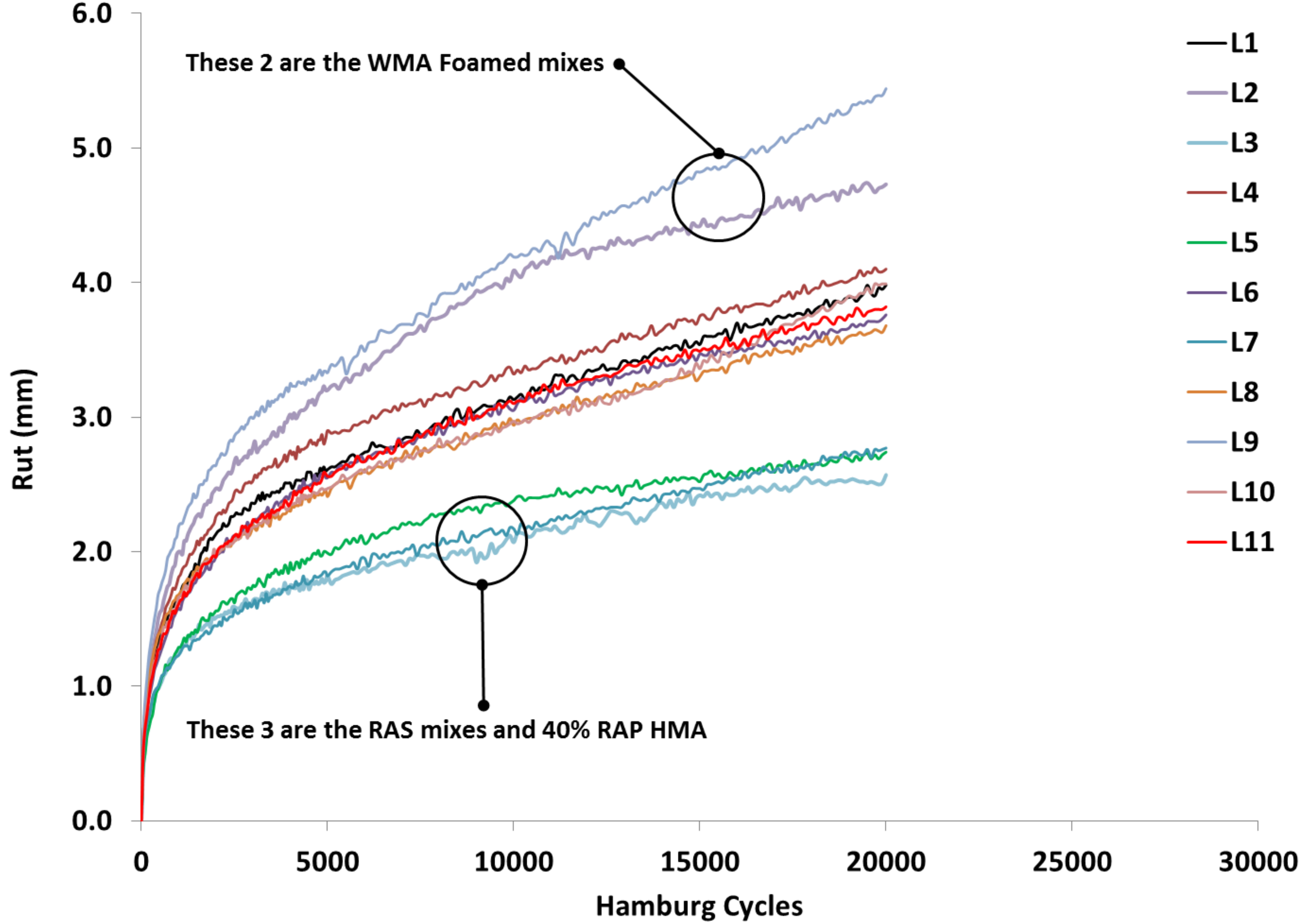
Hamburg Wheel Tracking



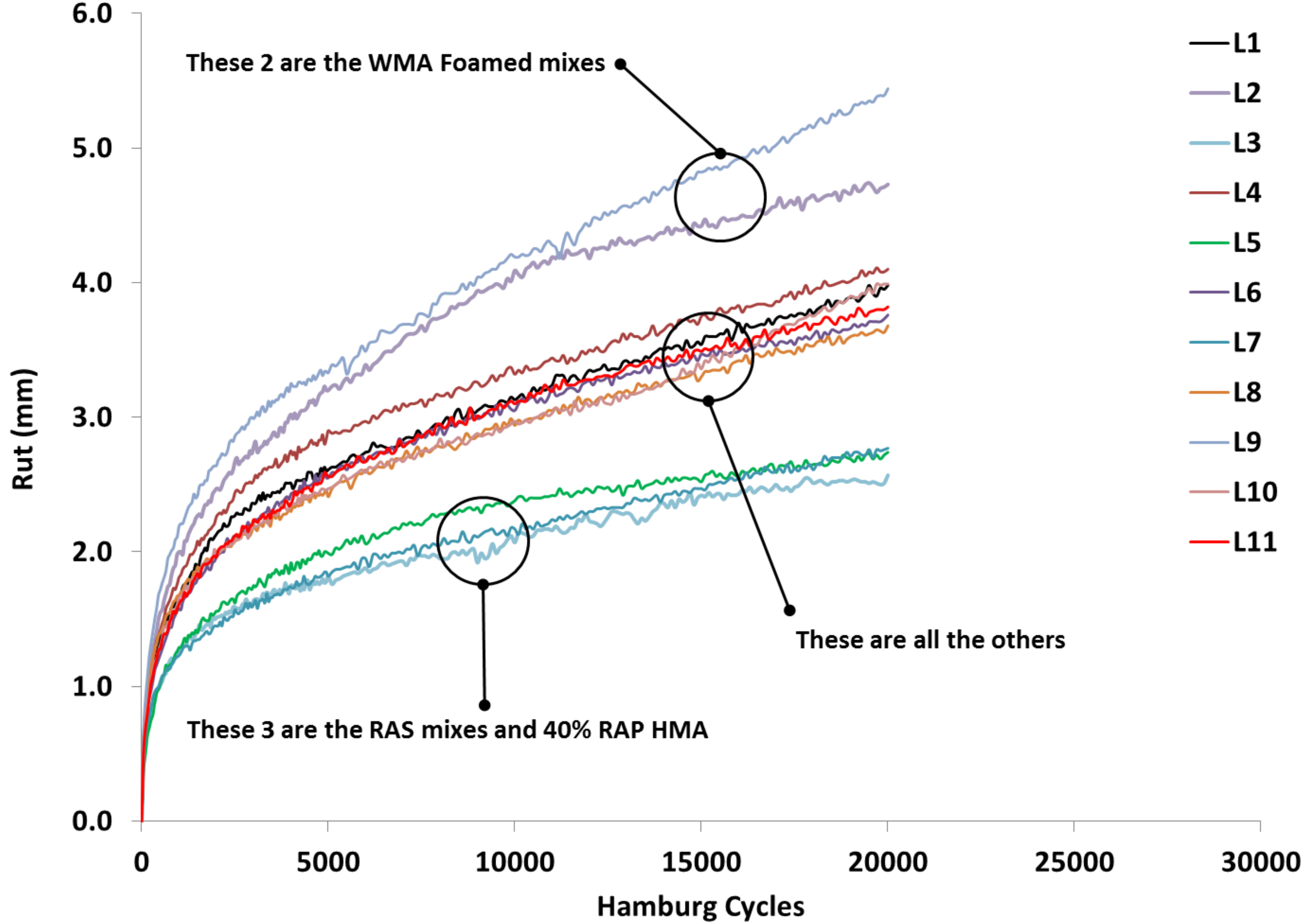
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Rut (mm)
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11



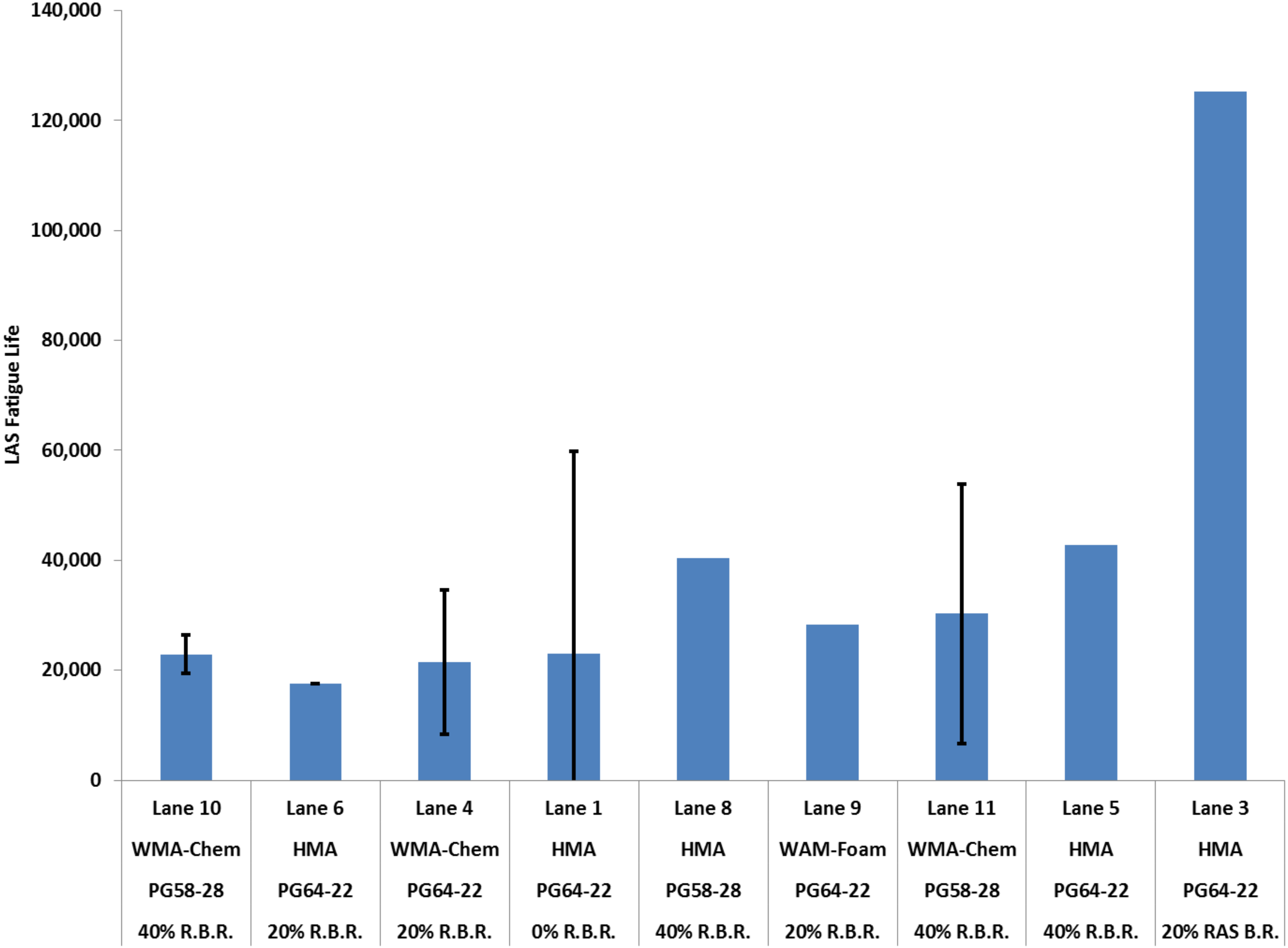
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Rut (mm)
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11
These 3 are the RAS mixes and 40% RAP HMA



6.0
5.0
4.0
3.0
2.0
1.0
0.0
Rut (mm)
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles
These 2 are the WMA Foamed mixes
These 3 are the RAS mixes and 40% RAP HMA
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11



6.0
5.0
4.0
3.0
2.0
1.0
0.0
Rut (mm)
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles
These 2 are the WMA Foamed mixes
These are all the others
These 3 are the RAS mixes and 40% RAP HMA
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11



140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
LAS Fatigue Life
Lane 10 WMA-Chem PG58-28 40% R.B.R.
Lane 6 HMA PG64-22 20% R.B.R.
Lane 4 WMA-Chem PG64-22 20% R.B.R.
Lane 1 HMA PG64-22 0% R.B.R.
Lane 8 HMA PG58-28 40% R.B.R.
Lane 9 WAM-Foam PG64-22 20% R.B.R.
Lane 11 WMA-Chem PG58-28 40% R.B.R.
Lane 5 HMA PG64-22 40% R.B.R.
Lane 3 HMA PG64-22 20% RAS B.R.

Single Drum Plant
Counter Flow - 500 t.p.h.

Go / No-Go Test Strips

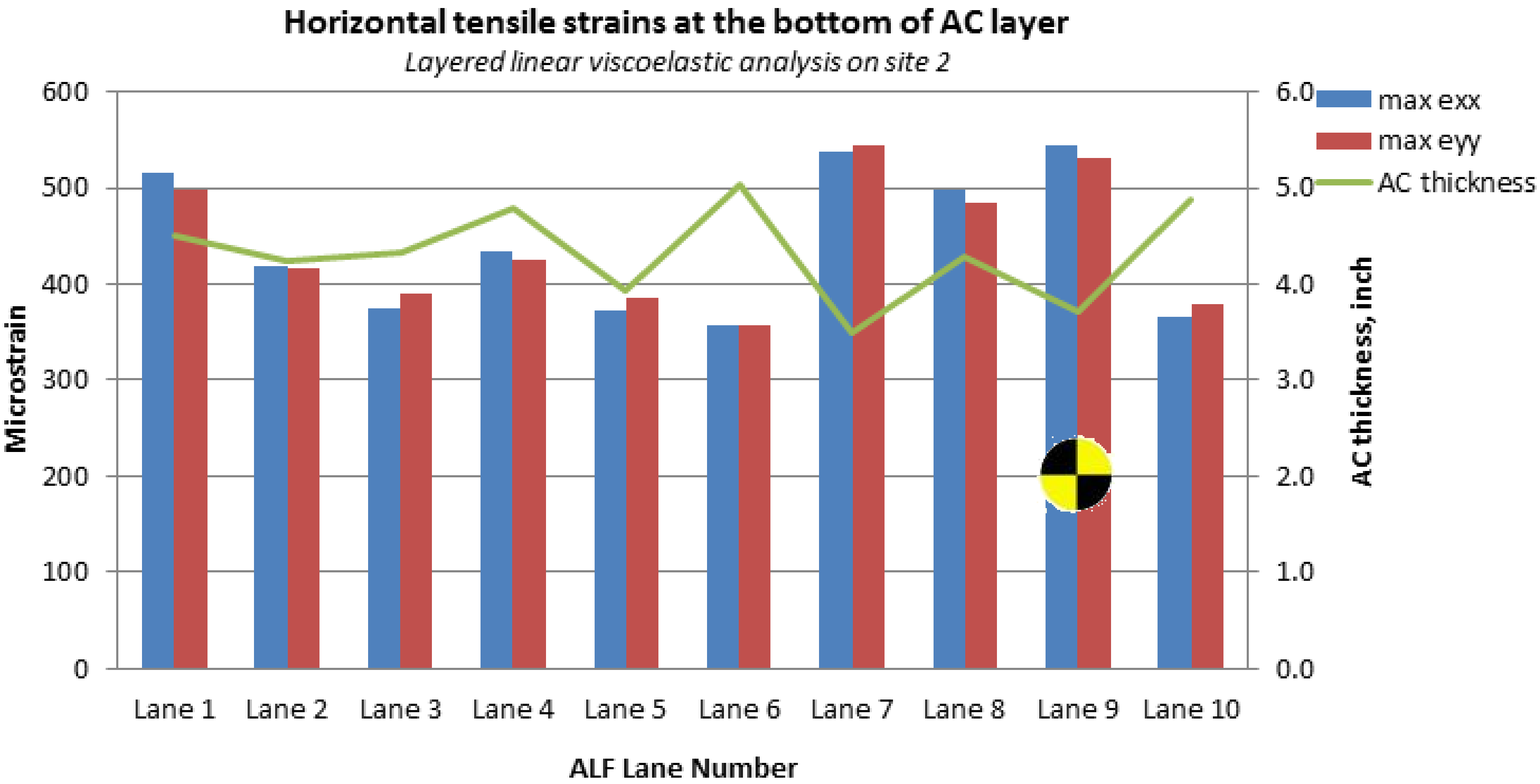
- **Produce mix (+ sufficient plant waste) in the A.M.**
- **Store in the silo**
- **Place 2-inch lift test strip in Parking Lot**
- **~3 Hours for Accept / Reject Test**

Go / No-Go Test Strips

- **<u>If Accepted</u> – place mix in the ALF lanes during the afternoon with stored silo mix**
- **Repeat same sampling and quality tests**

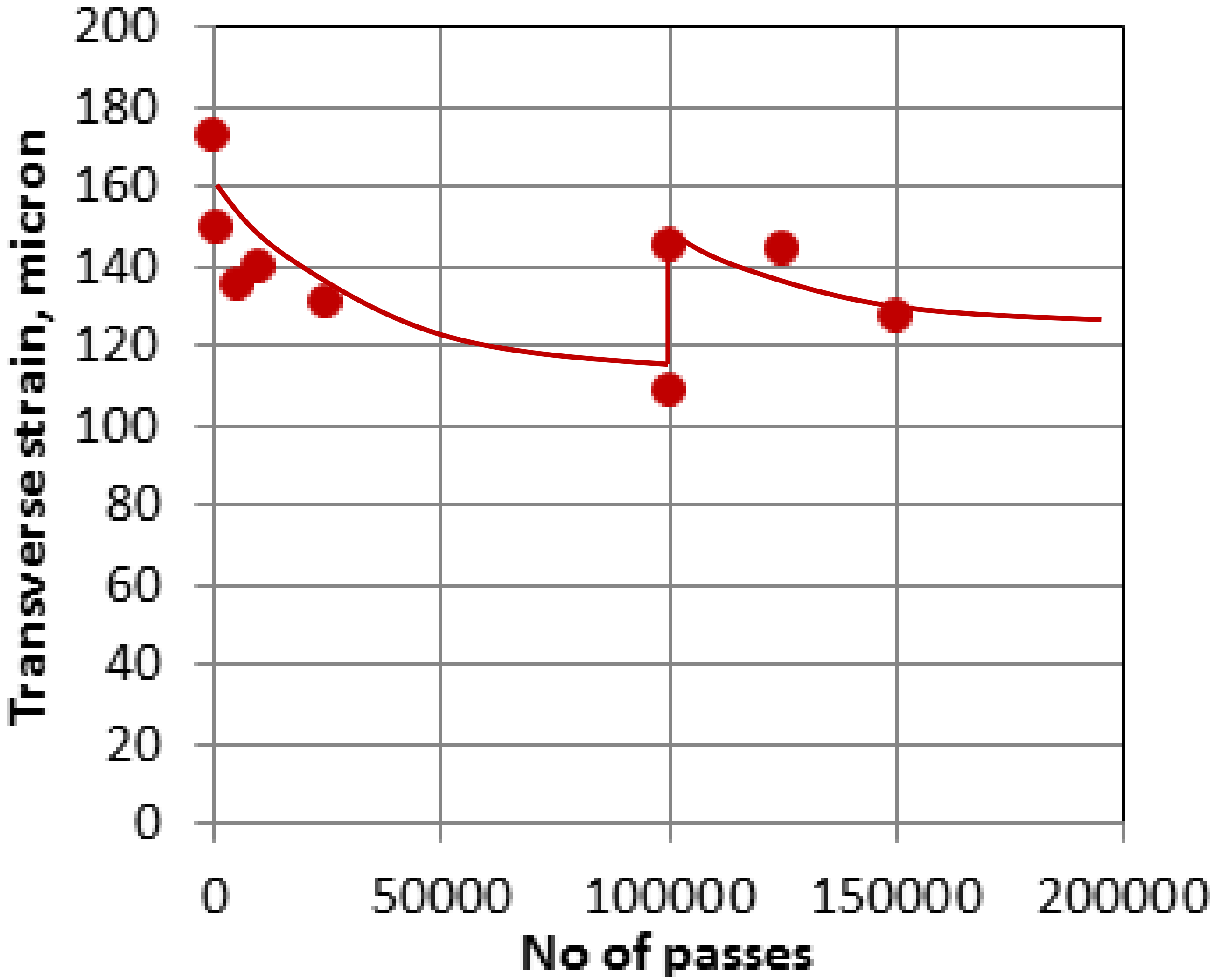
- **<u>If Rejected</u> - Try another day**
- **Adjust plant and laydown**

Structural Analysis

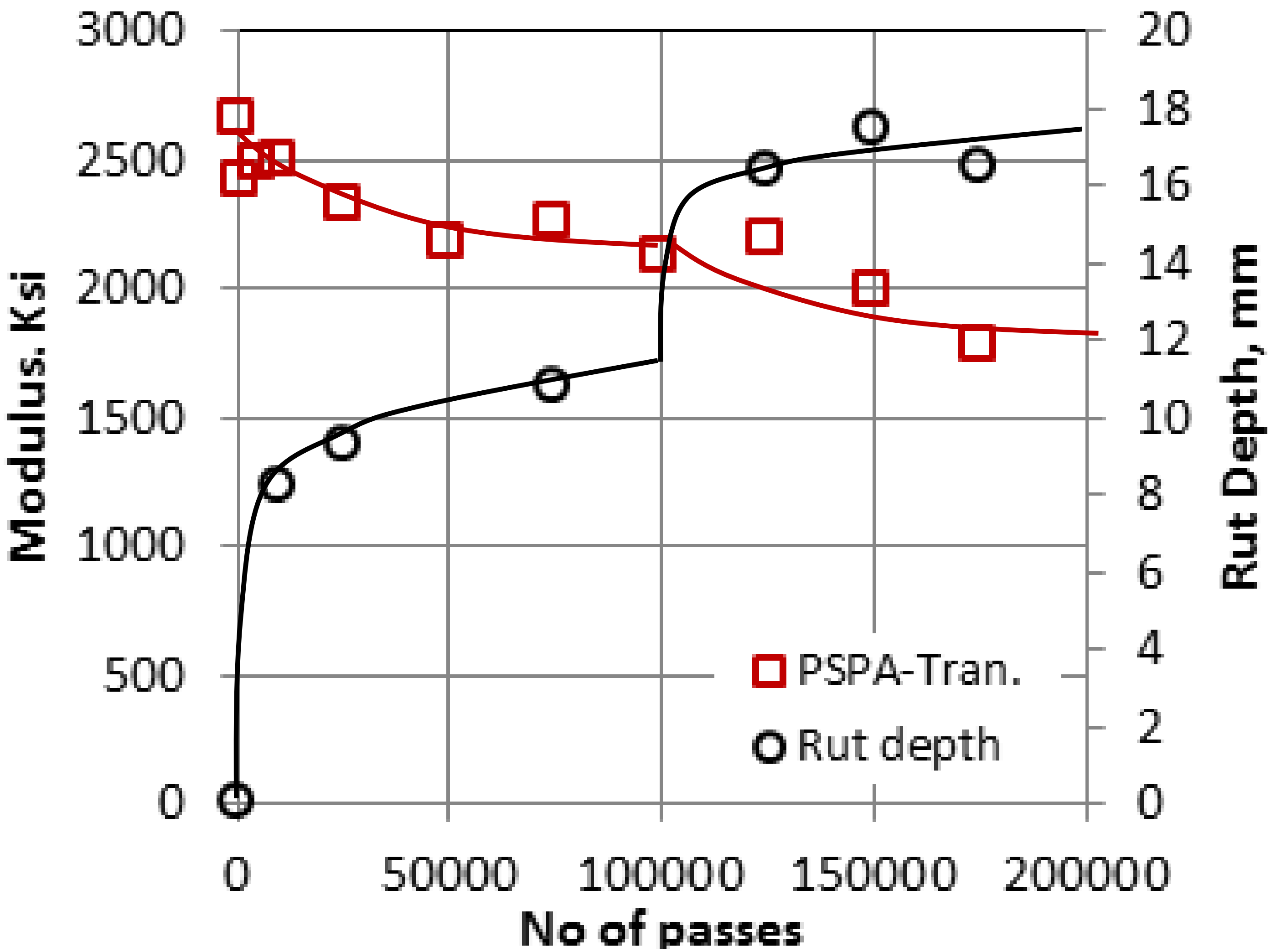


Thus far the trends in strains tend to follow the trends in modulus

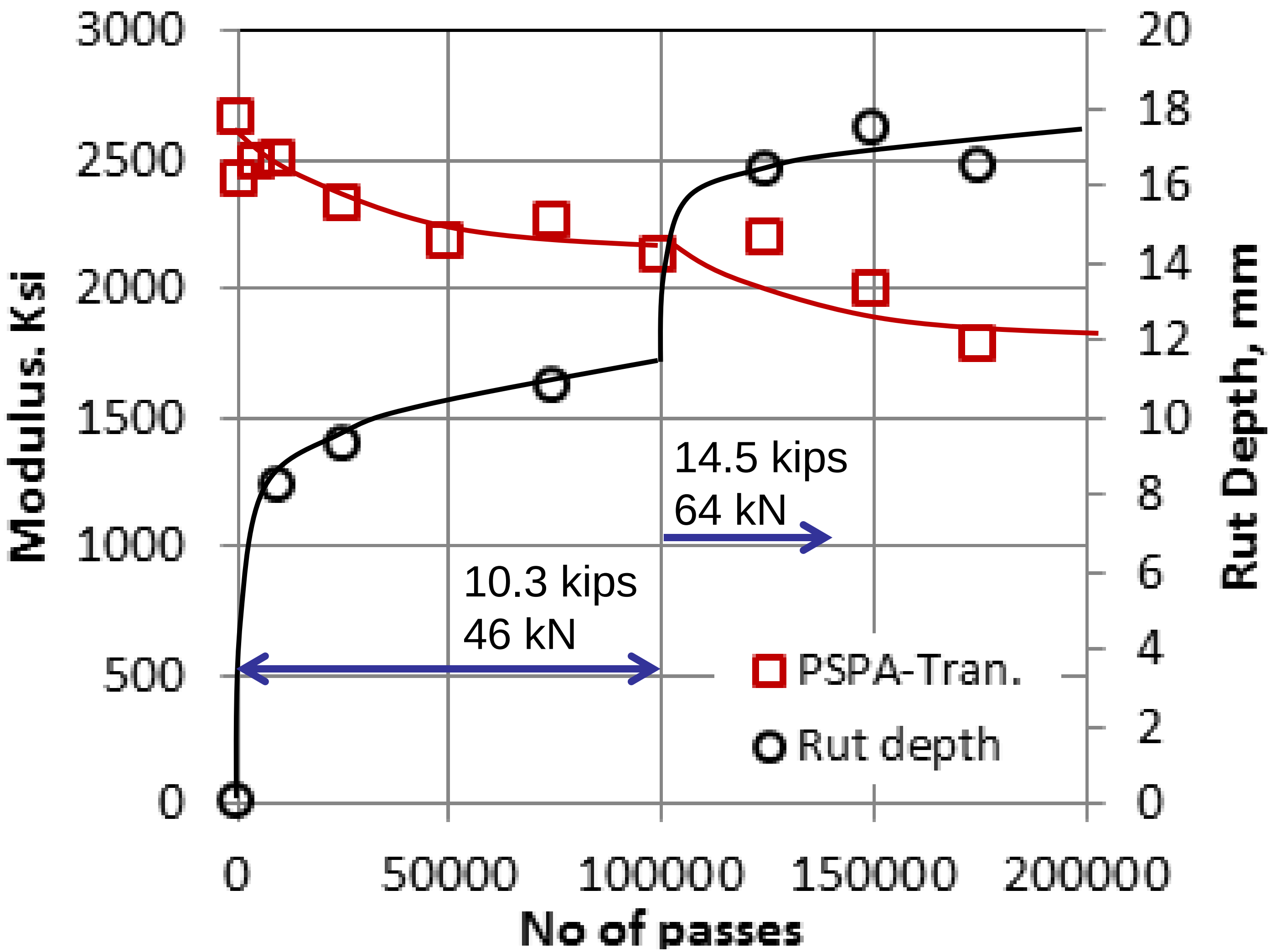
Responses and Performance in ALF Shakedown



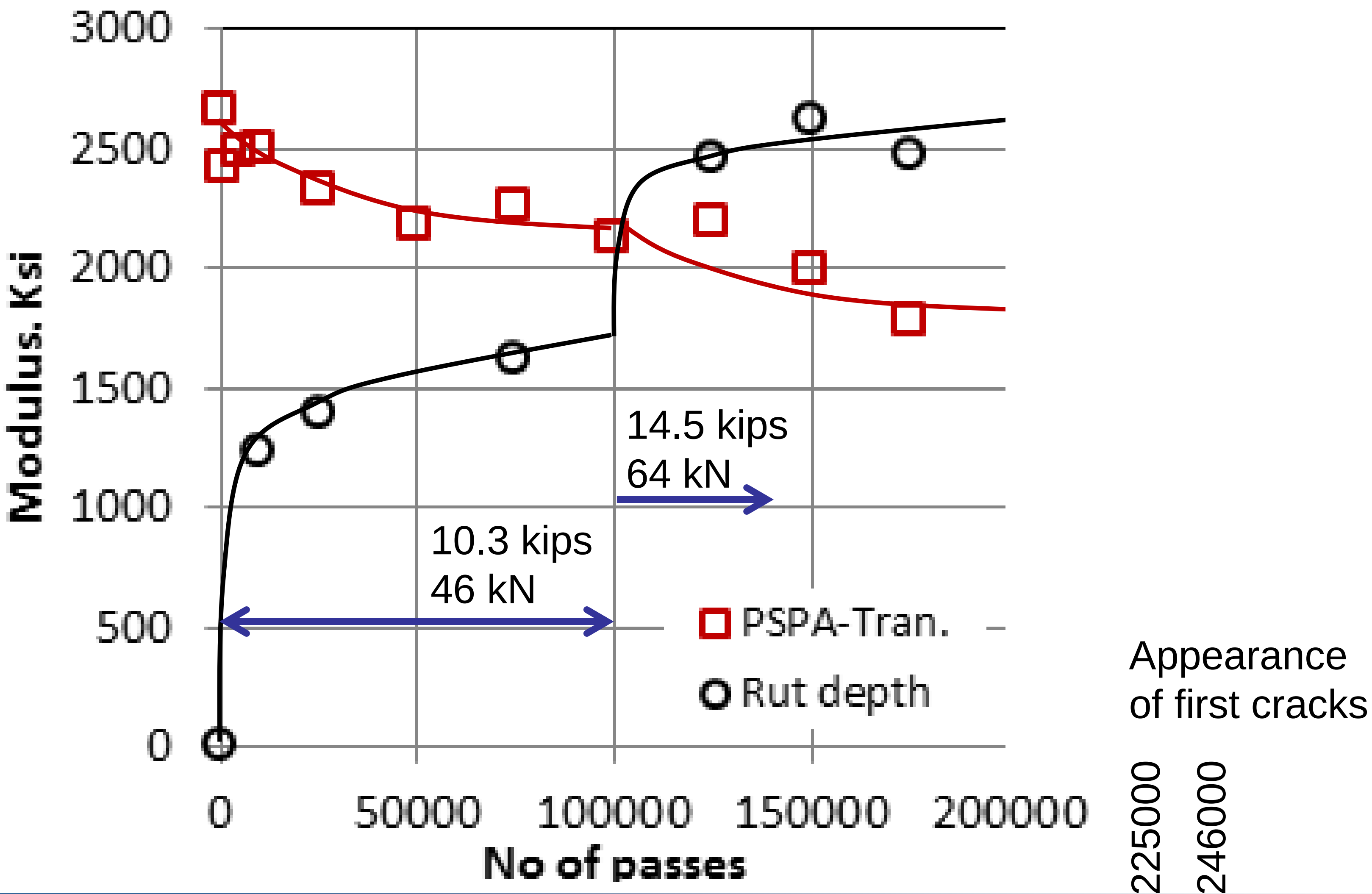
Responses and Performance in ALF Shakedown

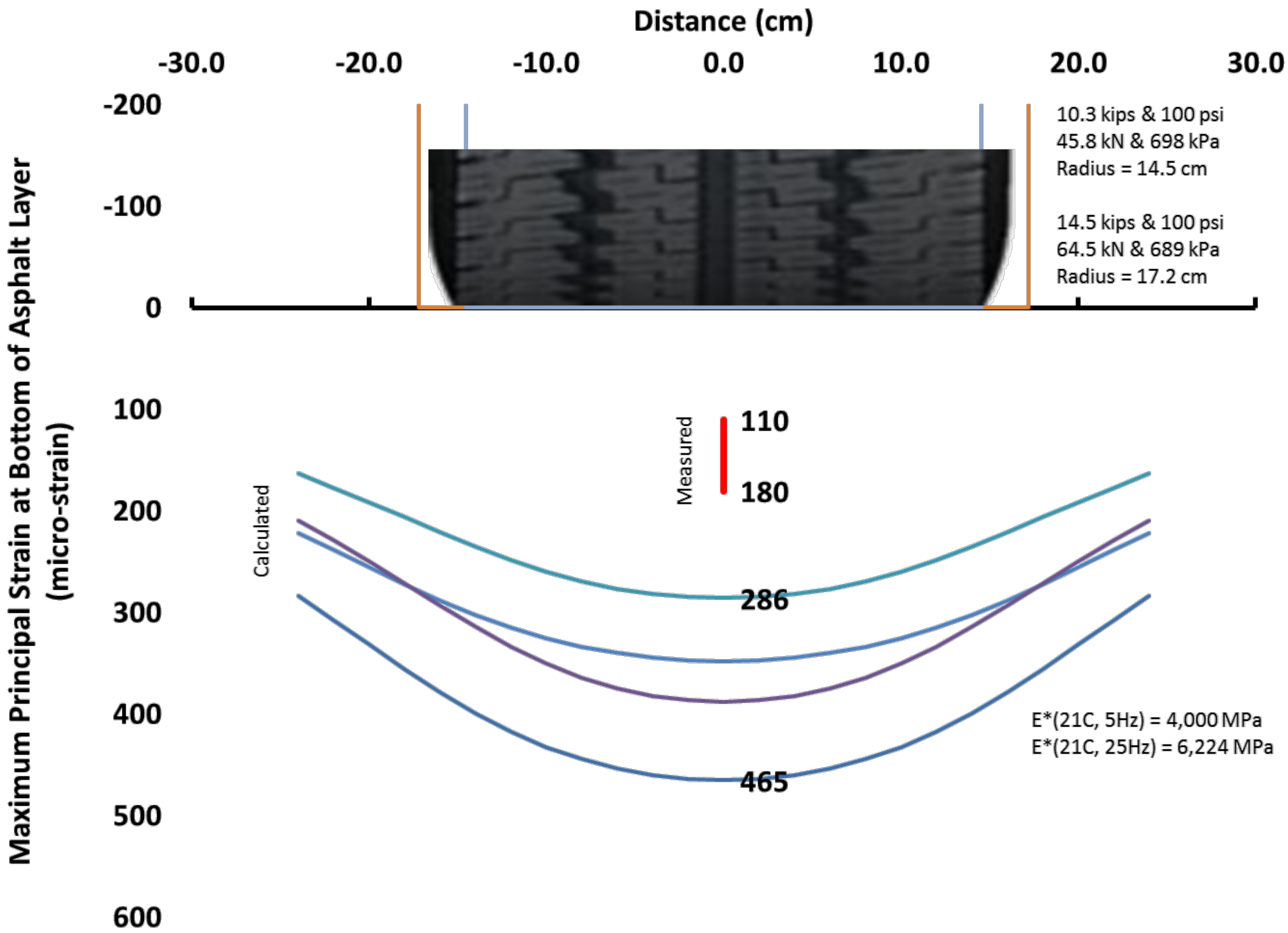


Responses and Performance in ALF Shakedown



Responses and Performance in ALF Shakedown

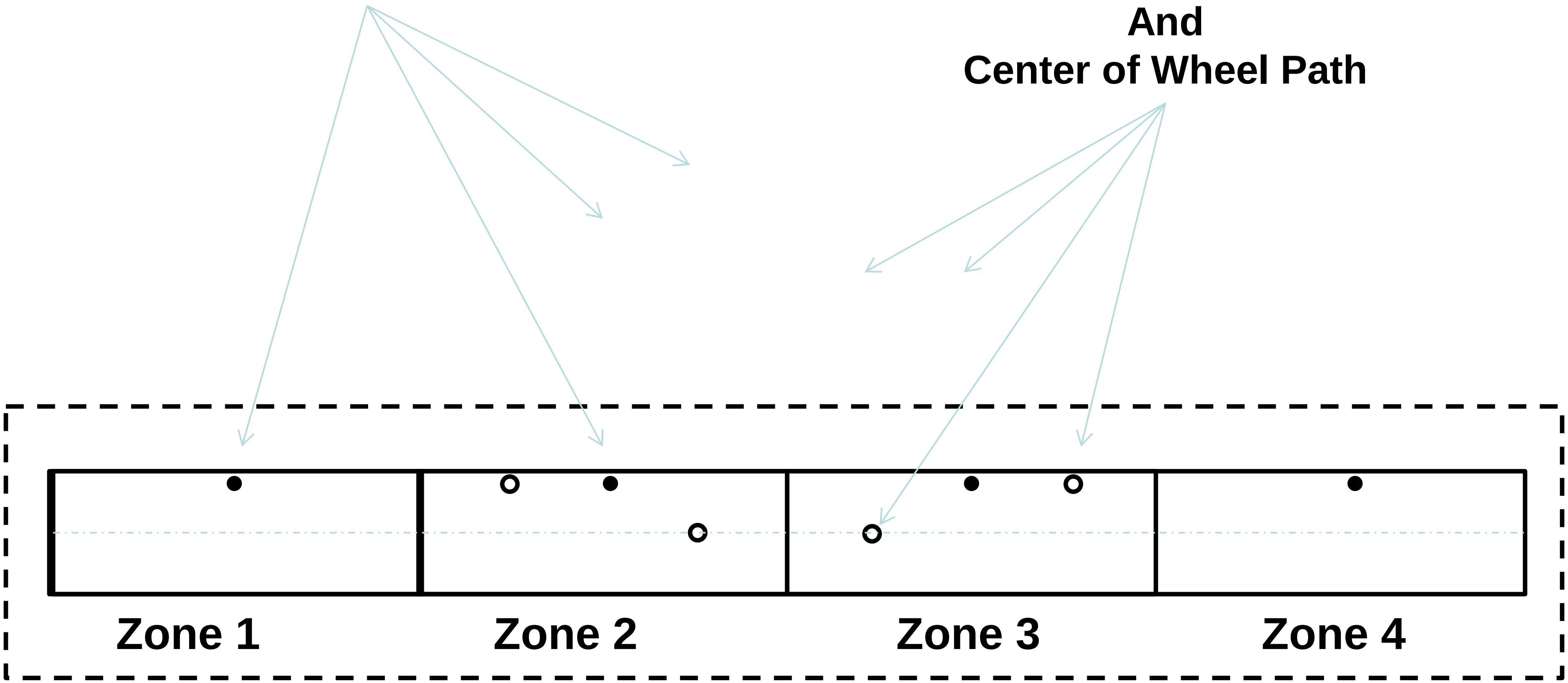


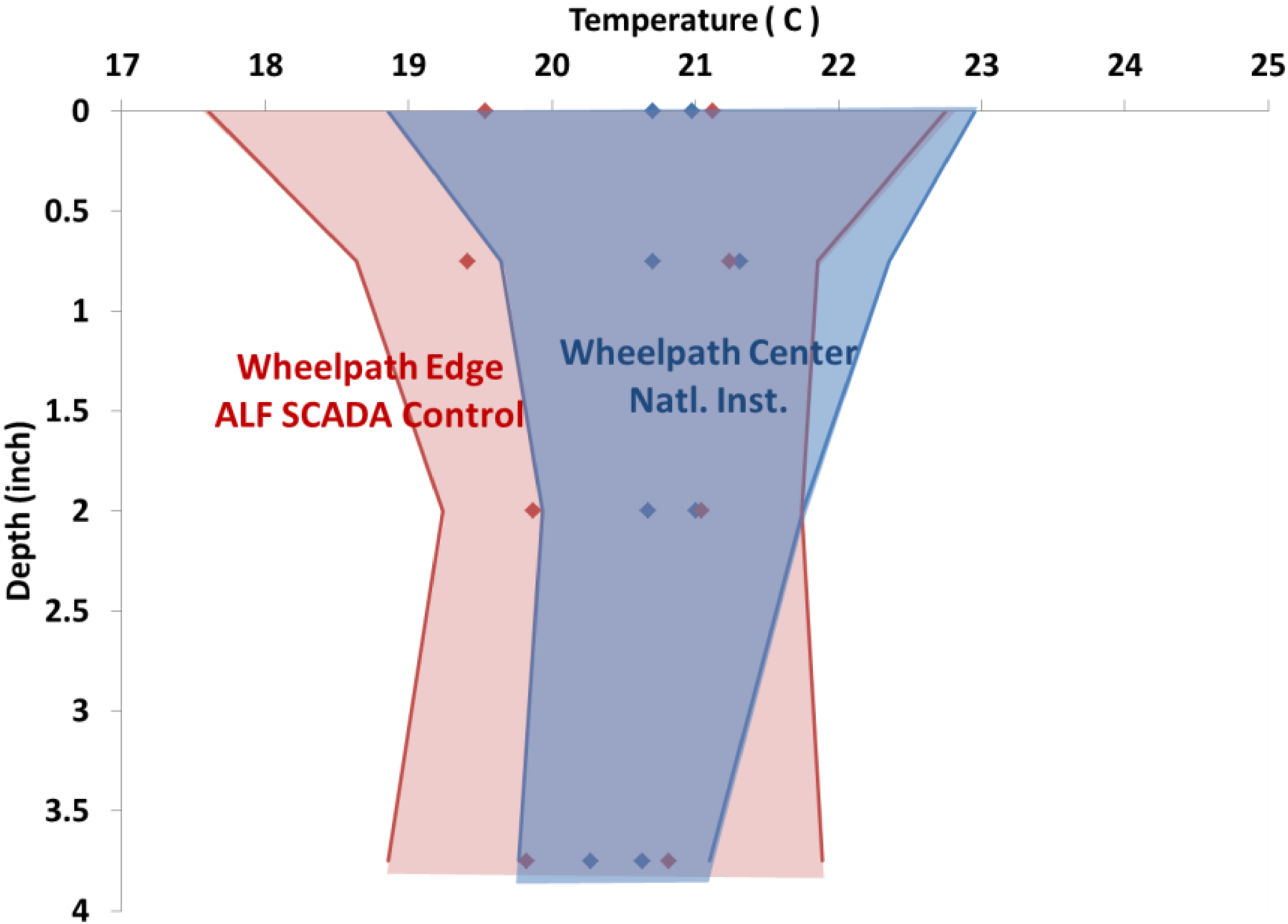


Distance (cm)
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
Maximum Principal Strain at Bottom of Asphalt Layer (micro-strain)
-200
-100
0
100
200
300
400
500
600
10.3 kips & 100 psi
45.8 kN & 698 kPa
Radius = 14.5 cm
14.5 kips & 100 psi
64.5 kN & 689 kPa
Radius = 17.2 cm
Measured
110
180
Calculated
286
465
E*(21C, 5Hz) = 4,000 MPa
E*(21C, 25Hz) = 6,224 MPa

Independent Control Thermocouples
Embedded @ 0.75-inch
4 Zones

Passive Measurement Thermocouples
Embedded @ 0, 0.75, 2, 3.75-inch
Edge of Wheel Path
And
Center of Wheel Path




Temperature (C)
17
18
19
20
21
22
23
24
25
0
0.5
1
1.5
2
2.5
3
3.5
4
Depth (inch)
Wheelpath Edge
ALF SCADA Control
Wheelpath Center
Natl. Inst.

	20% ABR Shingle Hot Mix 64-22		
	Back Of Truck	Behind Paver	Diff
Air Voids	4.61	2.39	2.22
VMA	15.95	13.79	2.16
VFA	71.07	82.73	-11.66
AC	4.96	5.08	-0.12
Gmm*	2.741	2.739	0.002
75 µm (#200)	5.7	7.0	-1.29

How much do engineering properties vary depending on density?

Witczack |E*| Predictive Model

$$\log_{10}E^{*} = -0.349 + 0.754\left(|G_b^{*}|^{-0.0052}\right) \times \left(6.65 - 0.032\rho_{200} + 0.0027\rho_{200}^{2} + 0.011\rho_{4} - 0.0001\rho_{4}^{2} + 0.006\rho_{38} - 0.00014\rho_{38}^{2} - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_a + V_{beff}}\right)\right) + \frac{2.56 + 0.03V_a + 0.71\left(\frac{V_{beff}}{V_a + V_{beff}}\right) + 0.012\rho_{38} - 0.0001\rho_{38}^{2} - 0.01\rho_{34}}{1 + e^{(-0.7814 - 0.5785\log|G_b^{*}| + 0.8834\log\delta_b)}}$$

Hirsch |E*| Predictive Model

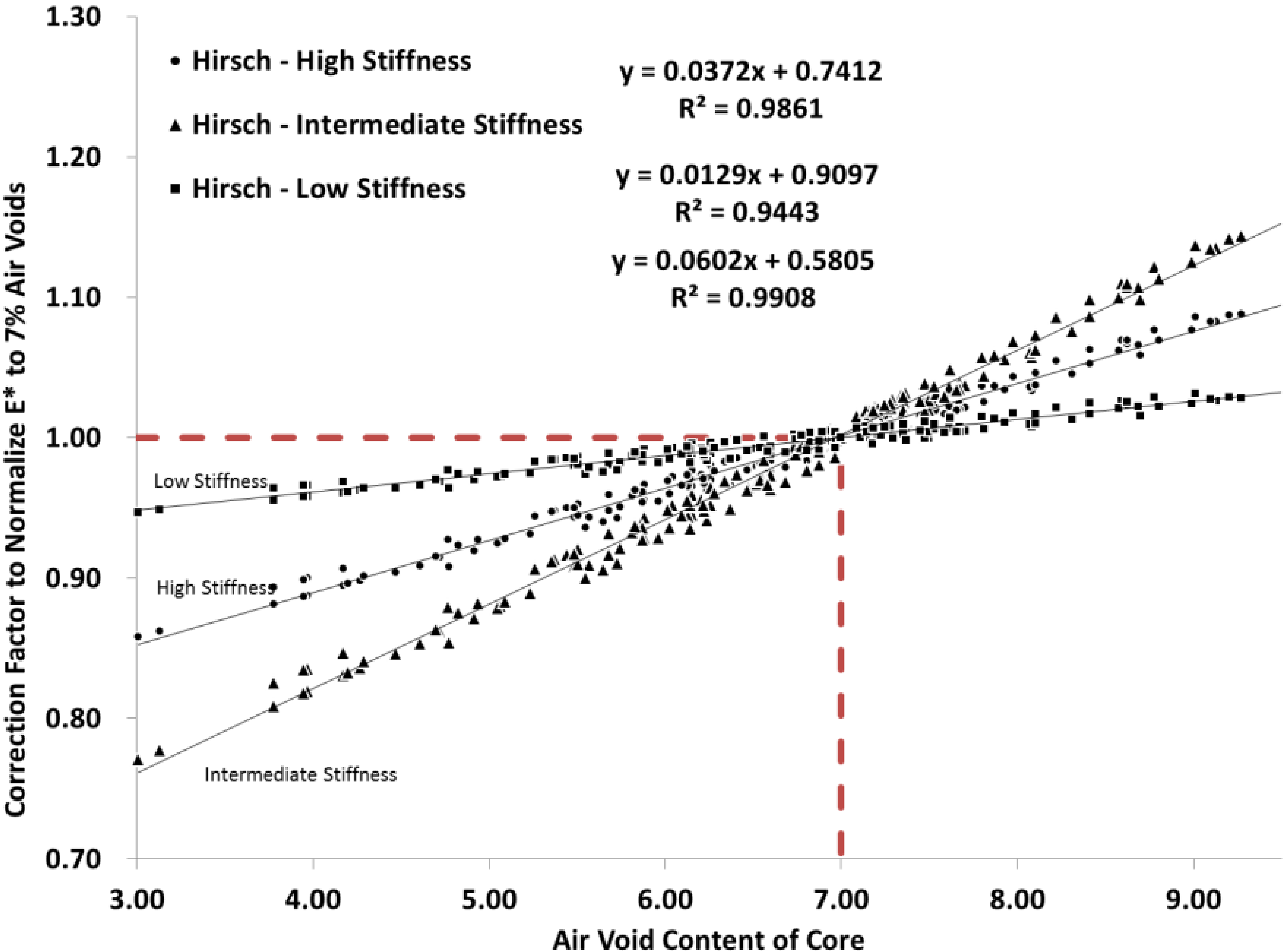
$$|E^{*}|_{mix} = Pc \times \left[4200000 \times \left(1 - \frac{VMA}{100}\right) + 3 \times |G^{*}|_{binder}\left(\frac{VFA \times VMA}{10000}\right)\right] + (1 - Pc) \times \left[\frac{1 - \frac{VMA}{100}}{4200000} + \frac{VMA}{3 \times VFA \times |G^{*}|_{binder}}\right]^{-1}$$

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

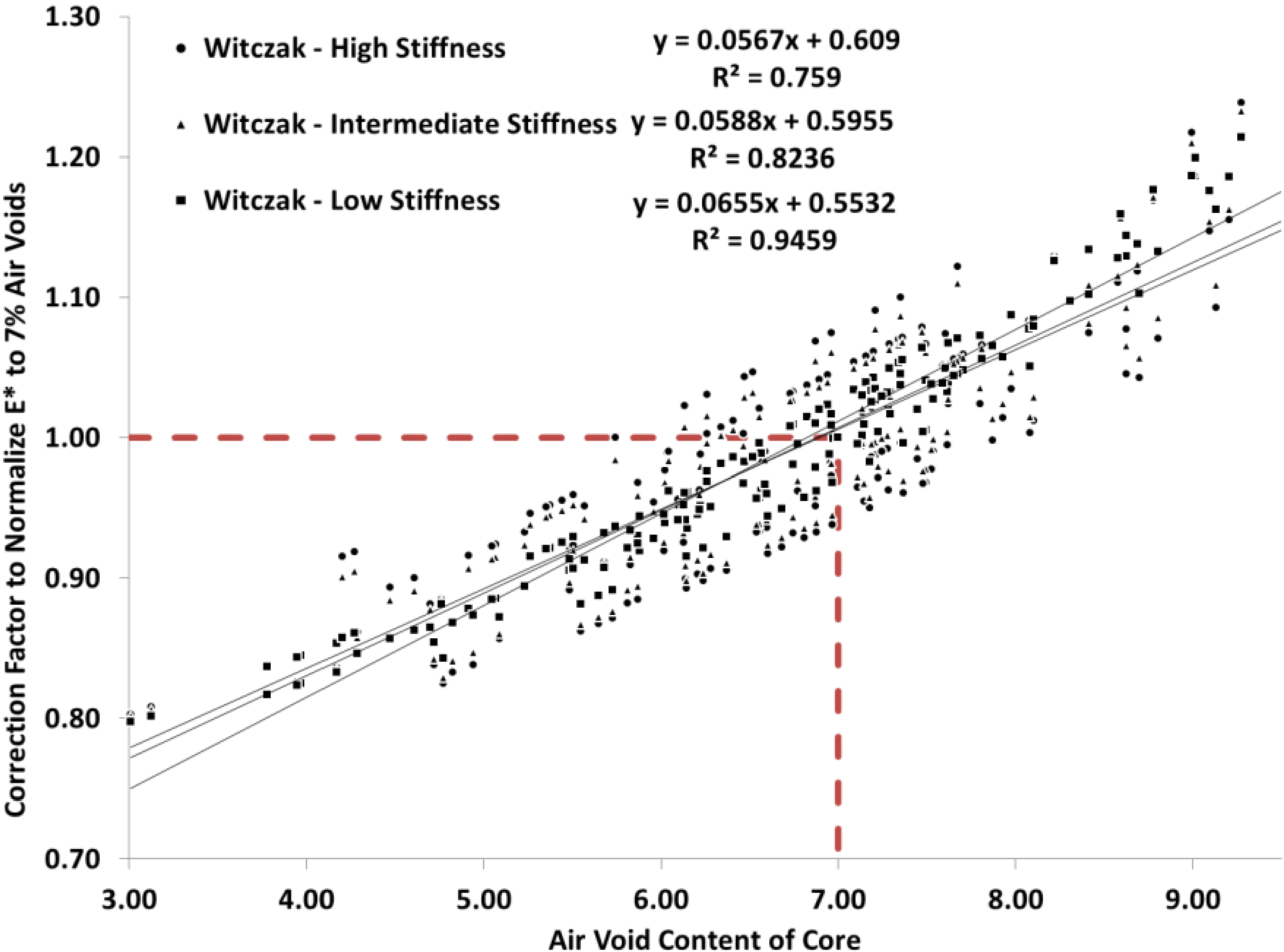
How much do engineering properties vary depending on density?

- **|E*| Normalization Approach:**

$$\frac{Predicted\ |E*|\ @\ Target\ 7\%\ Air\ Voids}{Predicted\ |E*|\ @\ in-place\ Volumetrics}$$

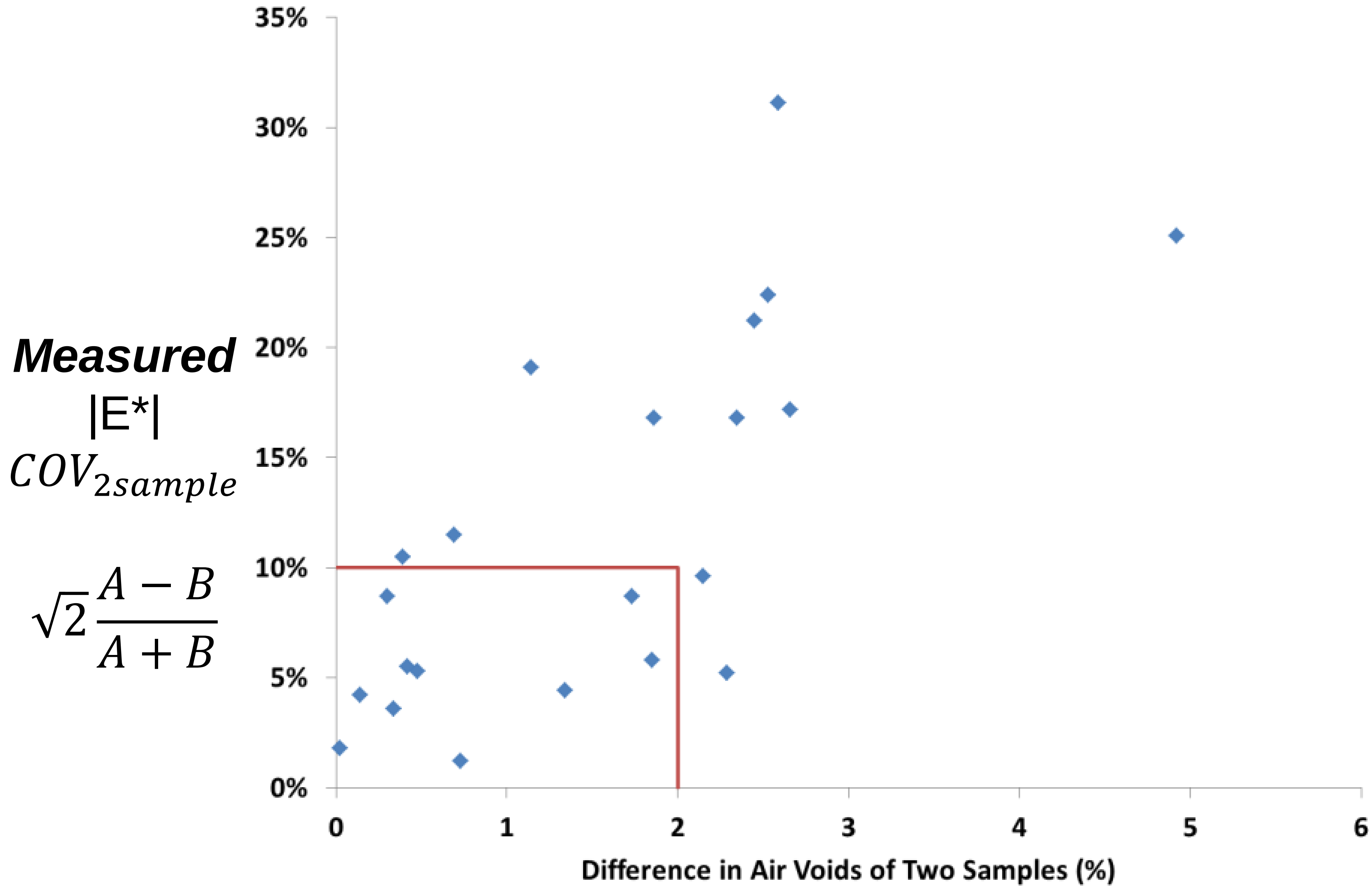


Hirsch - High Stiffness
Hirsch - Intermediate Stiffness
Hirsch - Low Stiffness
y = 0.0372x + 0.7412
R² = 0.9861
y = 0.0129x + 0.9097
R² = 0.9443
y = 0.0602x + 0.5805
R² = 0.9908
Low Stiffness
High Stiffness
Intermediate Stiffness
1.30
1.20
1.10
1.00
0.90
0.80
0.70
3.00
4.00
5.00
6.00
7.00
8.00
9.00
Correction Factor to Normalize E* to 7% Air Voids
Air Void Content of Core



Witczak - High Stiffness
Witczak - Intermediate Stiffness
Witczak - Low Stiffness
y = 0.0567x + 0.609
R² = 0.759
y = 0.0588x + 0.5955
R² = 0.8236
y = 0.0655x + 0.5532
R² = 0.9459
Correction Factor to Normalize E* to 7% Air Voids
Air Void Content of Core
1.30
1.20
1.10
1.00
0.90
0.80
0.70
3.00
4.00
5.00
6.00
7.00
8.00
9.00

…it seems that about every 1% change in air void content (and associated VMA, VFA changes) there is about a 5% change in |E*|

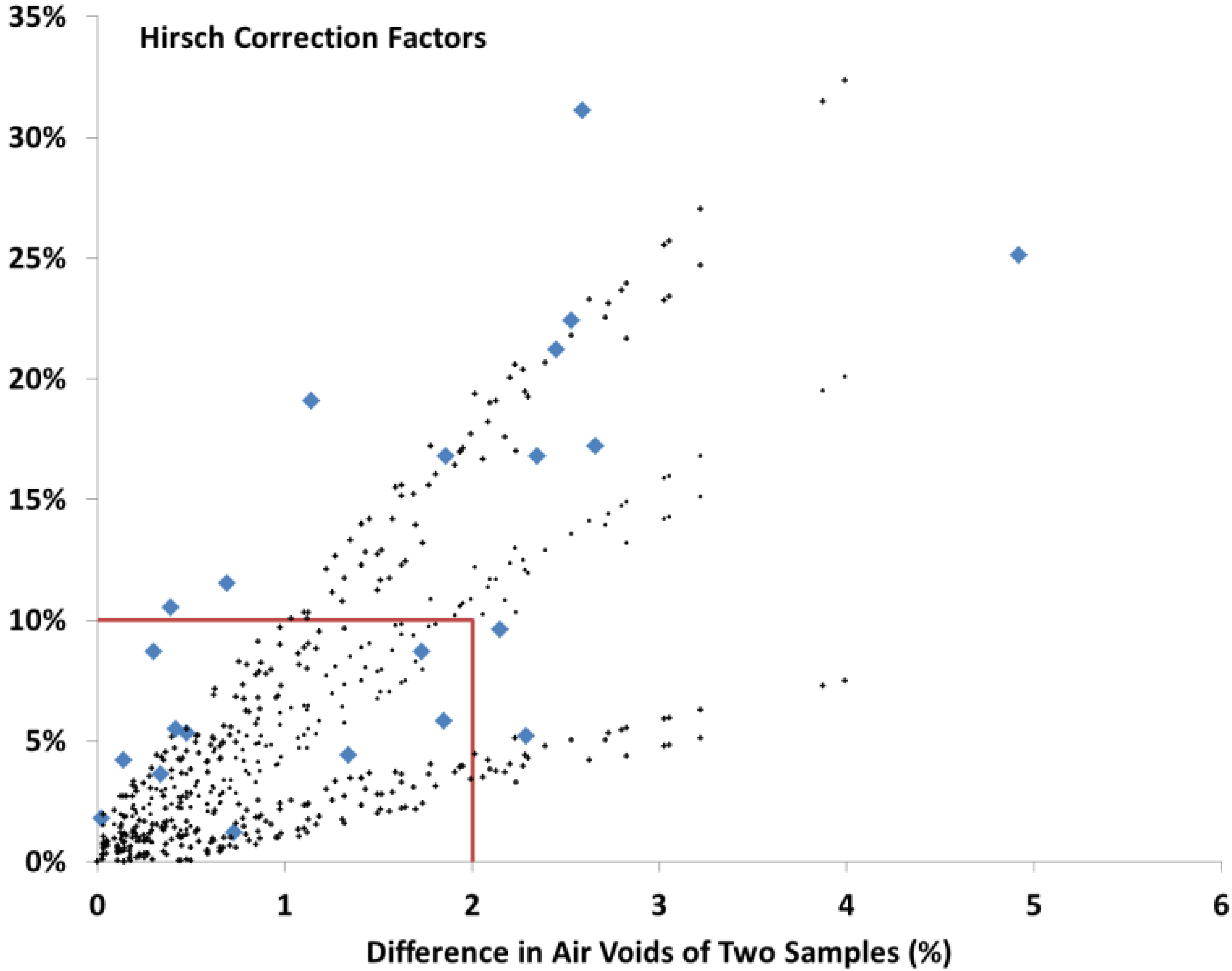


Measured
|E*|
$COV_{2sample}$
$\sqrt{2}\frac{A-B}{A+B}$
35%
30%
25%
20%
15%
10%
5%
0%
0
1
2
3
4
5
6
Difference in Air Voids of Two Samples (%)

Measured

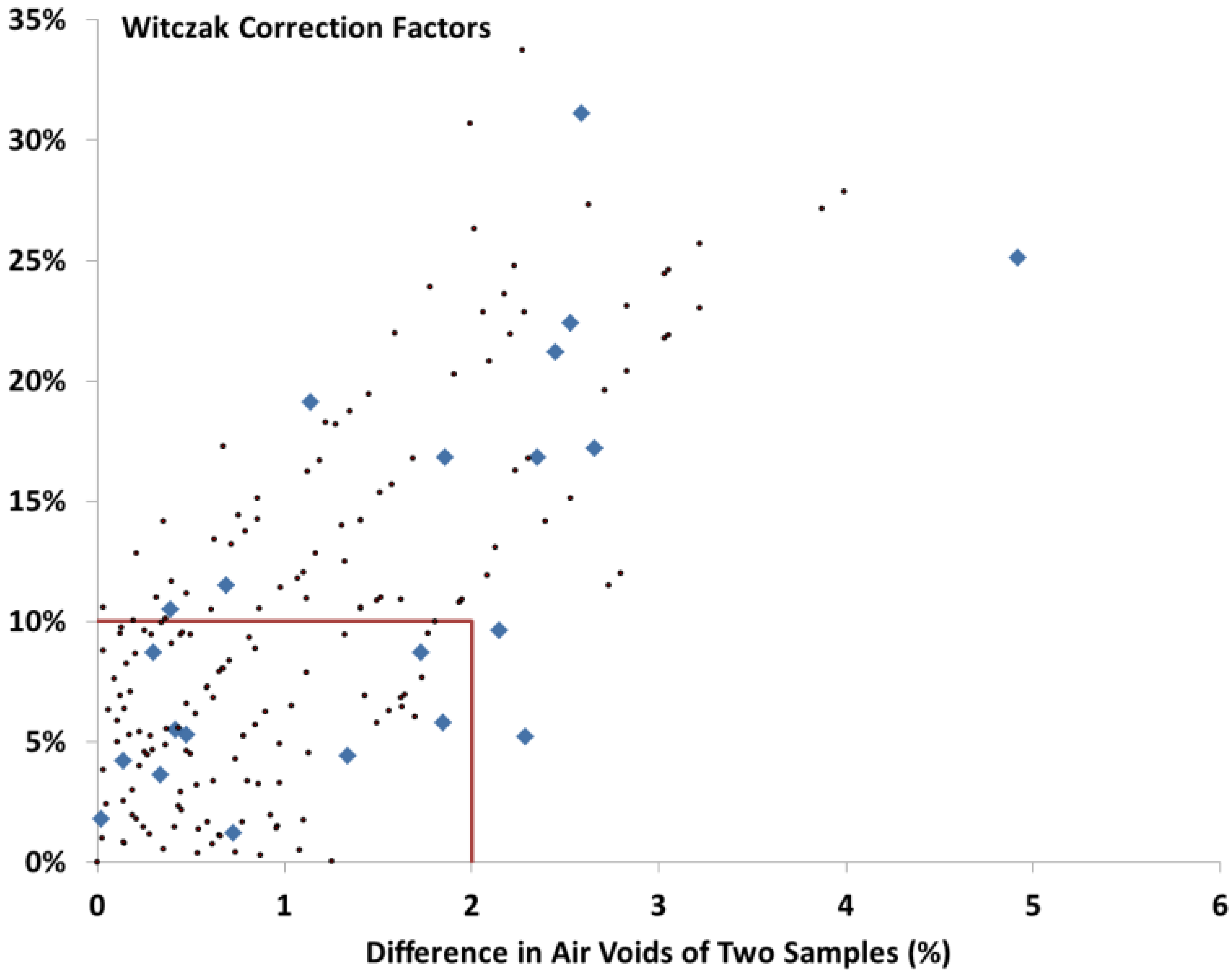
|E*|

$$COV_{2sample} = \sqrt{2}\,\frac{A-B}{A+B}$$



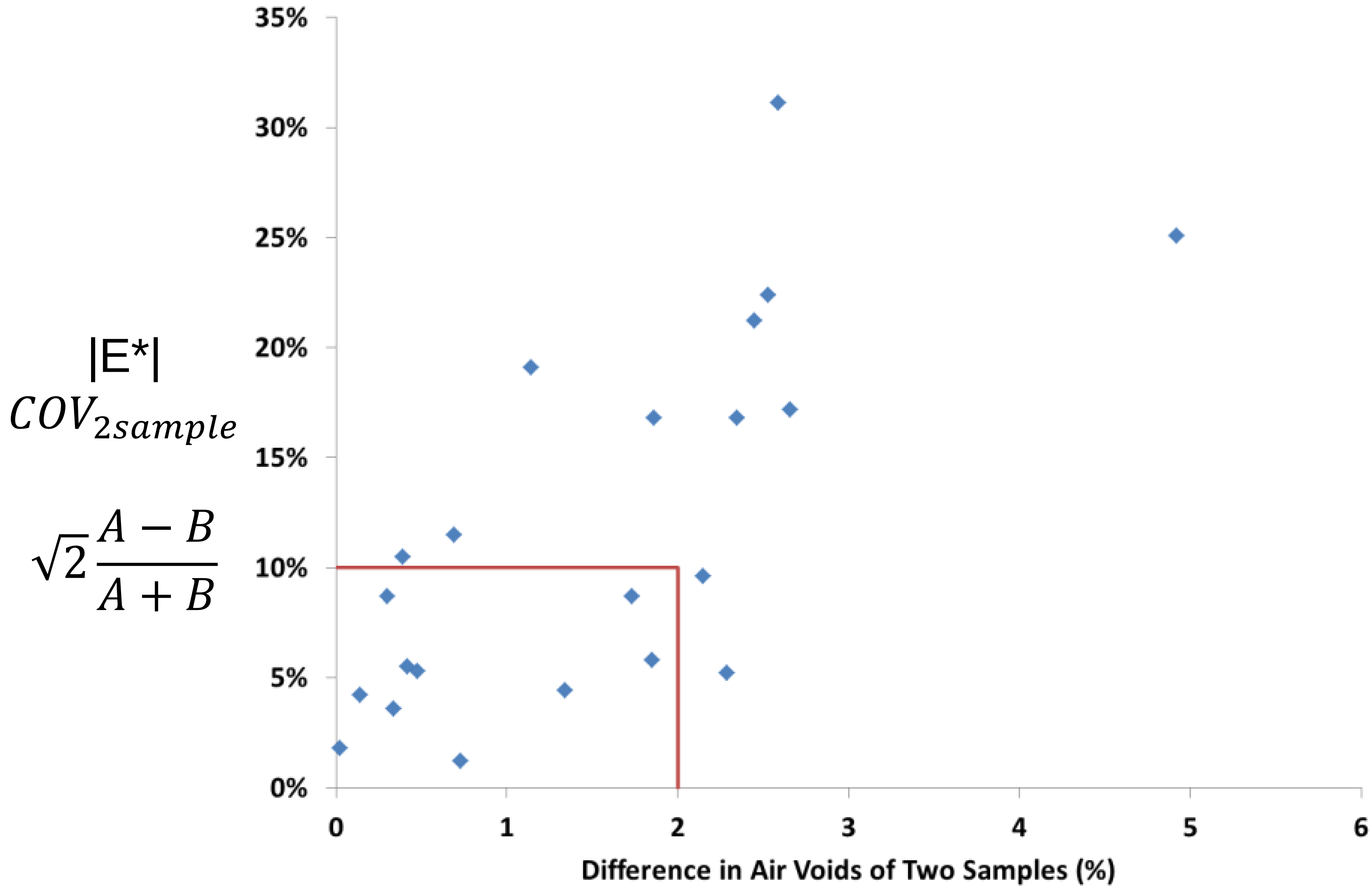
Measured
|E*|
$COV_{2sample}$

$$\sqrt{2}\frac{A-B}{A+B}$$

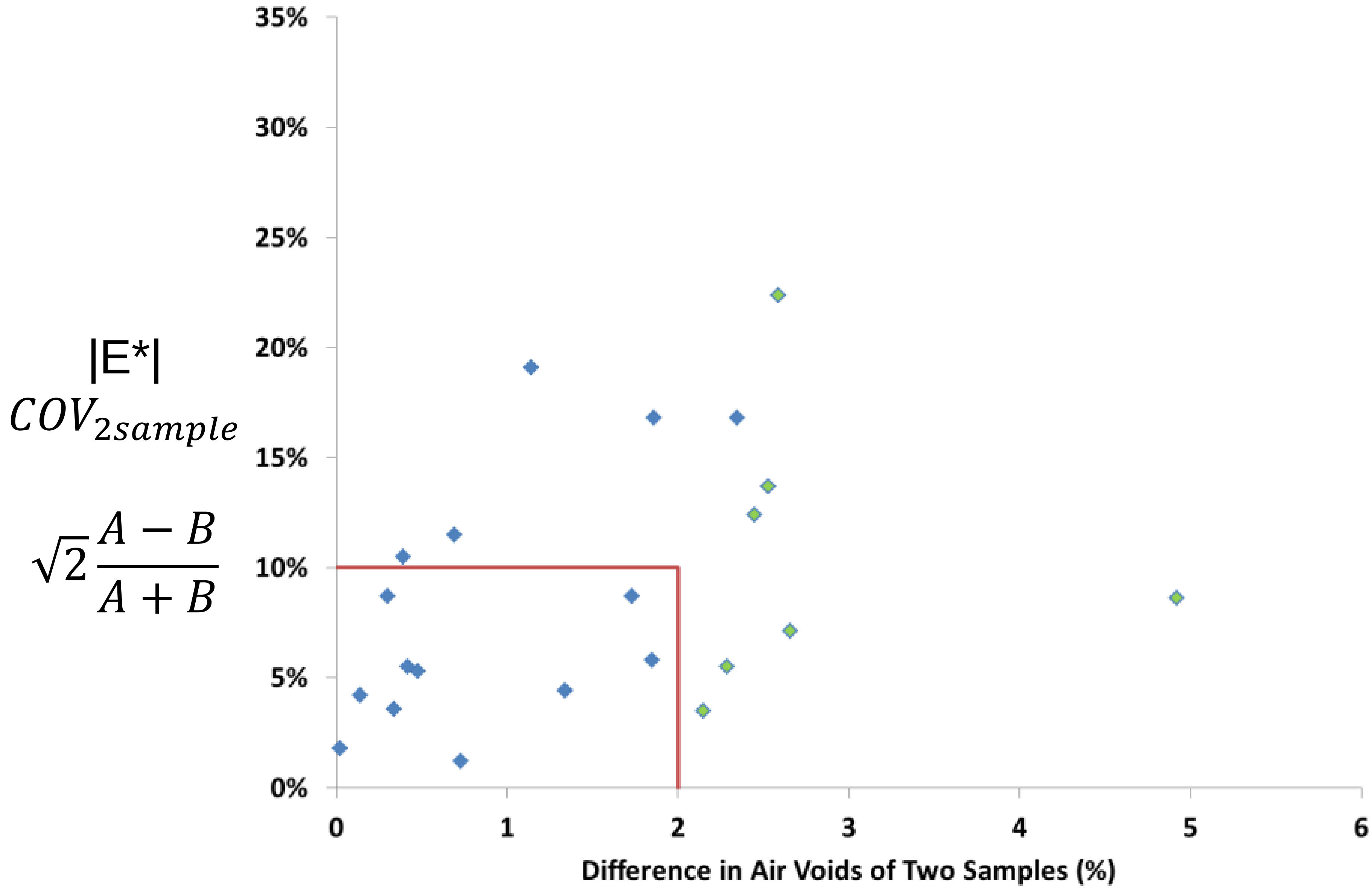


First round |E*| characterization used 2-replicates for each lift

…if the difference in %AV of the paired |E*| samples was greater than 2%, then the measured |E*| was adjusted/corrected…



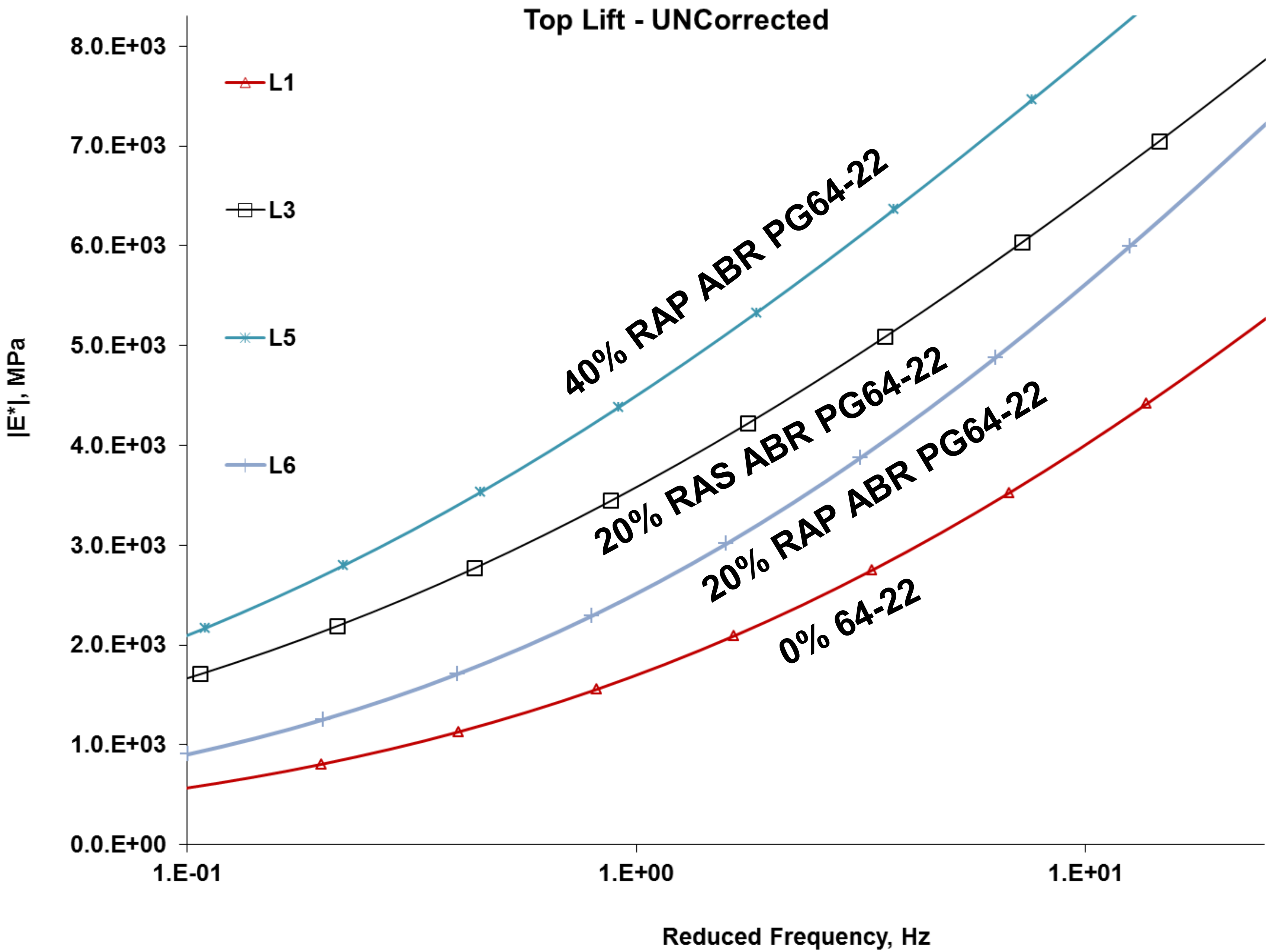
|E*|
$COV_{2sample}$
$\sqrt{2}\frac{A-B}{A+B}$
35%
30%
25%
20%
15%
10%
5%
0%
0
1
2
3
4
5
6
Difference in Air Voids of Two Samples (%)



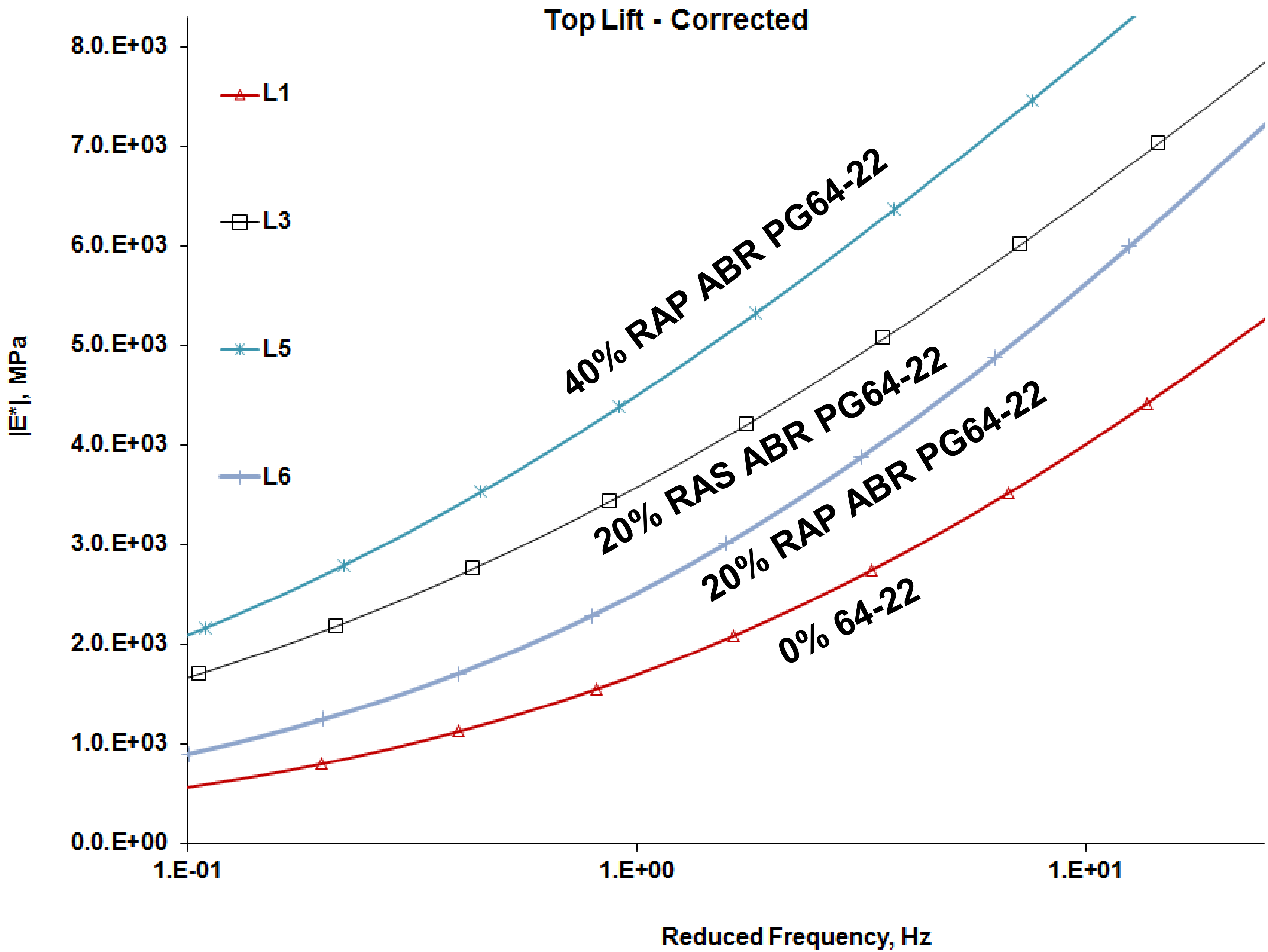
|E*|
$COV_{2sample}$
$\sqrt{2}\frac{A-B}{A+B}$
35%
30%
25%
20%
15%
10%
5%
0%
0
1
2
3
4
5
6
Difference in Air Voids of Two Samples (%)

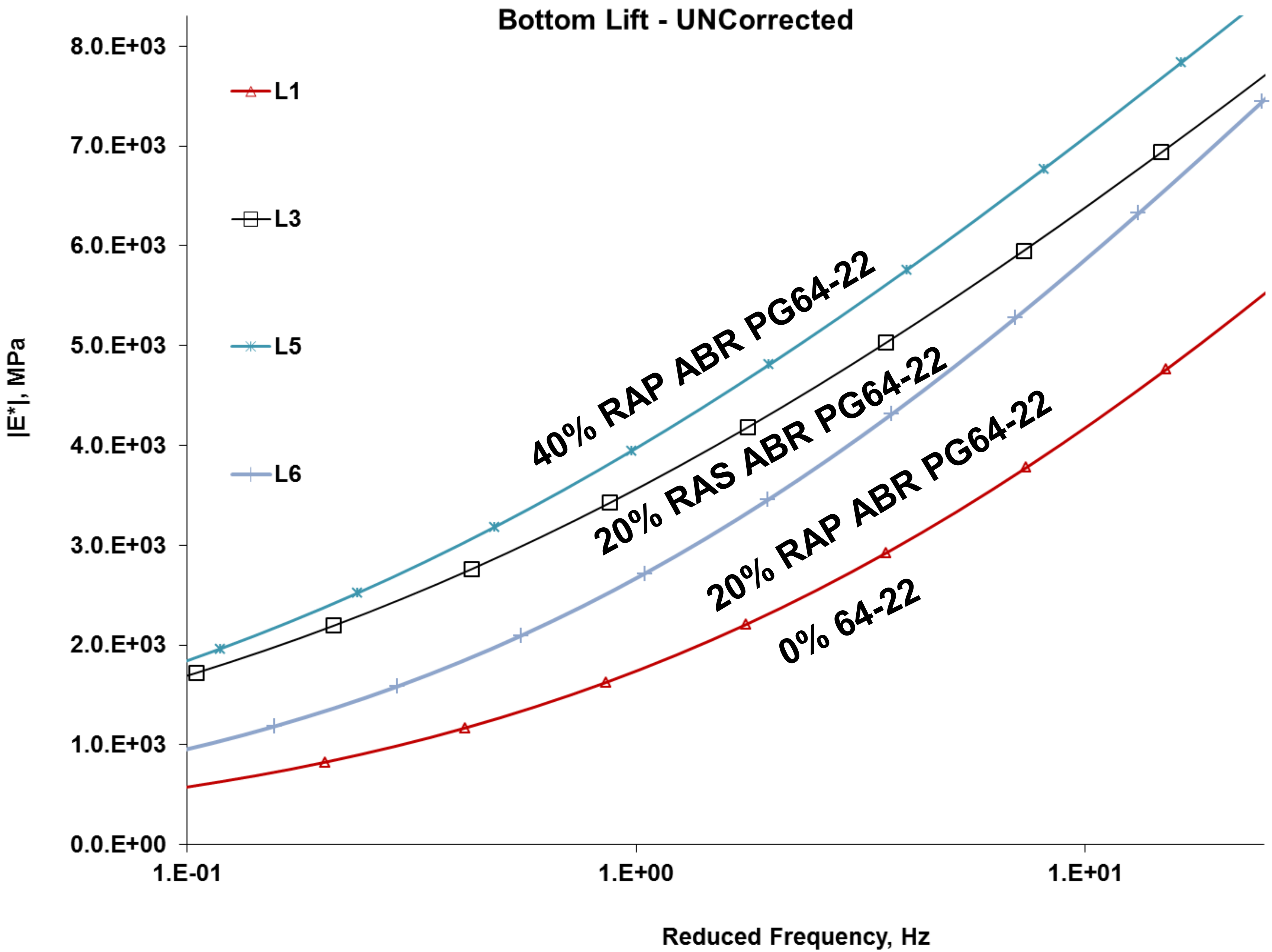
Effect of Recycle Content

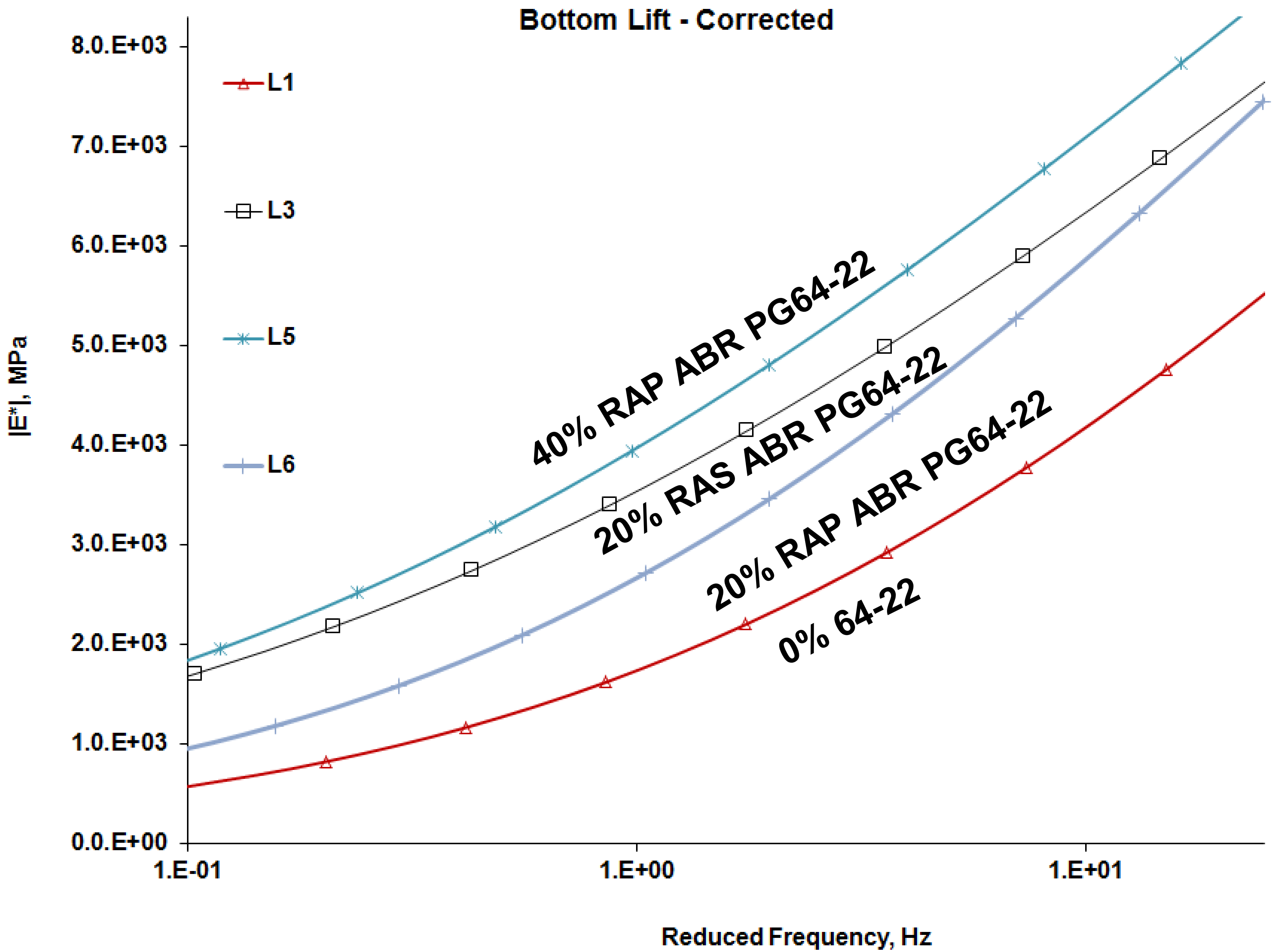
HMA / WMA Production Temperature Warm Mix Technology Recycle Content	300ºF - 320ºF		240ºF - 270ºF	
	-		Foam	Chem.
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28

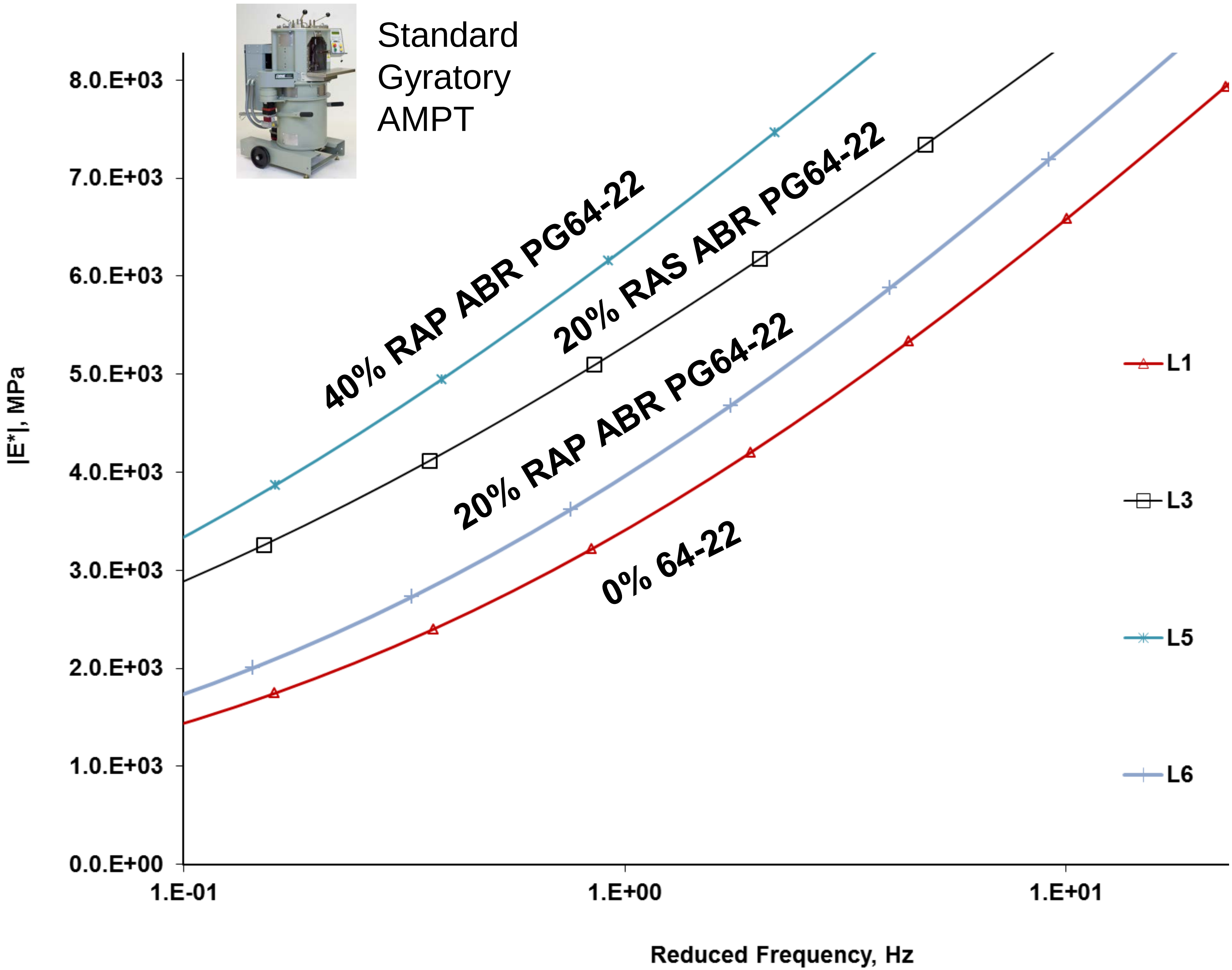


Top Lift - UNCorrected
|E*|, MPa
0.0.E+00
1.0.E+03
2.0.E+03
3.0.E+03
4.0.E+03
5.0.E+03
6.0.E+03
7.0.E+03
8.0.E+03
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
L1
L3
L5
L6
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22


Top Lift - Corrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L1
L3
L5
L6
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz


Bottom Lift - UNCorrected
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
L1
L3
L5
L6
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22

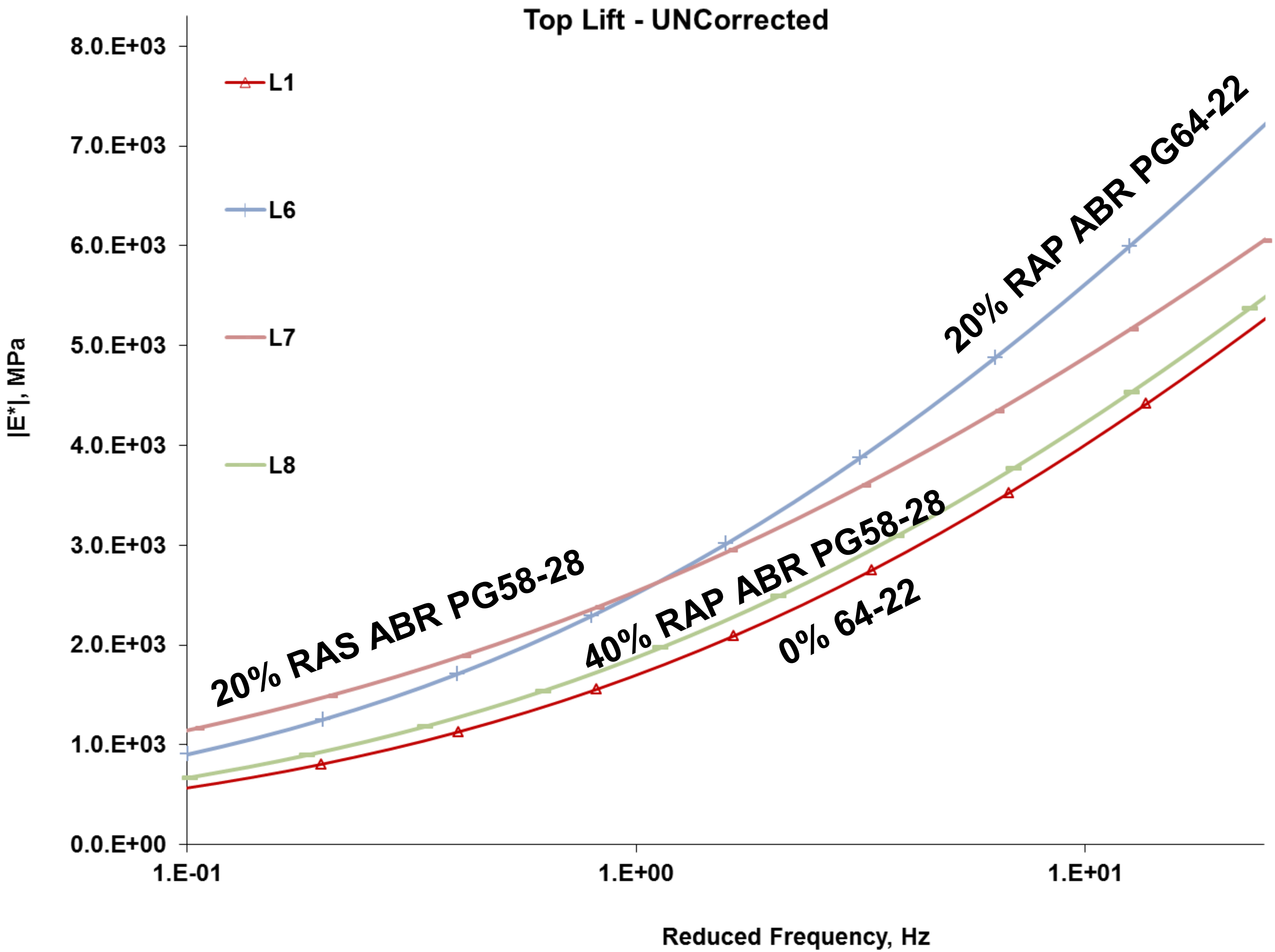

Bottom Lift - Corrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L1
L3
L5
L6
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



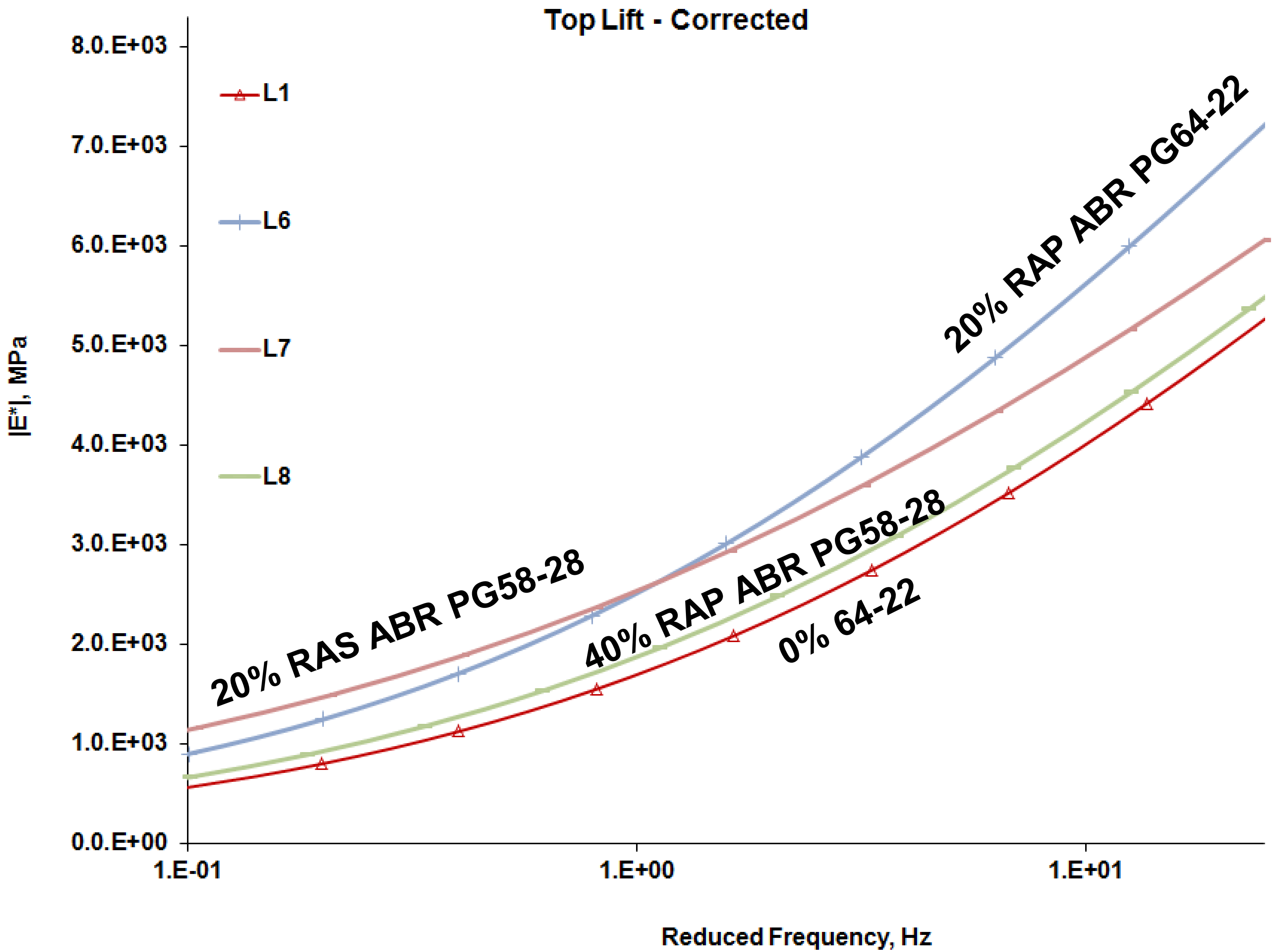
Standard
Gyratory
AMPT
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22
L1
L3
L5
L6

Effect of Offset with Softer Binder PG

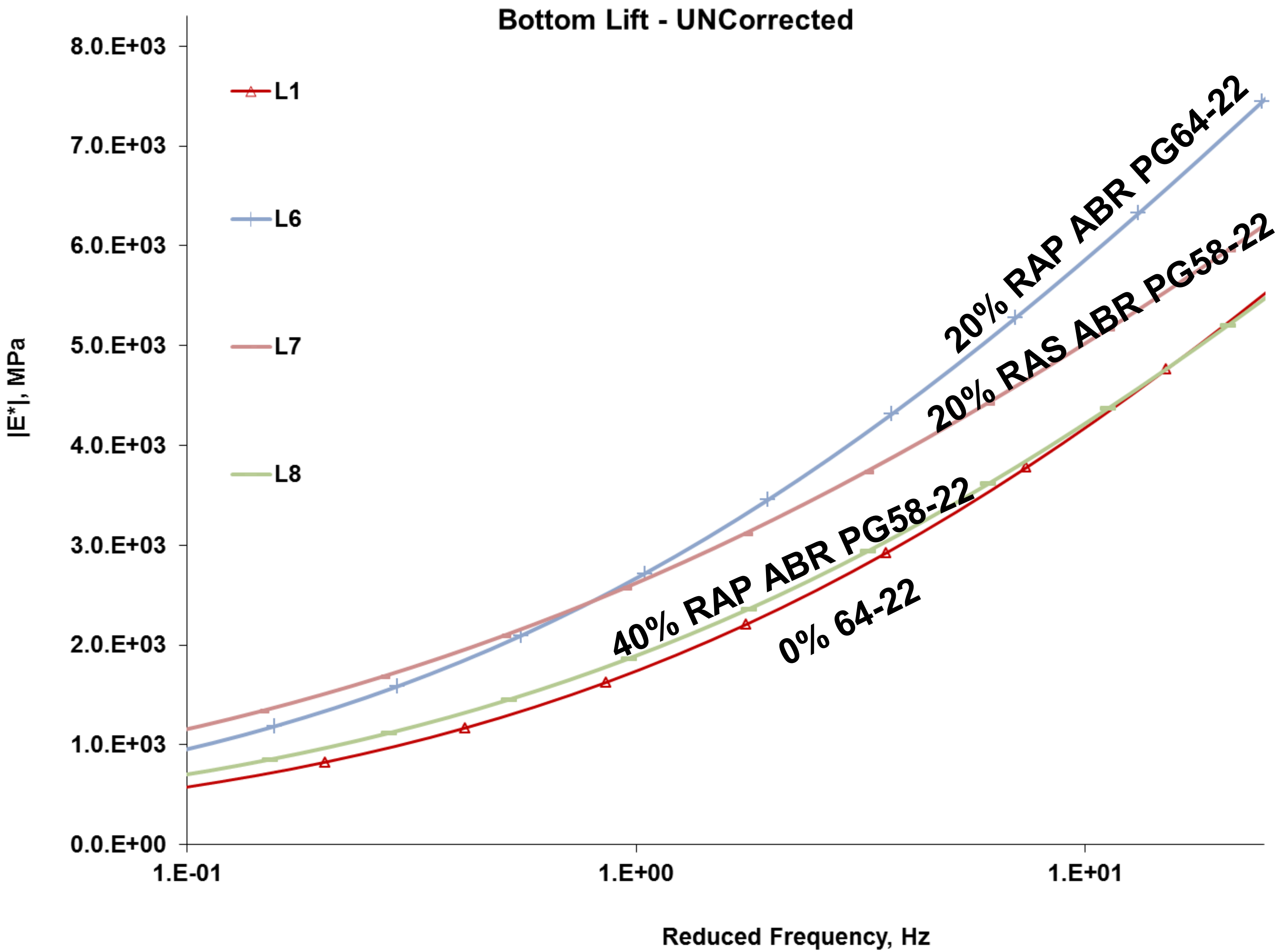
HMA / WMA → Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✔ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✔ PG64-22		✔ PG64-22	✔ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✔ PG64-22	✔ PG58-28		
40% ABR RAP ≈ 44% by weight	✔ PG64-22	✔ PG58-28	✔ PG58-28	✔ PG58-28



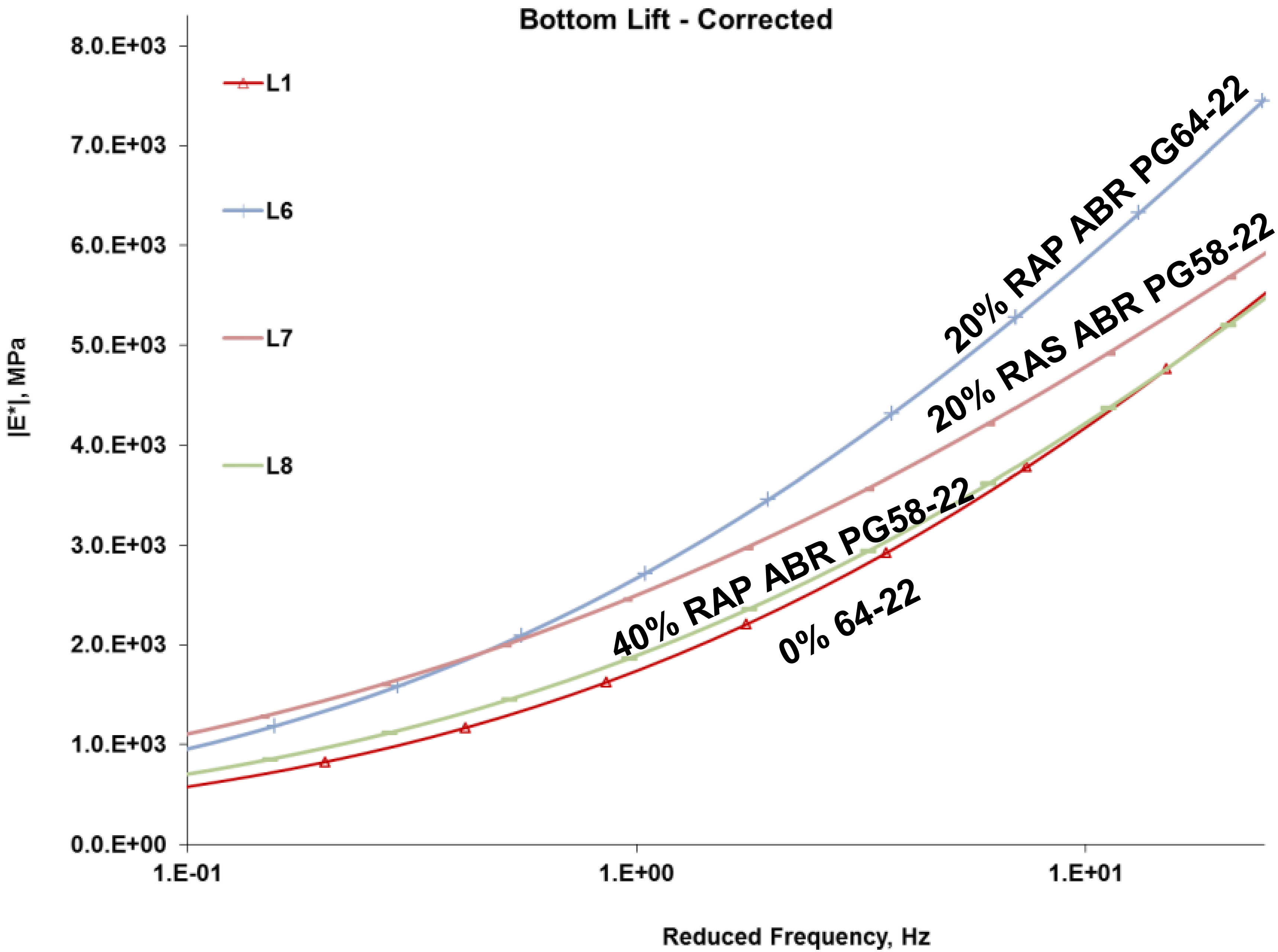
Top Lift - UNCorrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L1
L6
L7
L8
20% RAP ABR PG64-22
20% RAS ABR PG58-28
40% RAP ABR PG58-28
0% 64-22
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



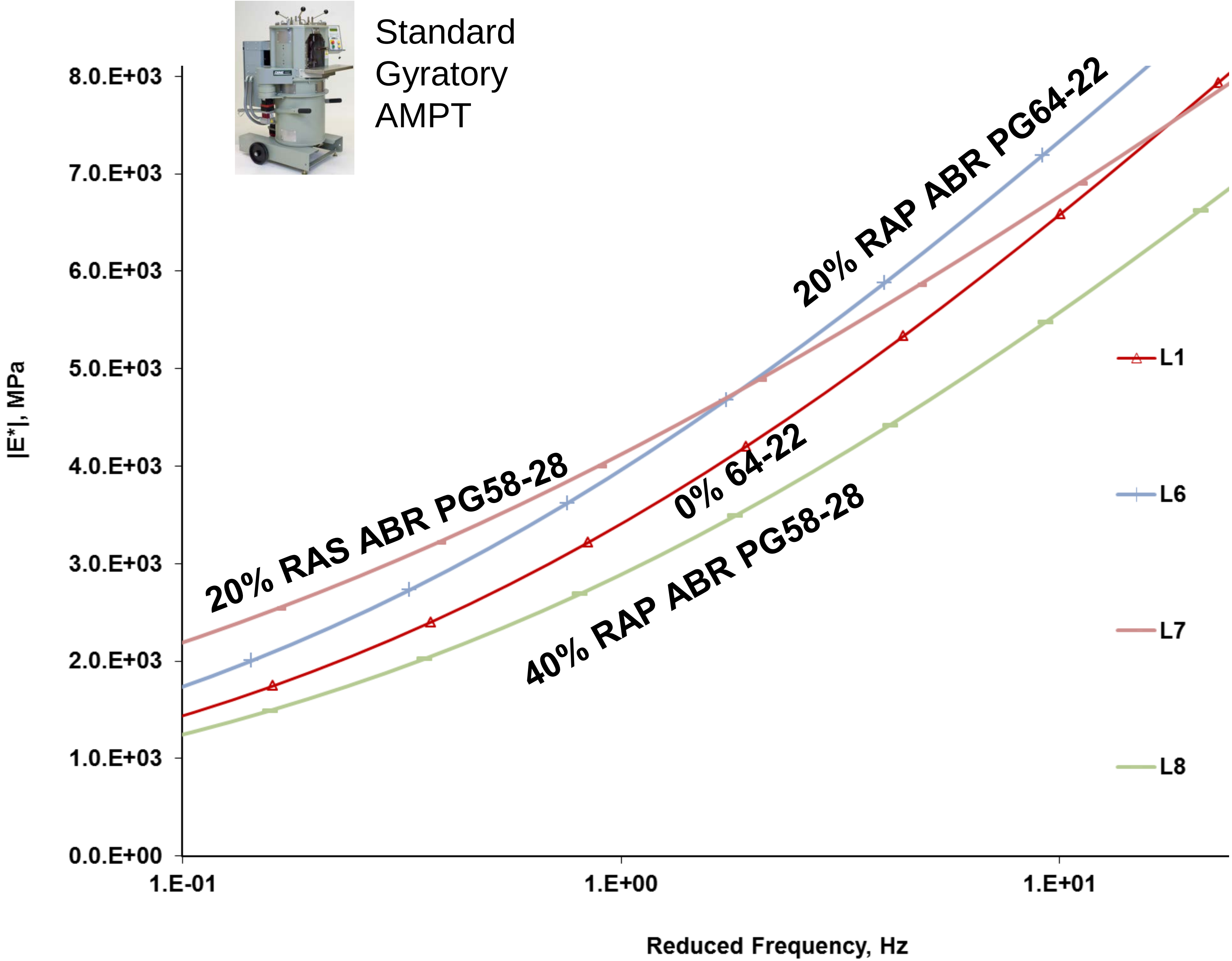
Top Lift - Corrected
L1
L6
L7
L8
20% RAP ABR PG64-22
20% RAS ABR PG58-28
40% RAP ABR PG58-28
0% 64-22
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



Bottom Lift - UNCorrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L1
L6
L7
L8
20% RAP ABR PG64-22
20% RAS ABR PG58-22
40% RAP ABR PG58-22
0% 64-22
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

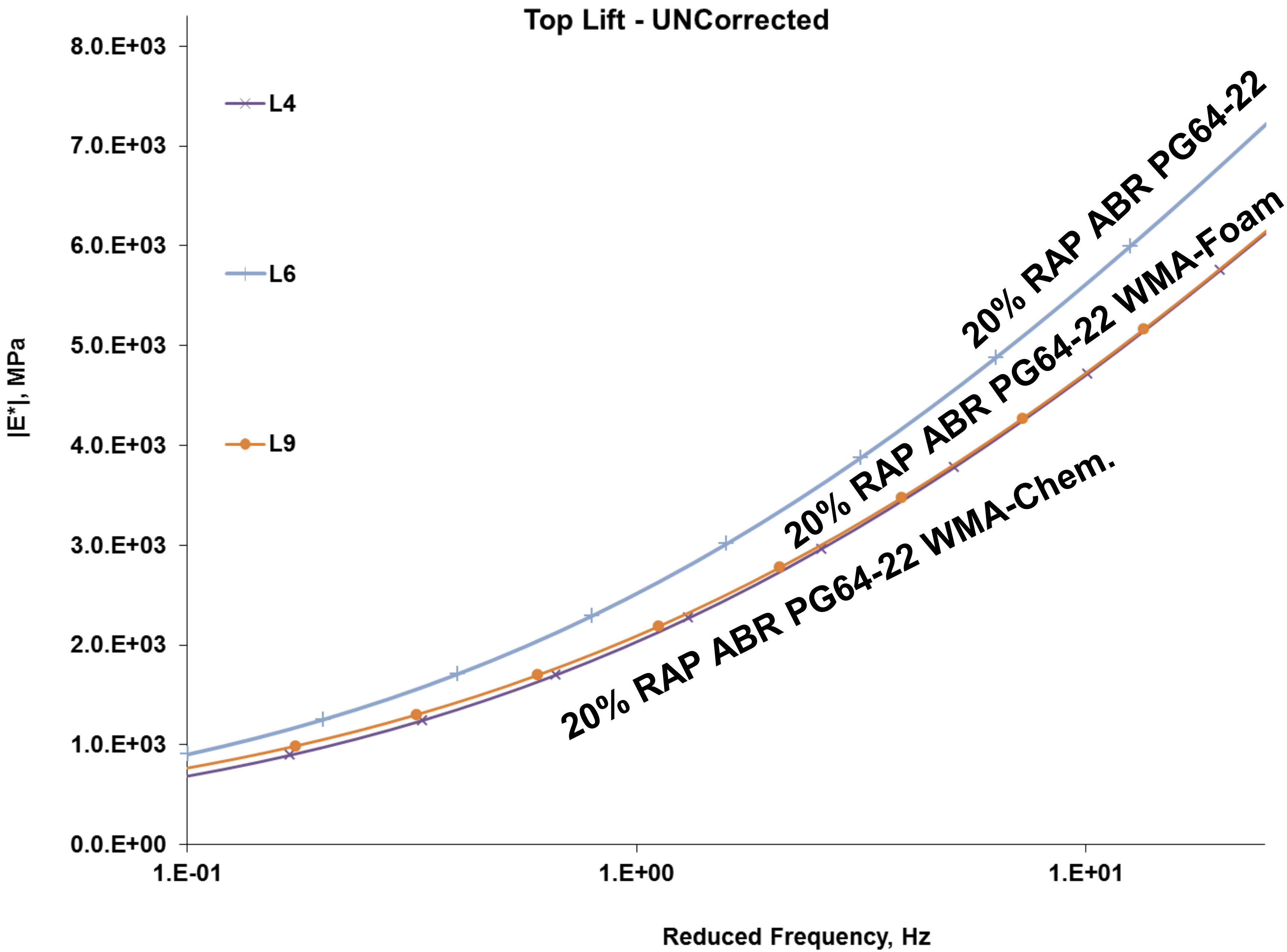


Bottom Lift - Corrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L1
L6
L7
L8
20% RAP ABR PG64-22
20% RAS ABR PG58-22
40% RAP ABR PG58-22
0% 64-22
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

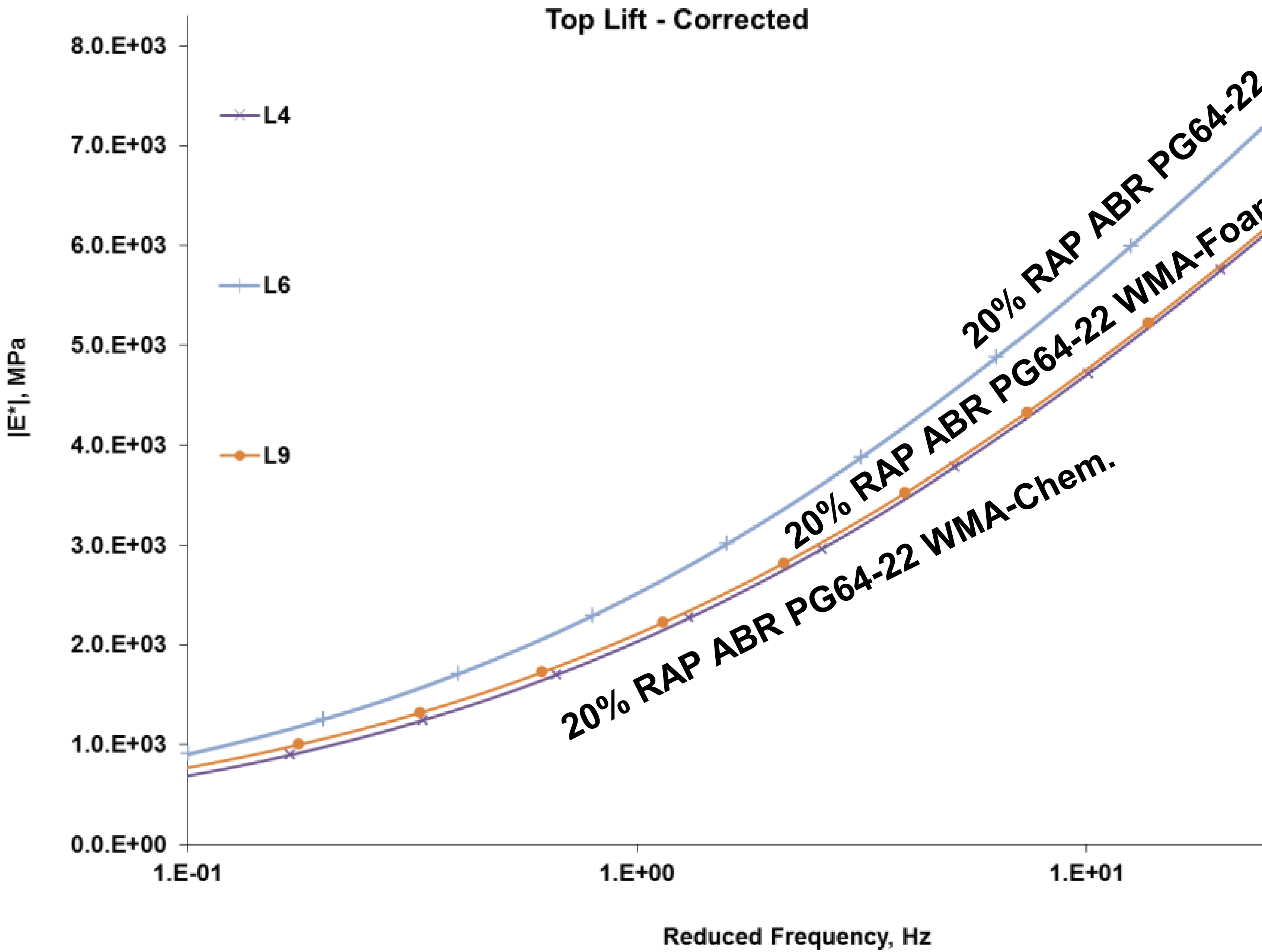

Standard
Gyratory
AMPT
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
20% RAP ABR PG64-22
20% RAS ABR PG58-28
0% 64-22
40% RAP ABR PG58-28
L1
L6
L7
L8

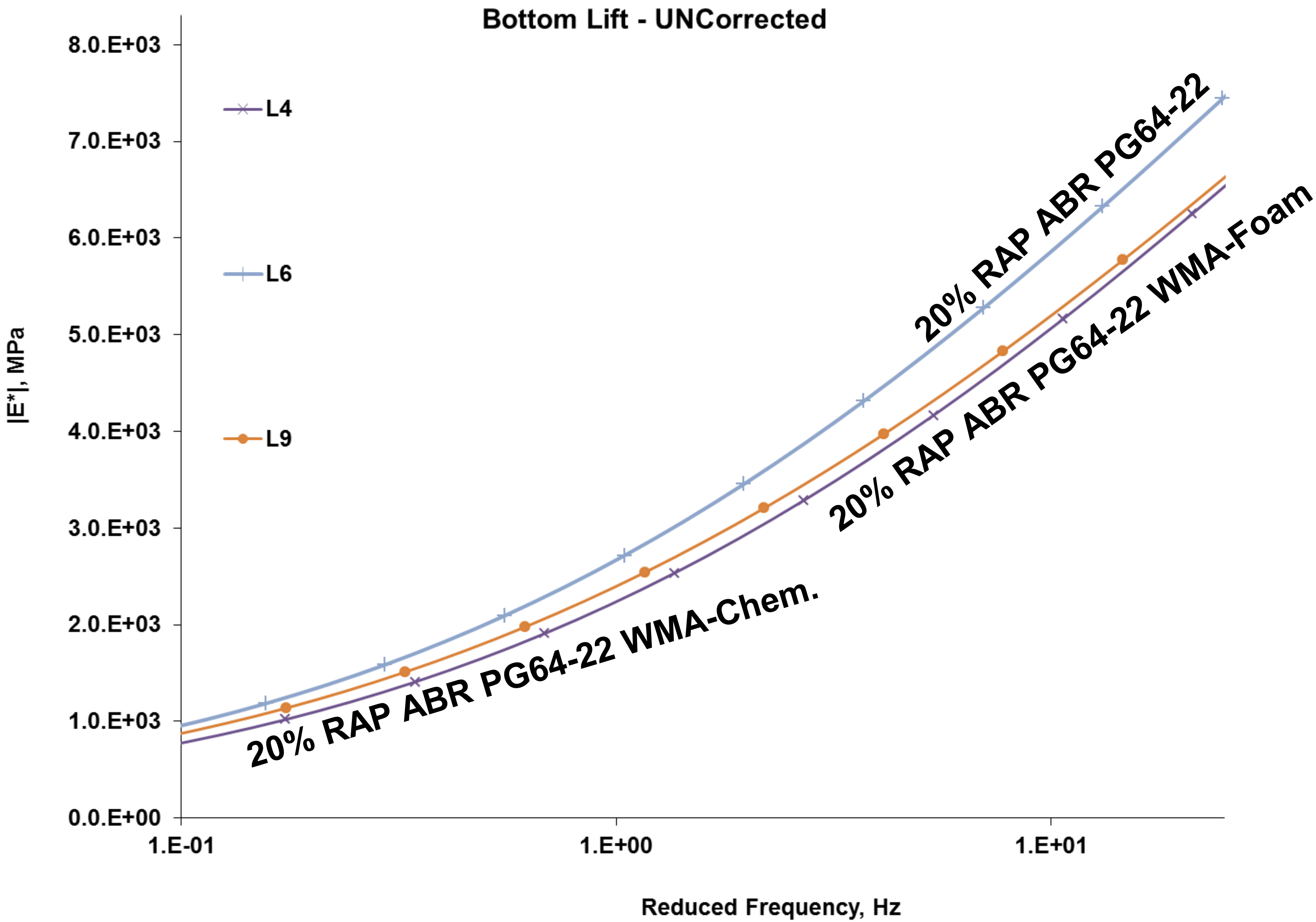
Effect of WMA (1 of 2)

HMA / WMA	300°F - 320°F		240°F - 270°F	
Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28

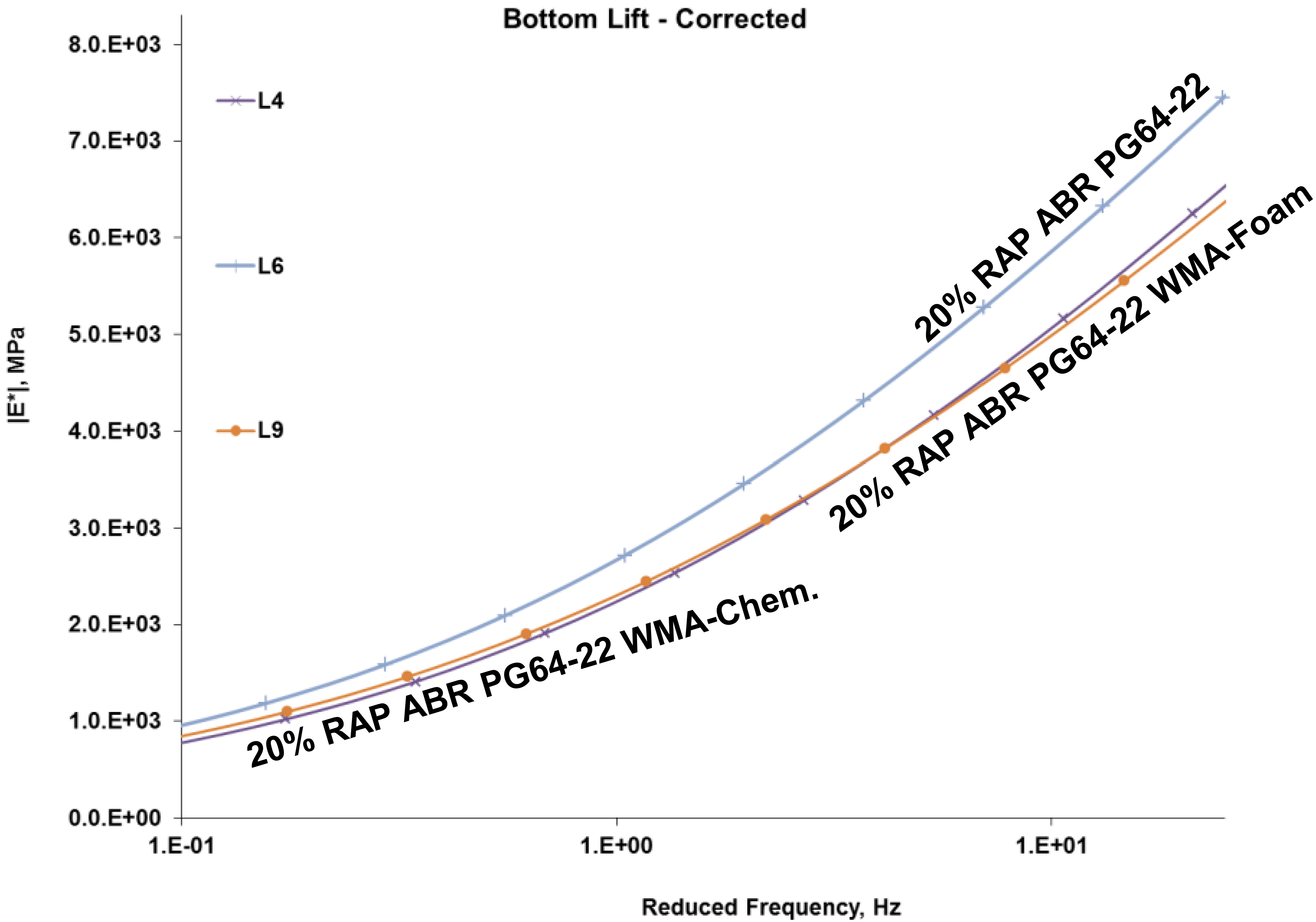


Top Lift - UNCorrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L4
L6
L9
20% RAP ABR PG64-22
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

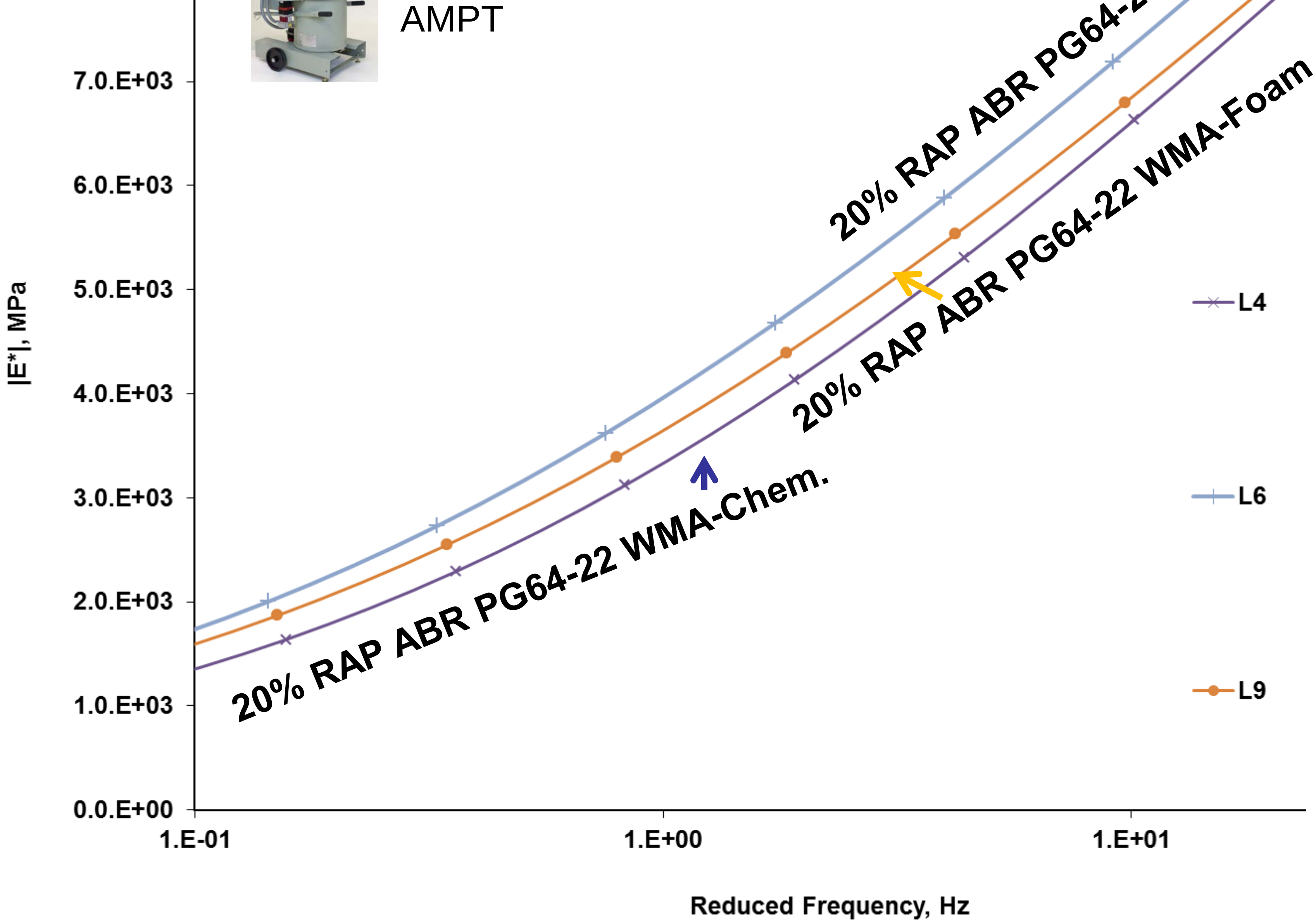

Top Lift - Corrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L4
L6
L9
20% RAP ABR PG64-22
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



Bottom Lift - UNCorrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
L4
L6
L9
20% RAP ABR PG64-22
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.

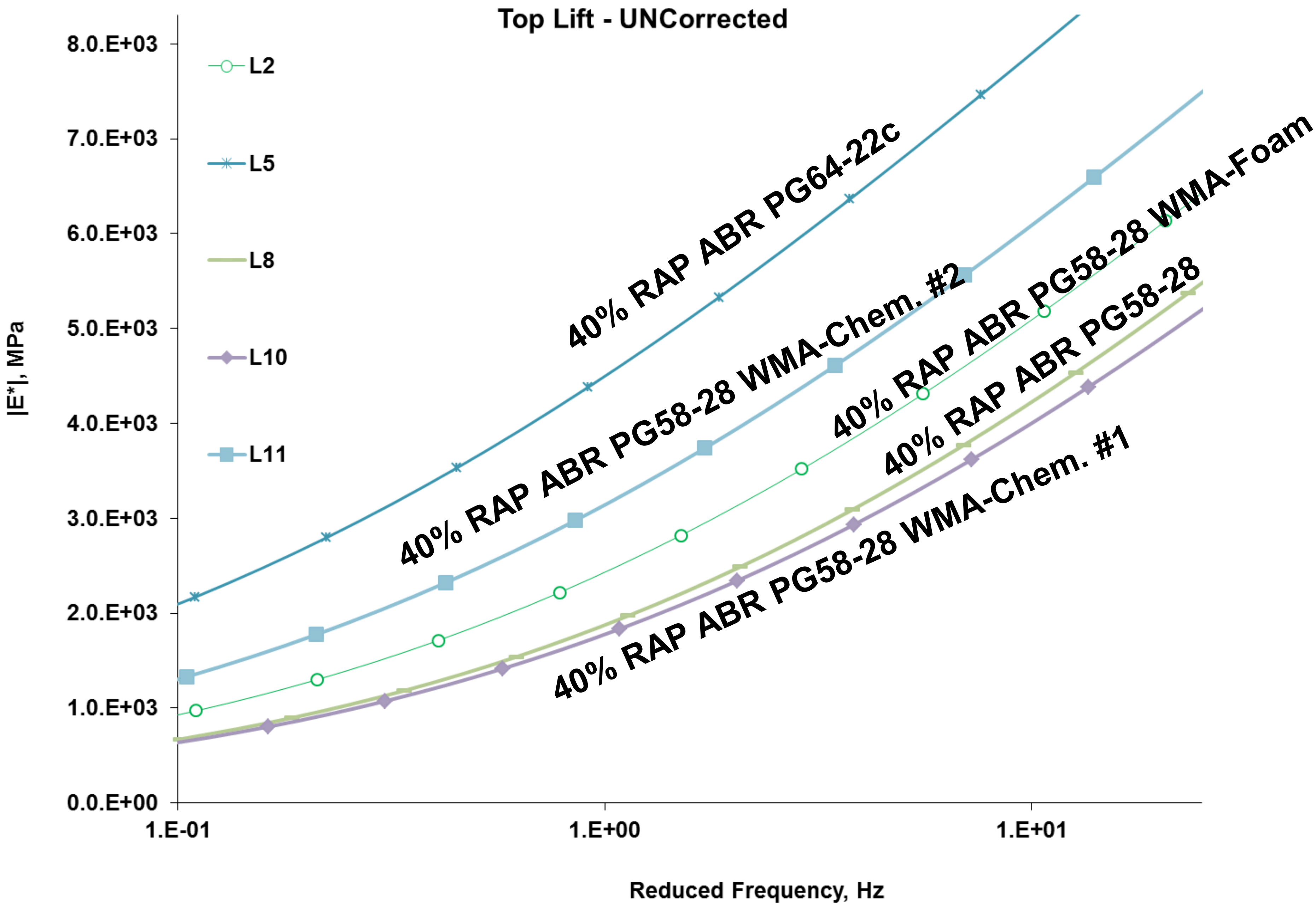

Bottom Lift - Corrected
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
L4
L6
L9
20% RAP ABR PG64-22
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

Standard
Gyratory
AMPT

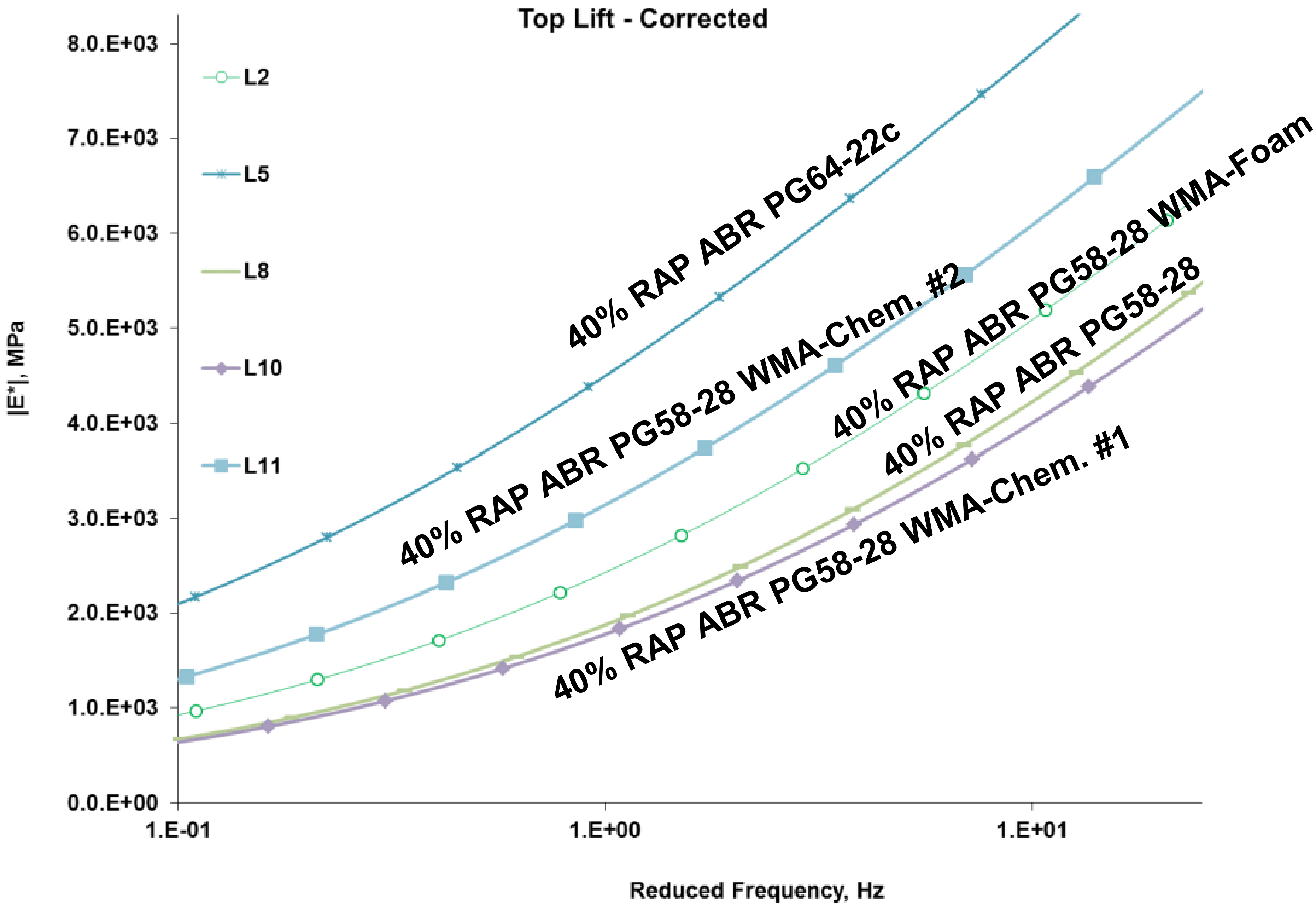


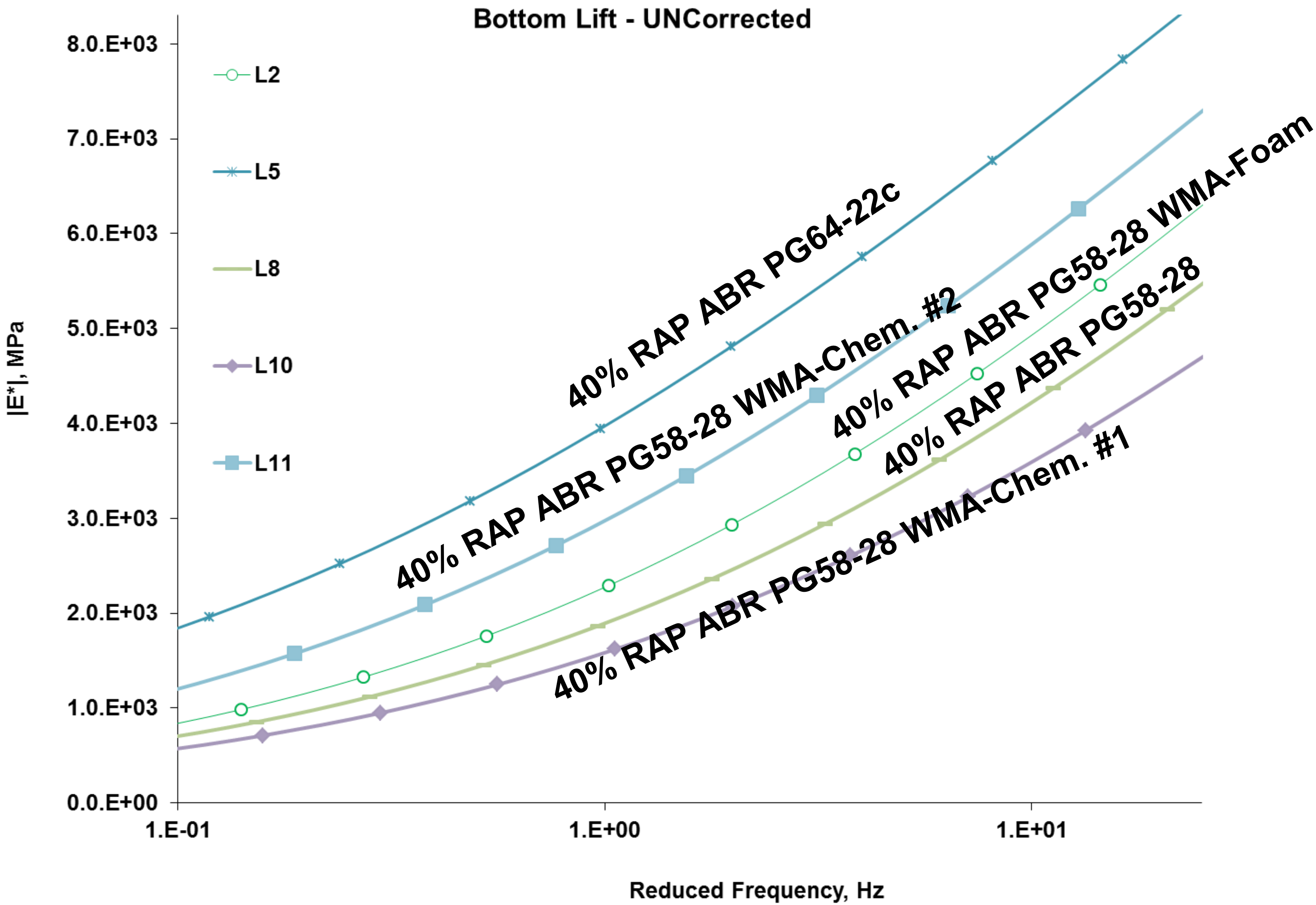
Effect of WMA (2 of 2)

HMA / WMA Production Temperature	300ºF - 320ºF		240ºF - 270ºF	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28

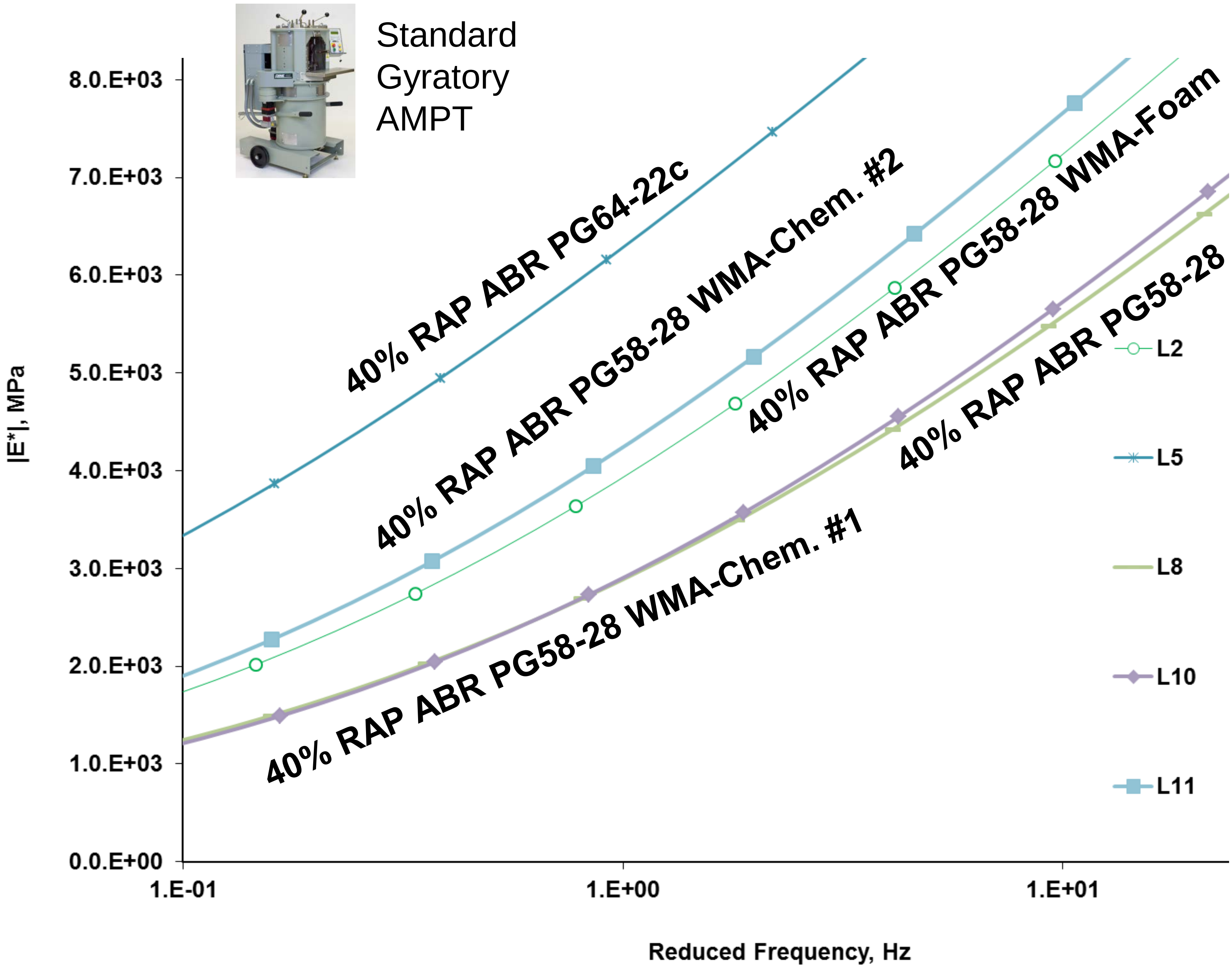


Top Lift - UNCorrected
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L2
L5
L8
L10
L11
40% RAP ABR PG64-22c
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
40% RAP ABR PG58-28 WMA-Chem. #1
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz


Top Lift - Corrected
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
L2
L5
L8
L10
L11
40% RAP ABR PG64-22c
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
40% RAP ABR PG58-28 WMA-Chem. #1



Bottom Lift - UNCorrected
L2
L5
L8
L10
L11
40% RAP ABR PG64-22c
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
40% RAP ABR PG58-28 WMA-Chem. #1
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



Standard
Gyratory
AMPT
40% RAP ABR PG64-22c
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
40% RAP ABR PG58-28 WMA-Chem. #1
L2
L5
L8
L10
L11
|E*|, MPa
Reduced Frequency, Hz
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01

Intelligent Compaction – CAT Retrofit - HMA

- **Identified the need and for better guidance for GIS mapping protocols of the project for inclusion into onboard software pre construction.**
  - **Will assist operator to stay within project boundaries and to remove irrelevant data outside of the project.**
- **Identified that field verification of accelerometer calibration may be viable.**
  - **Potential use of commercial accelerometer shakers or other simple impact testing of the accelerometers.**
- **More in depth evaluation to come at Texas DOT Jimmy Si /UTEP Soheil Nazarian through the EDC-2 efforts.**

Intelligent Compaction – CAT Retrofit - HMA

- Not “fully” compatible with Veda
  - Data transfer is cumbersome and not easily accomplished.
  - Verification of data collected properly is not apparent until analysis is complete.
- Manufacturer’s web application can provide real time data (5 min delay)
  - This will allow inspector to monitor coverage and stiffness from a remote distance.
- Confirmed GPS accuracy as per current draft IC specs.

FHWA Pavement Test Facility 2013 Reconstruction

… so what does the ALF loading represent in real life?

AASHTO Load Equivalency Factor

…for "half-axle" ALF @ 14.5 kips a full axle is 29 kips

Table D.1. Axle Load Equivalency Factors for Flexible Pavements, Single Axles and p_t of 2.0

Axle Load (kips)	Pavement Structural Number (SN) 1	2	3	4	5	6
2	.0002	.0002	.0002	.0002	.0002	.0002
4	.002	.003	.002	.002	.002	.002
6	.009	.012	.011	.010	.009	.009
8	.030	.035	.036	.033	.031	.029
10	.075	.085	.090	.085	.079	.076
12	.165	.177	.189	.183	.174	.168
14	.325	.338	.354	.350	.338	.331
16	.589	.598	.613	.612	.603	.596
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.59	1.56	1.55	1.57	1.59
22	2.49	2.44	2.35	2.31	2.35	2.41
24	3.71	3.62	3.43	3.33	3.40	3.51
26	5.36	5.21	4.88	4.68	4.77	4.96
28	7.54	7.31	6.78	6.42	6.52	6.83
30	10.4	10.0	9.2	8.6	8.7	9.2

6.89

9.35

8.12

Load Equivalency Factor

- **Sometimes Approximated by**

$$EALF = \frac{\#W_{18kip}}{\#W_i} \approx \left(\frac{P_i}{18kip}\right)^4$$

…for "half-axle" ALF @ 14.5 kips…

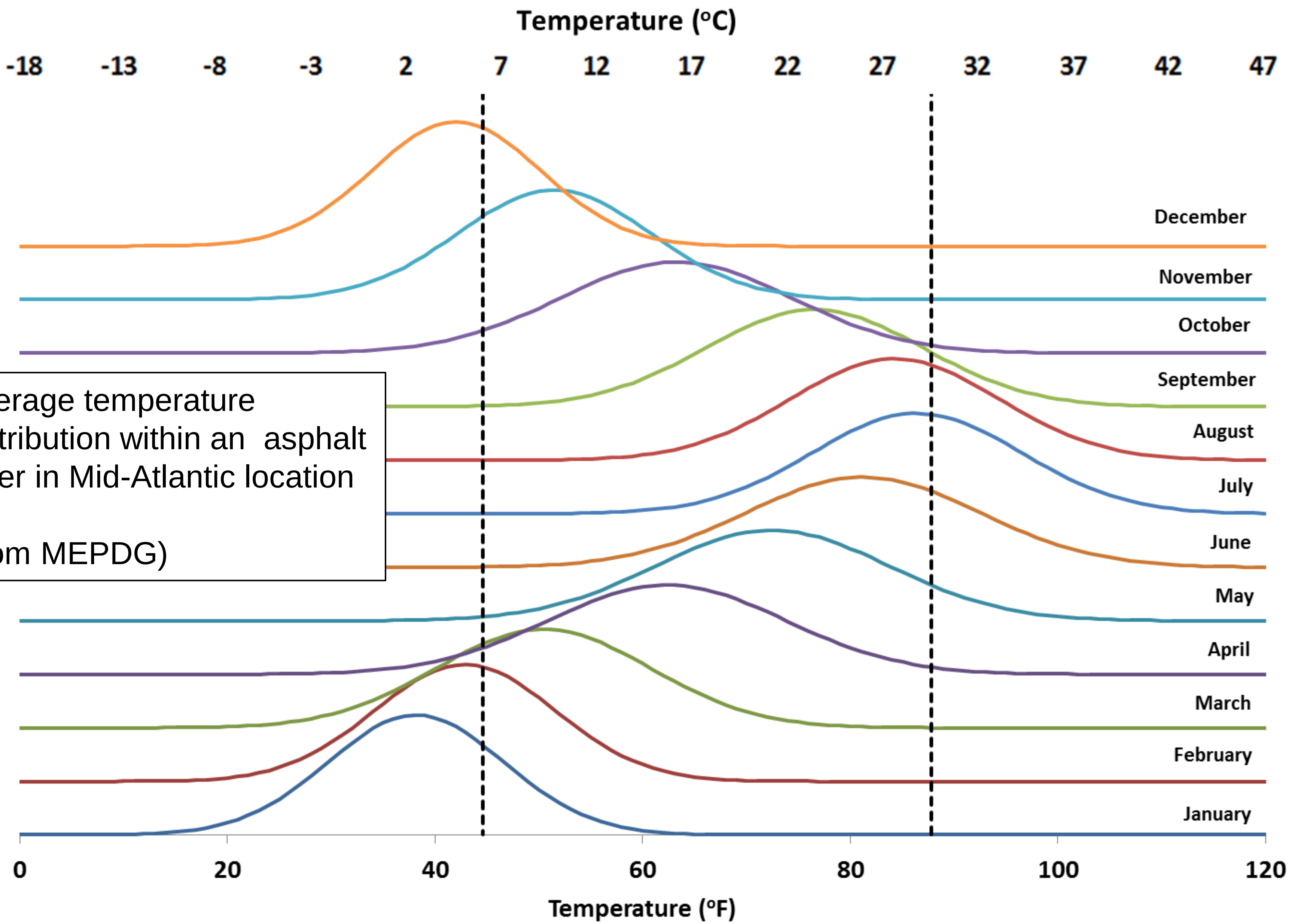
$$EALF \approx \left(\frac{14{,}500\ lb}{9{,}000\ lb}\right)^4 \approx 6.7$$

Load Equivalency Factor

- Empirically the LEF for the ALF in this experiment could range from 6.7 to 8.9; 7.8

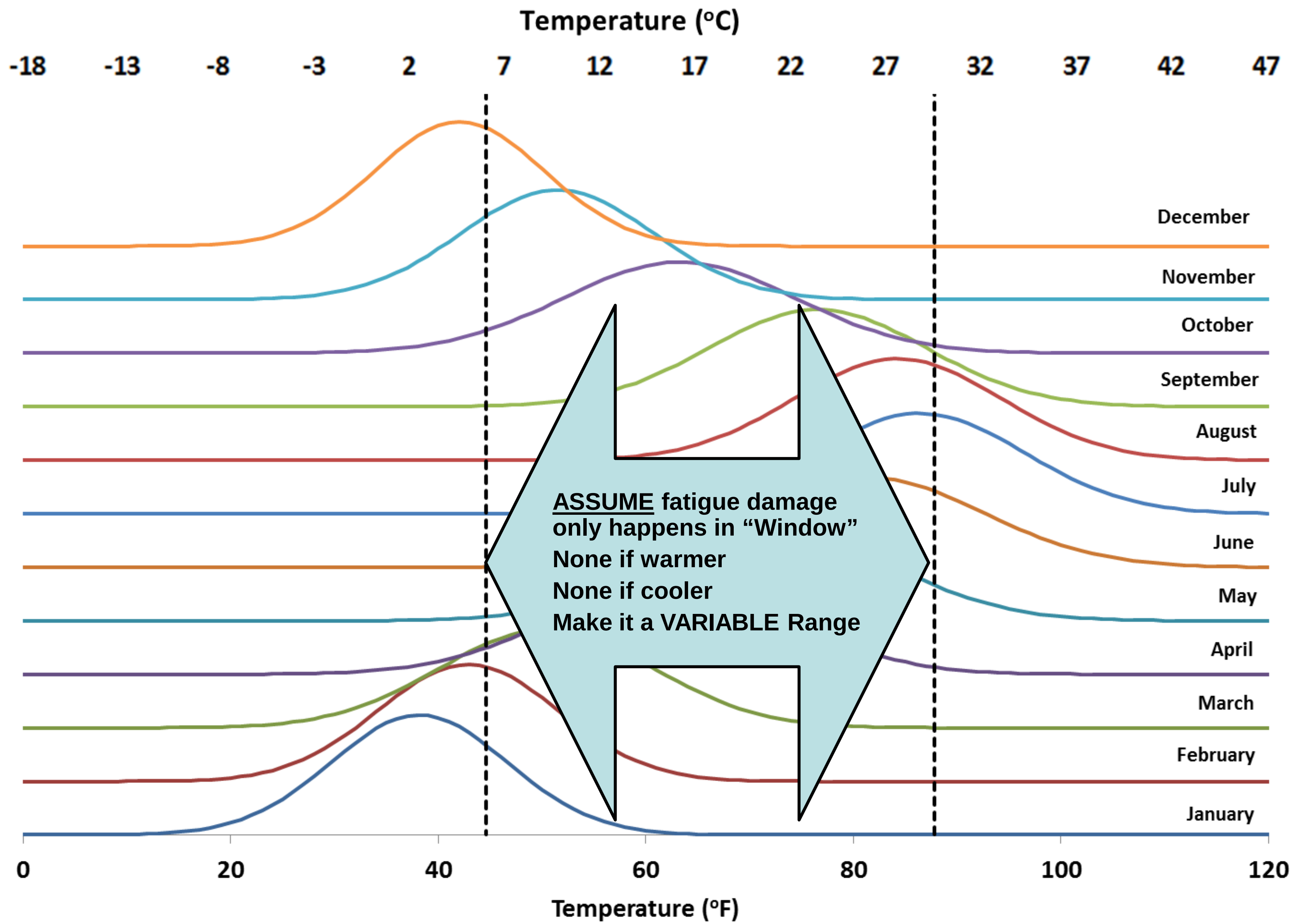
- 50,000 ALF Passes ≈ 390k ESALs
- 300,000 ALF Passes ≈ 2.3M ESALs

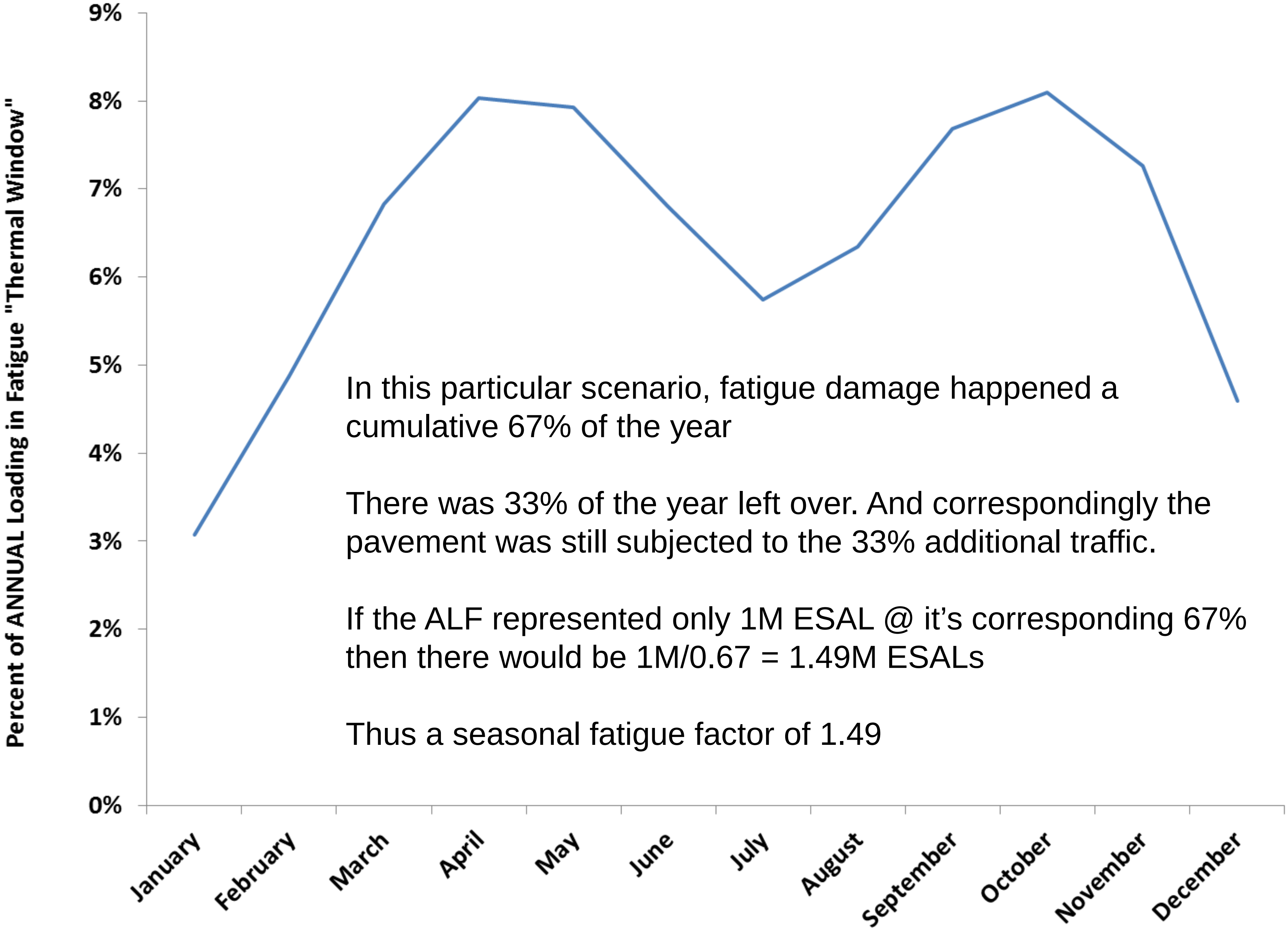
- ..but this ALF experiment is at a controlled temperature…



Average temperature distribution within an asphalt layer in Mid-Atlantic location

(from MEPDG)


Temperature (°C)
-18
-13
-8
-3
2
7
12
17
22
27
32
37
42
47
December
November
October
September
August
July
June
May
April
March
February
January
ASSUME fatigue damage only happens in "Window"
None if warmer
None if cooler
Make it a VARIABLE Range
0
20
40
60
80
100
120
Temperature (°F)

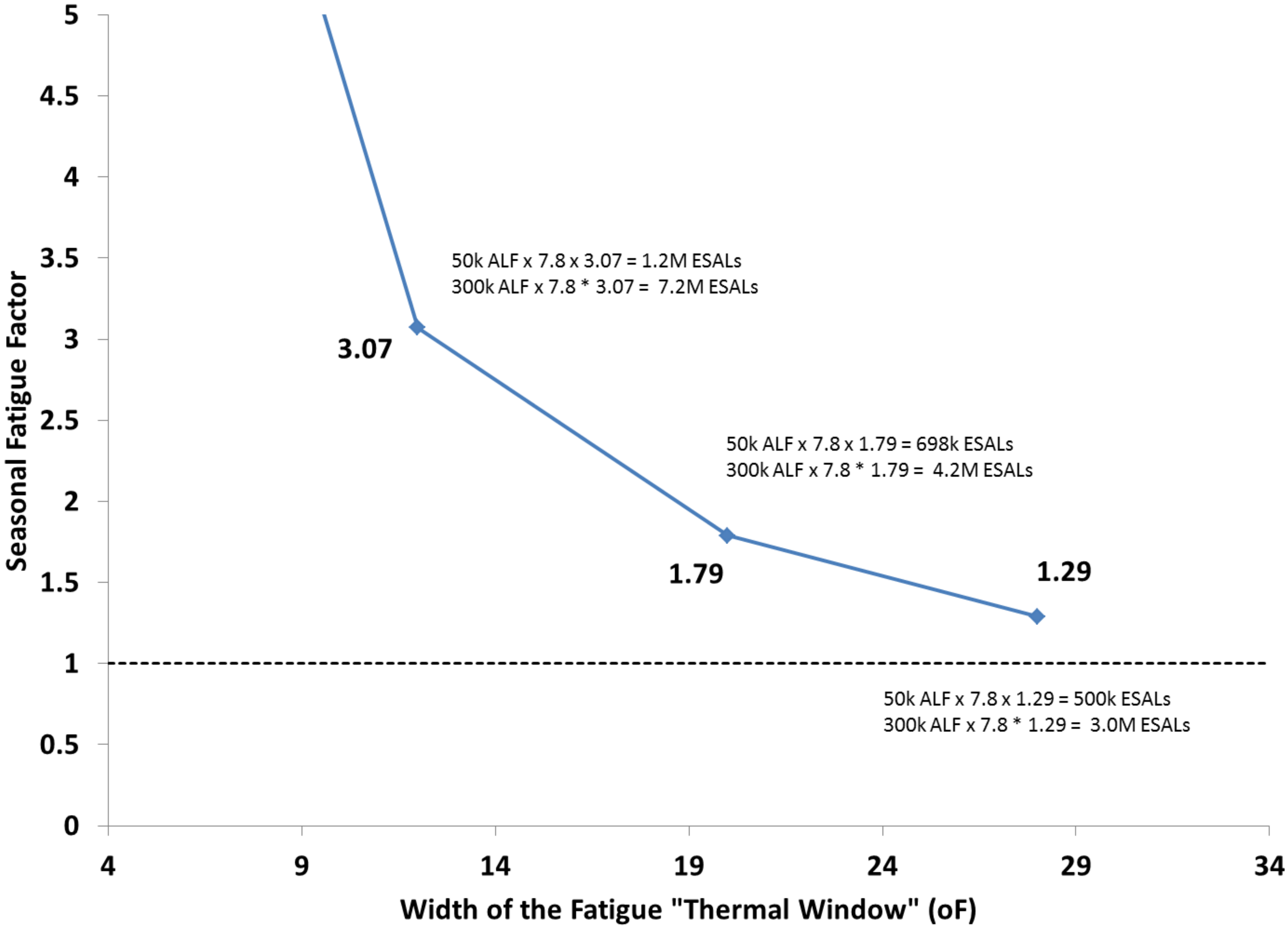


In this particular scenario, fatigue damage happened a cumulative 67% of the year

There was 33% of the year left over. And correspondingly the pavement was still subjected to the 33% additional traffic.

If the ALF represented only 1M ESAL @ it's corresponding 67% then there would be 1M/0.67 = 1.49M ESALs

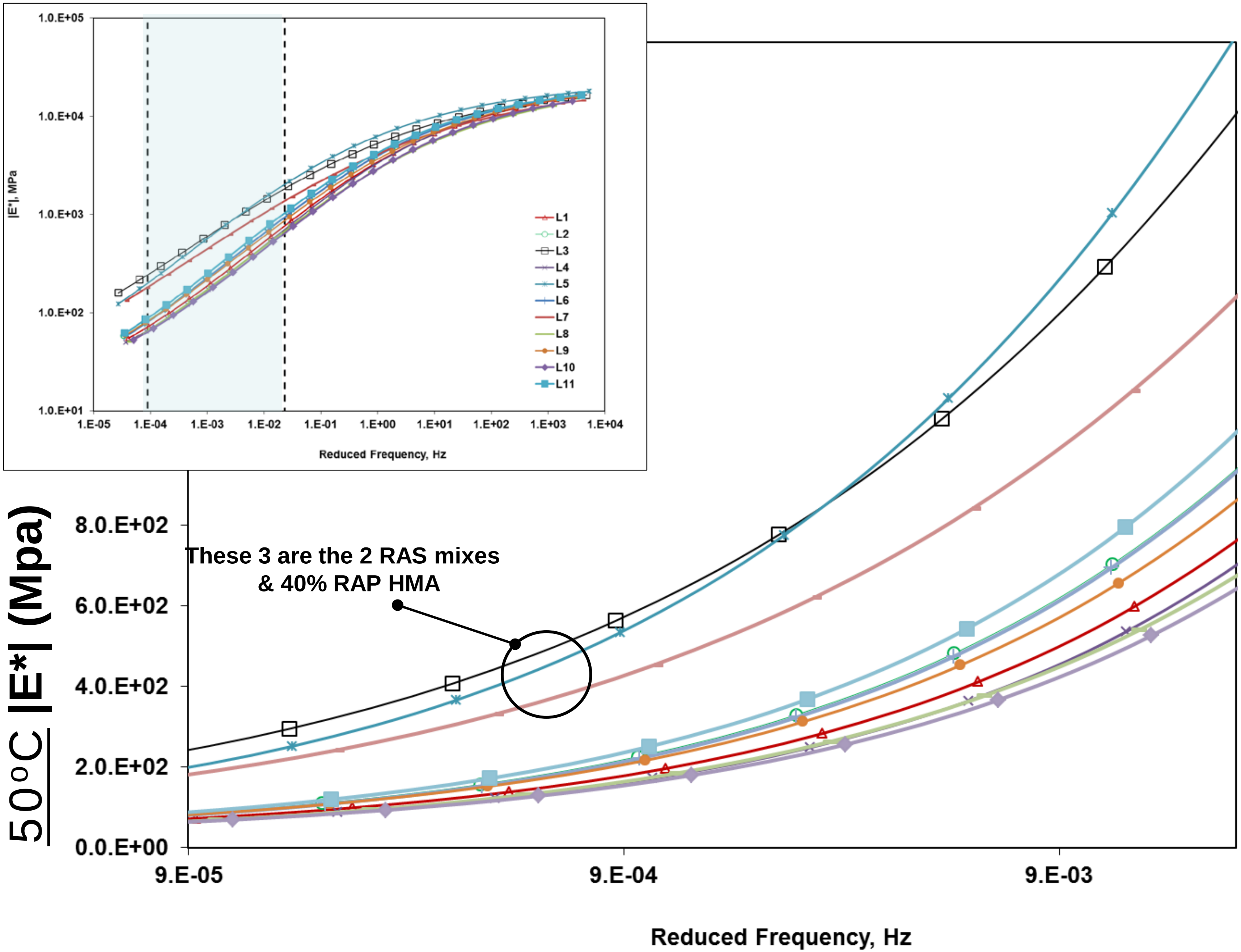
Thus a seasonal fatigue factor of 1.49


5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Seasonal Fatigue Factor
4
9
14
19
24
29
34
Width of the Fatigue "Thermal Window" (oF)
3.07
1.79
1.29
50k ALF x 7.8 x 3.07 = 1.2M ESALs
300k ALF x 7.8 * 3.07 = 7.2M ESALs
50k ALF x 7.8 x 1.79 = 698k ESALs
300k ALF x 7.8 * 1.79 = 4.2M ESALs
50k ALF x 7.8 x 1.29 = 500k ESALs
300k ALF x 7.8 * 1.29 = 3.0M ESALs

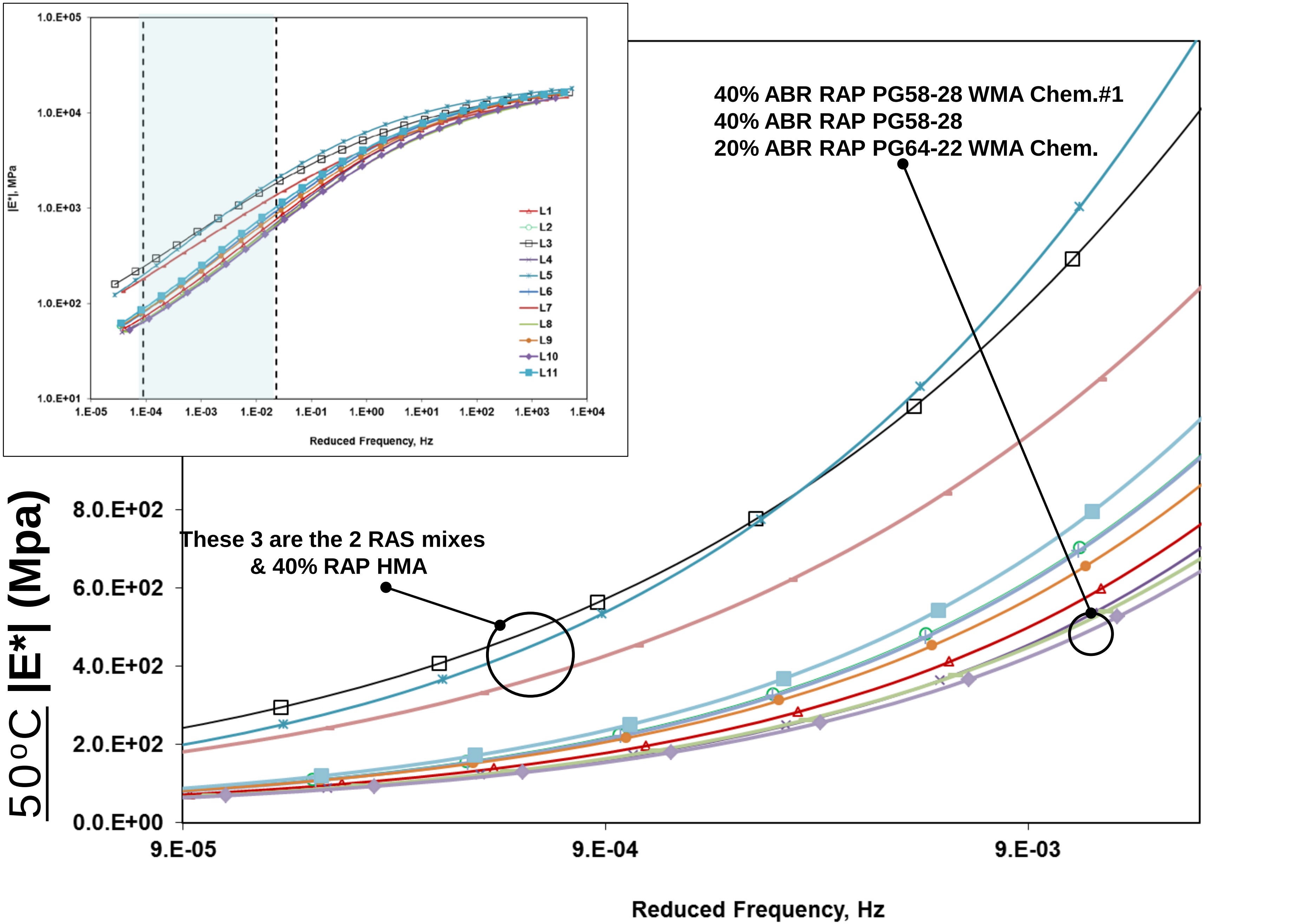
… so what does the ALF loading represent in real life?

…many empirical tools used and assumptions made, but possibly a factor of 10.

10k @ ALF corresponds 100k ESALs
100k @ ALF corresponds 1M ESALs



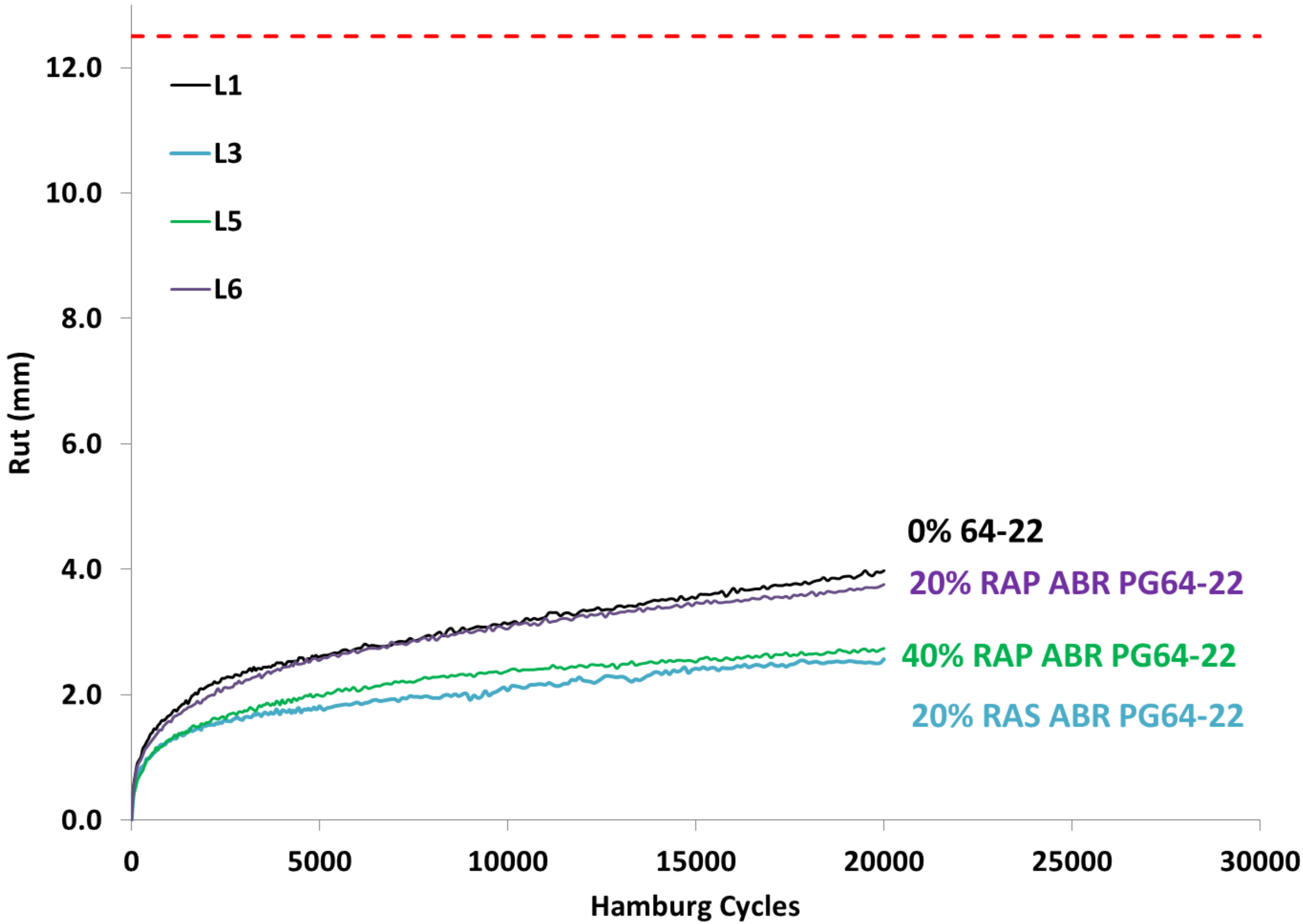
1.0.E+05
1.0.E+04
1.0.E+03
1.0.E+02
1.0.E+01
|E*|, MPa
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
Reduced Frequency, Hz
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11
50°C |E*| (Mpa)
8.0.E+02
6.0.E+02
4.0.E+02
2.0.E+02
0.0.E+00
These 3 are the 2 RAS mixes
& 40% RAP HMA
9.E-05
9.E-04
9.E-03
Reduced Frequency, Hz



40% ABR RAP PG58-28 WMA Chem.#1
40% ABR RAP PG58-28
20% ABR RAP PG64-22 WMA Chem.
These 3 are the 2 RAS mixes
& 40% RAP HMA
50°C |E*| (Mpa)
8.0.E+02
6.0.E+02
4.0.E+02
2.0.E+02
0.0.E+00
9.E-05
9.E-04
9.E-03
Reduced Frequency, Hz
|E*|, MPa
1.0.E+05
1.0.E+04
1.0.E+03
1.0.E+02
1.0.E+01
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
Reduced Frequency, Hz
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11

Effect of Recycle Content

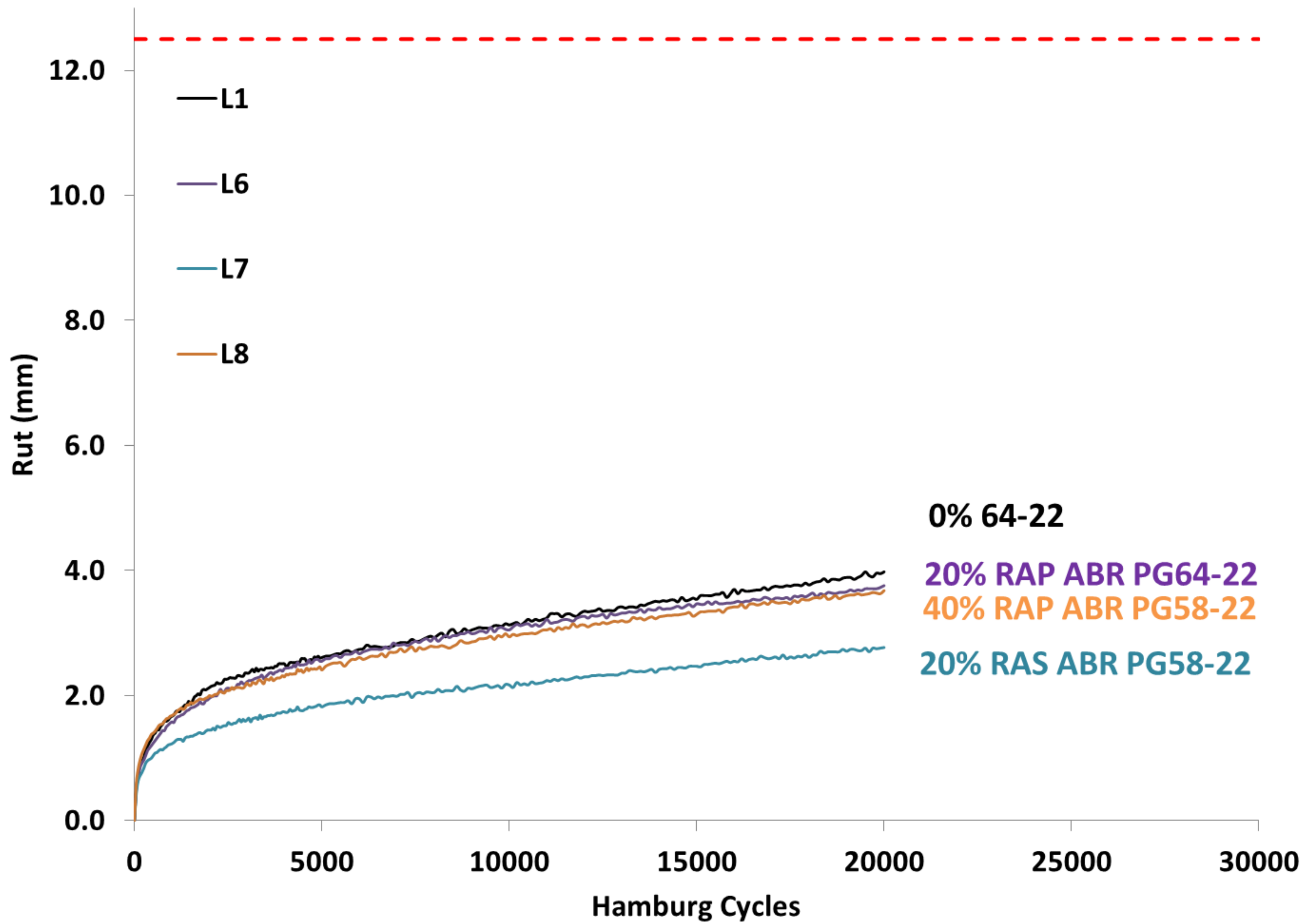
HMA / WMA — Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology / Recycle Content	-		Foam	Chem.
0%	✔ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✔ PG64-22		✔ PG64-22	✔ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✔ PG64-22	✔ PG58-28		
40% ABR RAP ≈ 44% by weight	✔ PG64-22	✔ PG58-28	✔ PG58-28	✔ PG58-28



12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut (mm)
L1
L3
L5
L6
0% 64-22
20% RAP ABR PG64-22
40% RAP ABR PG64-22
20% RAS ABR PG64-22
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles

Effect of Offset with Softer Binder PG

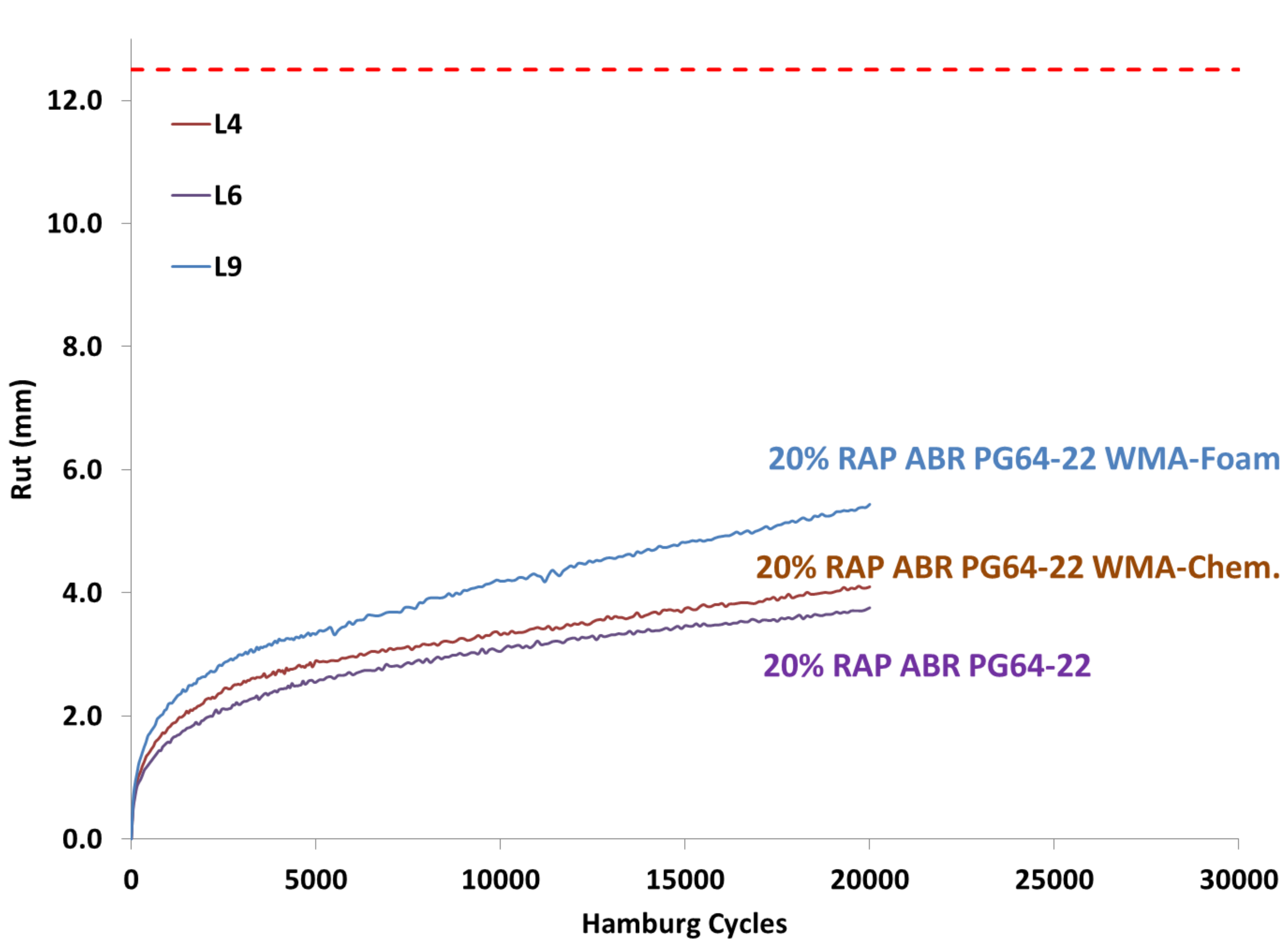
HMA / WMA Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28



12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut (mm)
L1
L6
L7
L8
0% 64-22
20% RAP ABR PG64-22
40% RAP ABR PG58-22
20% RAS ABR PG58-22
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles

Effect of WMA (1 of 2)

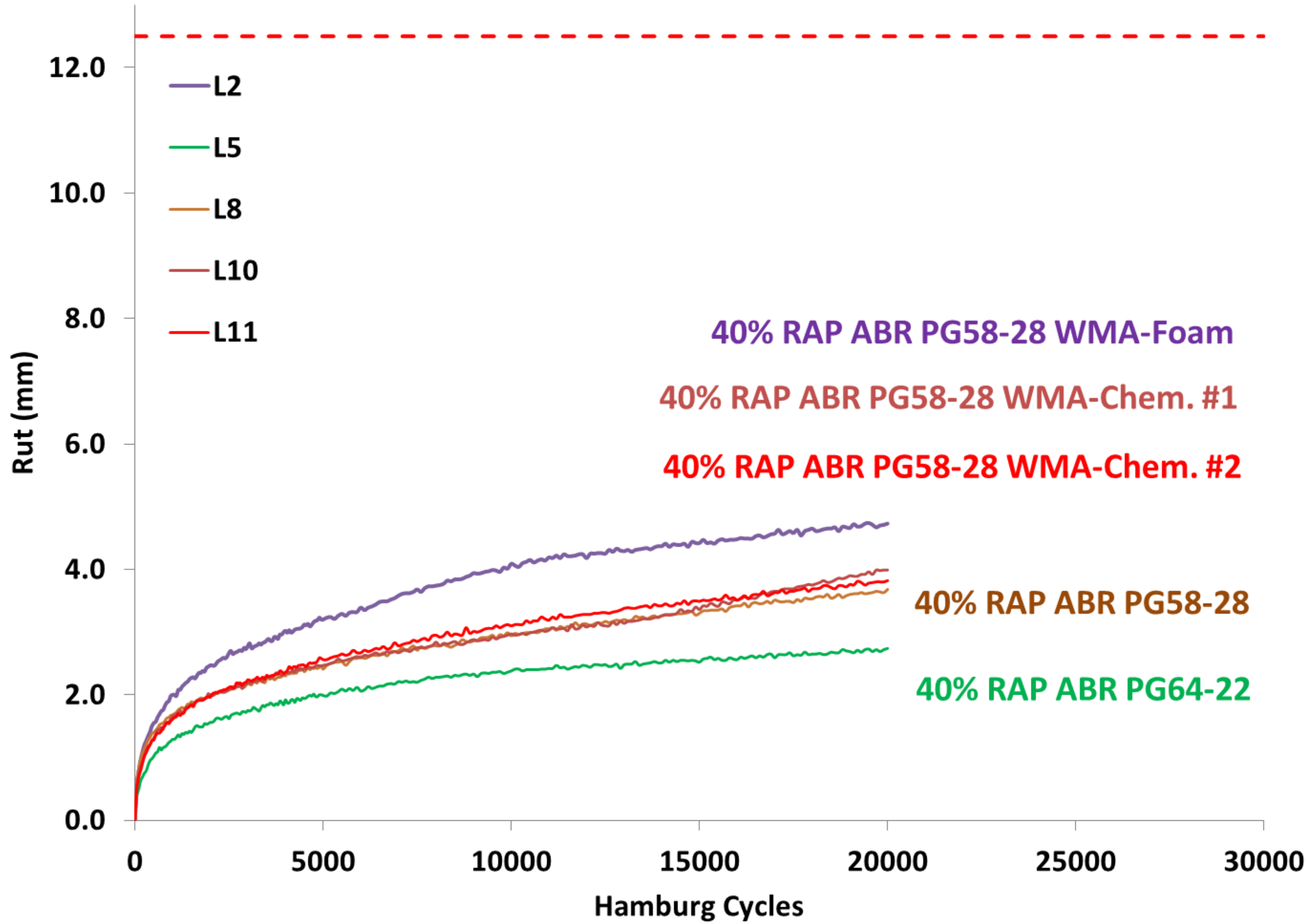
HMA / WMA Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28



12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut (mm)
L4
L6
L9
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.
20% RAP ABR PG64-22
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles

Effect of WMA (2 of 2)

HMA / WMA Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28



12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut (mm)
L2
L5
L8
L10
L11
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28 WMA-Chem. #1
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28
40% RAP ABR PG64-22
0
5000
10000
15000
20000
25000
30000
Hamburg Cycles

Outcomes

- **Material selection guidelines that provide equivalent performance to current mixtures**
- **Identify asphalt mixture laboratory tests that capture structural fatigue cracking**
- **Performance Based Mix Design**

ALL Validated with full-scale accelerated pavement tests

- Calibration Section for HMA Performance Related Specification (HMA PRS)

Performance Based Mix Design

- **Identify optimal binder content by balancing cracking and rutting (not volumetrics alone)**
- **Provide guidelines for contractors to adjust mixes to achieve the desired performance**

(%)	100% CA LUW (ALF Lane)			95% LUW CA			88% LUW CA		
Design VMA	15	14.5	14.7	14.1	13.5	13.7	12.9	12.5	12.8
Design A.V	5.3	3.8	3.0	4.9	3.7	2.9	5.1	3.9	3.1
Binder Content	4.2	4.5	4.9	3.8	4.1	4.4	3.2	3.6	3.9
G_{mm}	2.769	2.754	2.735	2.775	2.760	2.746	2.803	2.783	2.769
VFA	64.7	73.8	79.6	65.2	72.6	78.7	60.5	68.8	75.8
Performance Specimen Compacted Density	~~5.0%~~	5% **C**	5% **F**	~~5.0%~~	5% **J**	5% **M**	~~5.0%~~	5% **Q**	5% **T**
	7% **A**	7% **D**	7% **G**	7% **H**	7% **K**	7% **N**	7% **O**	7% **R**	7% **U**
	9% **B**	9% **E**	~~9.0%~~	9% **I**	9% **L**	~~9.0%~~	9% **P**	9% **S**	~~9.0%~~

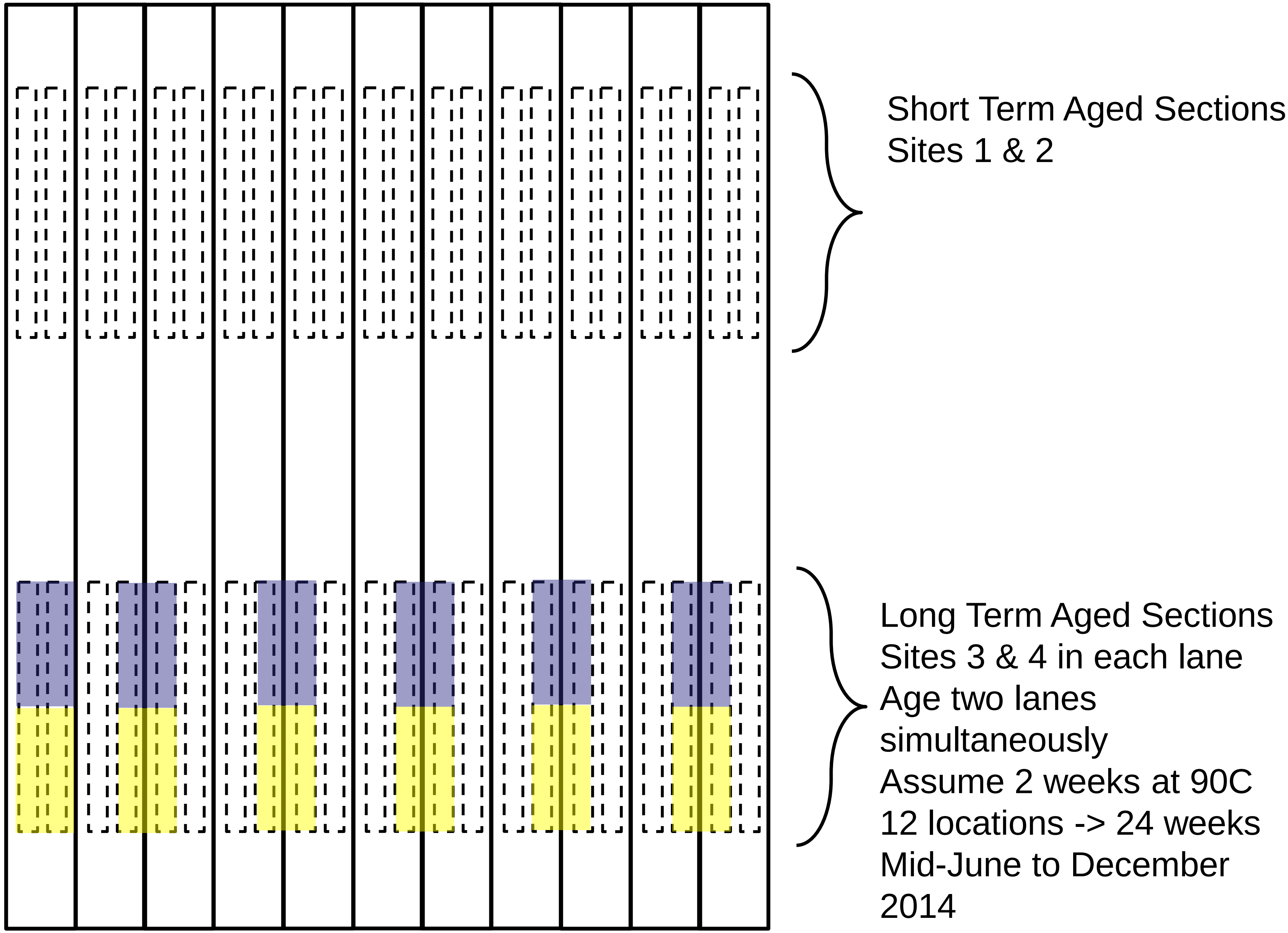
Florida DOT – Heavy Vehicle Simulator Program

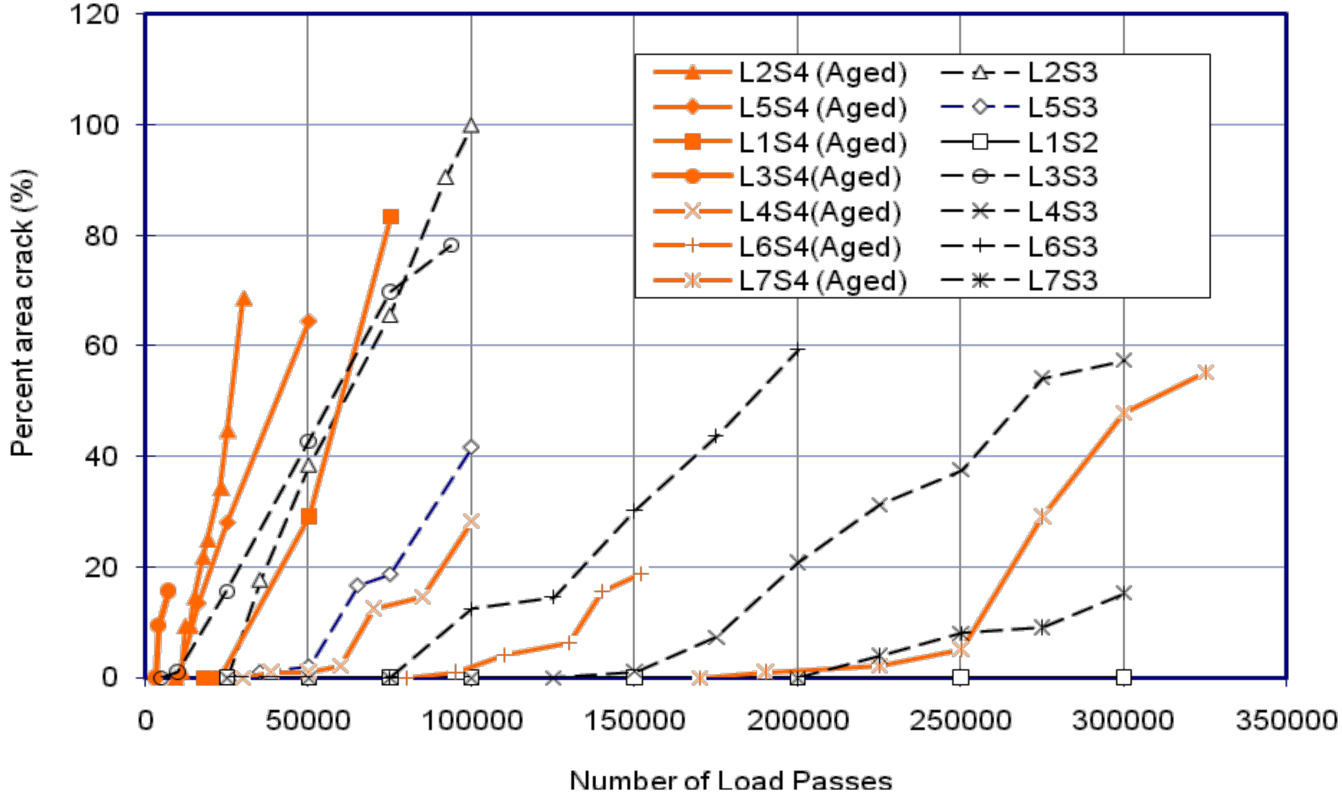
Accelerated Pavement Aging System (APAS)

10 ft by 24 ft

- Developed in 2005
- Simulate aging
  - ✓ 12 10ft long heaters
  - ✓ Maintain 90°C at 2 in. depth
- Water system
  - ✓ 65 nozzles
  - ✓ 90°C to 30°C in 7 minutes


RAYMAX


Short Term Aged Sections
Sites 1 & 2
Long Term Aged Sections
Sites 3 & 4 in each lane
Age two lanes
simultaneously
Assume 2 weeks at 90C
12 locations -> 24 weeks
Mid-June to December
2014



Best 1	CR-AZ	Fiber	Best 1
2	Fiber	Terpolymer	2
3	SBS-LG	SBS-LG	3
4	Terpolymer	CR-AZ	4
5	CR-TB	CR-TB	5
6	Control	Control	6
7 Worst	Air Blown	Air Blown	7 Worst

Unaged		Aged	
Best 1	SBS-LG	Terpolymer	Best 1
2	Terpolymer	SBS-LG	2
3	CR-TB	CR-TB	3
4	Control	Control	4
5	Air Blown	Air Blown	5

Will aging not affect the ranking of the RAP / WMA sections??

Anticipated Schedule

- Finish majority of laboratory study end 2014
- Finish ALF loading end 2015;
  - 10 ALF Lanes; each taking 1 to 3 months
- Finish project 2016

What was built?

How was it built?

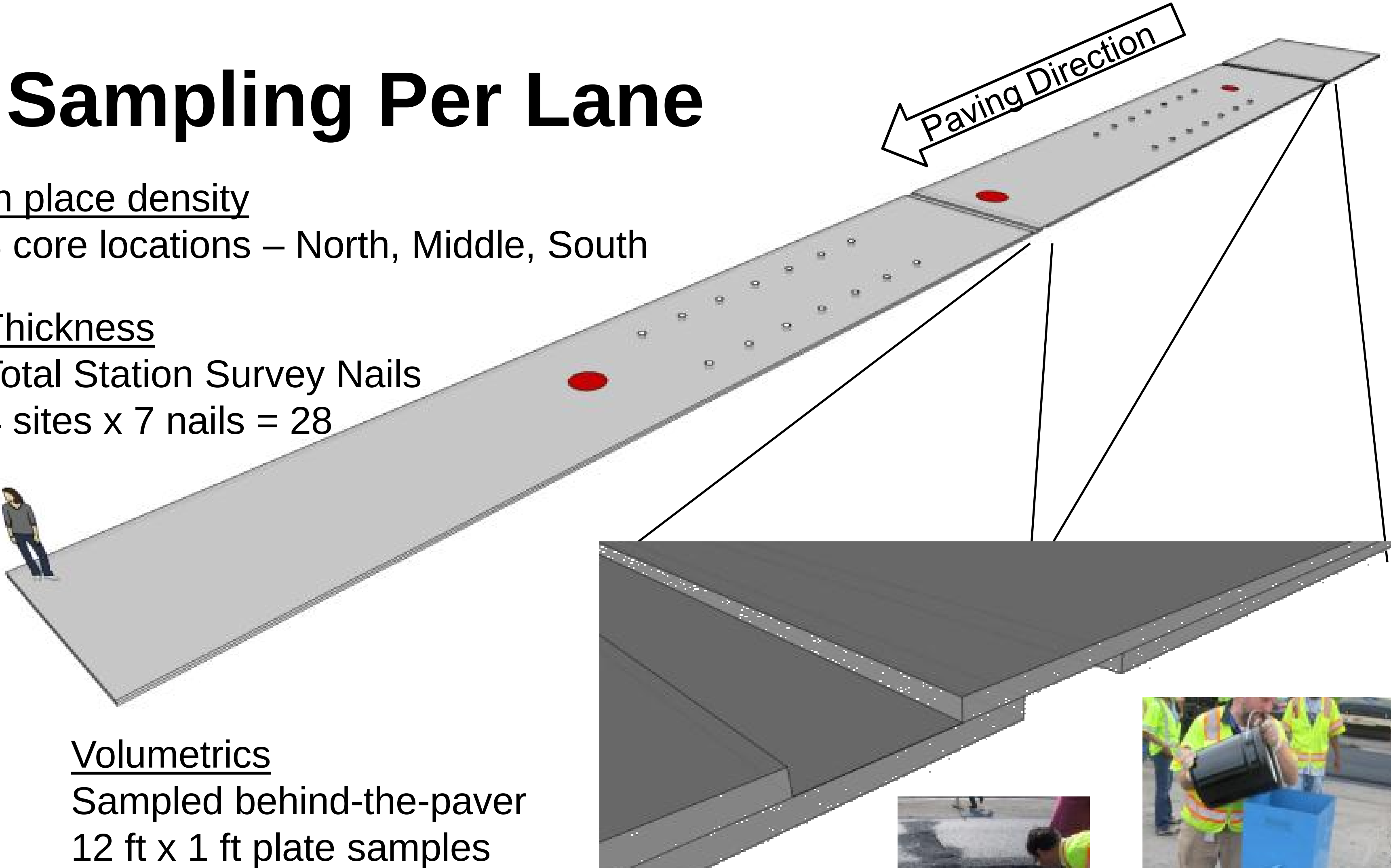
What is it saying? (so far)

FHWA Pavement Test Facility 2013 Reconstruction

- **101 calendar days**
  - Start on July 20th (milling)
  - End October 29th (striping)
- **16 : 11**
  Test Strips : ALF Lanes
- **~2,000 Total Tons of Mix**
- **~$430,000**
  + EFLHD Engineering & Construction Oversight

Finished Product

Sampling Per Lane



In place density
3 core locations – North, Middle, South

Thickness
Total Station Survey Nails
4 sites x 7 nails = 28

Volumetrics
Sampled behind-the-paver
12 ft x 1 ft plate samples
2 locations
Upper and Lower Lifts
4 buckets each plate
8 buckets to FHWA & 8 to Contractor

Stockpile Blends

	RAP	RAS	#78-A	#78-B	Screenings	Man. Sand
Control	-	-	42	22	26	10
20% ABR RAP	22	-	37	18	-	23
40% ABR RAP	44	-	33	18	5	-
20% ABR RAS	-	6	45	24	19	6

Lane 1 Vrigin Mix HMA PG64-22 (N_{design} = 65 Gyrations)

Dimension (mm)	Sieve Size	Sieve Size^0.45	Approved Mix Design: General Limits Bottom	General Limits Up	JMF Range Bottom	JMF Range Up	Target Value	Blend Percentage / Aggregate ID / Description	RAP (6549) 0.0	Shingles (6550) 0.0	Loudoun #78 (6551) 42.0	Dust (6552) 26.0	Manufactured Sand (6553) 10.0	Chantilly #78 (6555) 22.0	Blend Gradation (Total 100%)	Meet JMF?	Sieve Analysis from Acceptance: Bottom Lift	Top Lift	Average	Meet JMF?
37.5	11/2 inch	5.11	100	100	100	100	100	Virgin Mix PG64-22	100.0	100.0	100.0	100.0	100.0	100.0	100.0	Yes	100.0	100.0	100.0	Yes
25	1 inch	4.26	100	100	100	100	100		100.0	100.0	100.0	100.0	100.0	100.0	100.0	Yes	100.0	100.0	100.0	Yes
19	3/4 inch	3.76	100	100	100	100	100		100.0	100.0	100.0	100.0	100.0	100.0	100.0	Yes	100.0	100.0	100.0	Yes
12.5	1/2 inch	3.12	90	100	90	100	97		97.5	100.0	99.8	100.0	100.0	94.6	98.7	Yes	98.0	98.5	98.3	Yes
9.5	3/8 inch	2.75		90	82	90	86		91.6	100.0	91.5	100.0	100.0	66.1	89.0	Yes	86.1	86.4	86.2	Yes
4.75	# 4	2.02			41	55	48		67.2	99.2	27.9	95.7	98.1	11.9	49.1	Yes	47.1	48.1	47.6	Yes
2.36	# 8	1.47	28	58	26	34	30		49.5	97.4	5.3	69.3	67.6	2.1	27.5	Yes	28.7	28.8	28.8	Yes
1.18	# 16	1.08			18	24	21		37.5	80.9	3.6	49.6	41.7	2.0	19.0	Yes	20.1	20.1	20.1	Yes
0.6	# 30	0.79			13	19	16	Paving Date: 08/27/2013	28.4	60.2	3.0	36.6	26.0	2.0	13.8	Yes	15.0	15.0	15.0	Yes
0.3	# 50	0.58			9	15	12		20.4	53.0	2.7	26.1	15.1	1.9	9.8	Yes	11.0	11.0	11.0	Yes
0.15	# 100	0.43					8		14.6	44.9	2.3	17.9	8.2	1.8	6.9		7.8	7.8	7.8	
0.075	#200	0.31	3	8	4	8	6		10.3	34.6	1.8	11.6	4.7	1.6	4.6	Yes	5.3	5.3	5.3	Yes

Design Mix Requirements

Parameter	Tolerance		Target
G_{mm}	+0.015	-0.015	2.735
Air Voids	+1%	-1%	4.0
G_{mb}	+0.044	-0.044	2.632
G_{sb}	---		2.979
P_{ba}	+0.2	-0.2	5.00
VMA	>14		15.7
VFA	65	78	76.7
DB Ratio	0.6	1.8	1.2

Acceptance Tests

Parameter	Bottom Lift Value	Bottom Lift Pass?	Top Lift Value	Top Lift Pass?	Average Value	Average Pass?
G_{mm}	2.747	Yes	2.753	NO	2.750	Yes
Air Voids	3.91	Yes	4.64	Yes	4.28	Yes
G_{mb}	2.640	Yes	2.626	Yes	2.633	Yes
G_{sb}	---	---	---	---	2.977	---
P_{ba}	5.14	Yes	5.02	Yes	5.08	Yes
VMA	15.89	Yes	16.24	Yes	16.07	Yes
VFA	75.42	Yes	71.46	Yes	73.44	Yes
DB Ratio	1.03	Yes	1.05	Yes	1.04	Yes

Core #	Lift	Air Voids	Pass?
2	Overall	7.16	Yes
	Top	7.89	Yes
	Bottom	5.98	NO
1	Overall	6.7	Yes
	Top	6.93	Yes
	Bottom	5.7	NO
3	Overall	6.45	Yes
	Top	6.86	Yes
	Bottom	5.6	NO

Lane 1 Vrigin Mix HMA PG64-22 (N_{design} = 65 Gyrations)

Detailed Sheets Available for Each Lane … and for each parking lot test strip

Too cumbersome for a presentation overview

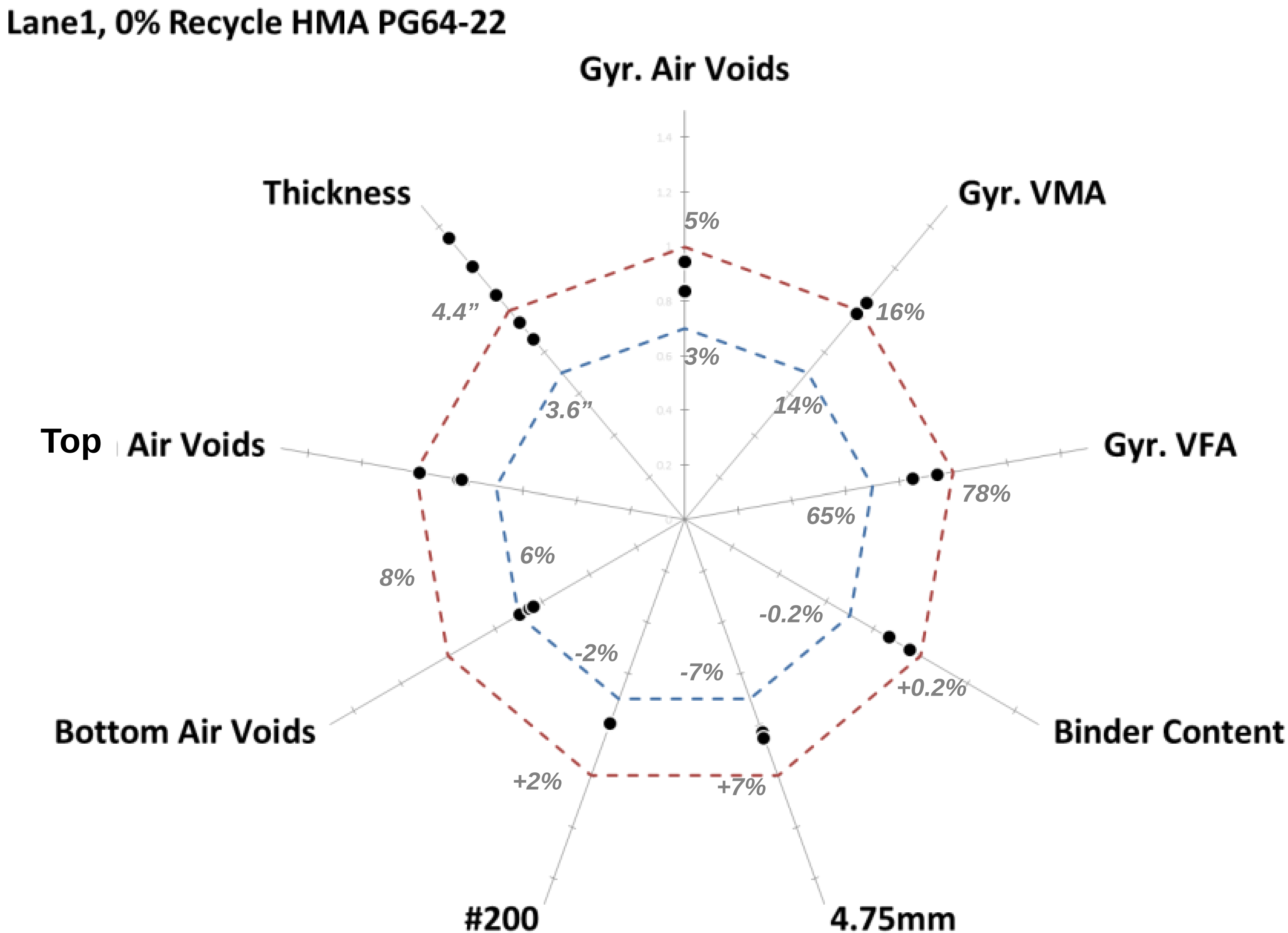
Dimension (mm)	Sieve Size	Sieve Size^0.45	Approved Mix Design: General Limits Bottom	General Limits Up	JMF Range Bottom	JMF Range Up	Target Value	Blend Percentage / Aggregate ID / Description	0.0 / 6549 / RAP	0.0 / 6550 / Shingles	42.0 / 6551 / Loudoun #78	26.0 / 6552 / Dust	10.0 / 6553 / Manufactured Sand	22.0 / 6555 / Chantilly #78	Total 100% / Blend Gradation	Meet JMF?	Sieve Analysis from Acceptance: Bottom Lift	Top Lift	Average	Meet JMF?
37.5	11/2 inch	5.11	100	100	100	100	100		100.0	100.0	100.0	100.0	100.0	100.0	100.0	Yes	100.0	100.0	100.0	Yes
25	1 inch	4.26	100	100	100	100	100												100.0	Yes
19	3/4 inch	3.76	100	100	100	100	100												100.0	Yes
12.5	1/2 inch	3.12	90	100	90	100	97												98.3	Yes
9.5	3/8 inch	2.75		90	82	90	86												86.2	Yes
4.75	# 4	2.02			41	55	48												47.6	Yes
2.36	# 8	1.47	28	58	26	34	30												28.8	Yes
1.18	# 16	1.08			18	24	21												20.1	Yes
0.6	# 30	0.79			13	19	16												15.0	Yes
0.3	# 50	0.58			9	15	12												11.0	Yes
0.15	# 100	0.43					8												7.8	
0.075	#200	0.31	3	8	4	8	6												5.3	Yes

Design Mix Requirements

Parameter	Tolerance		Target
G_{mm}	+0.015	-0.015	2.735
Air Voids	+1%	-1%	4.0
G_{mb}	+0.044	-0.044	2.632
G_{sb}	---		2.979
P_{ba}	+0.2	-0.2	5.00
VMA	>14		15.7
VFA	65	78	76.7
DB Ratio	0.6	1.8	1.2

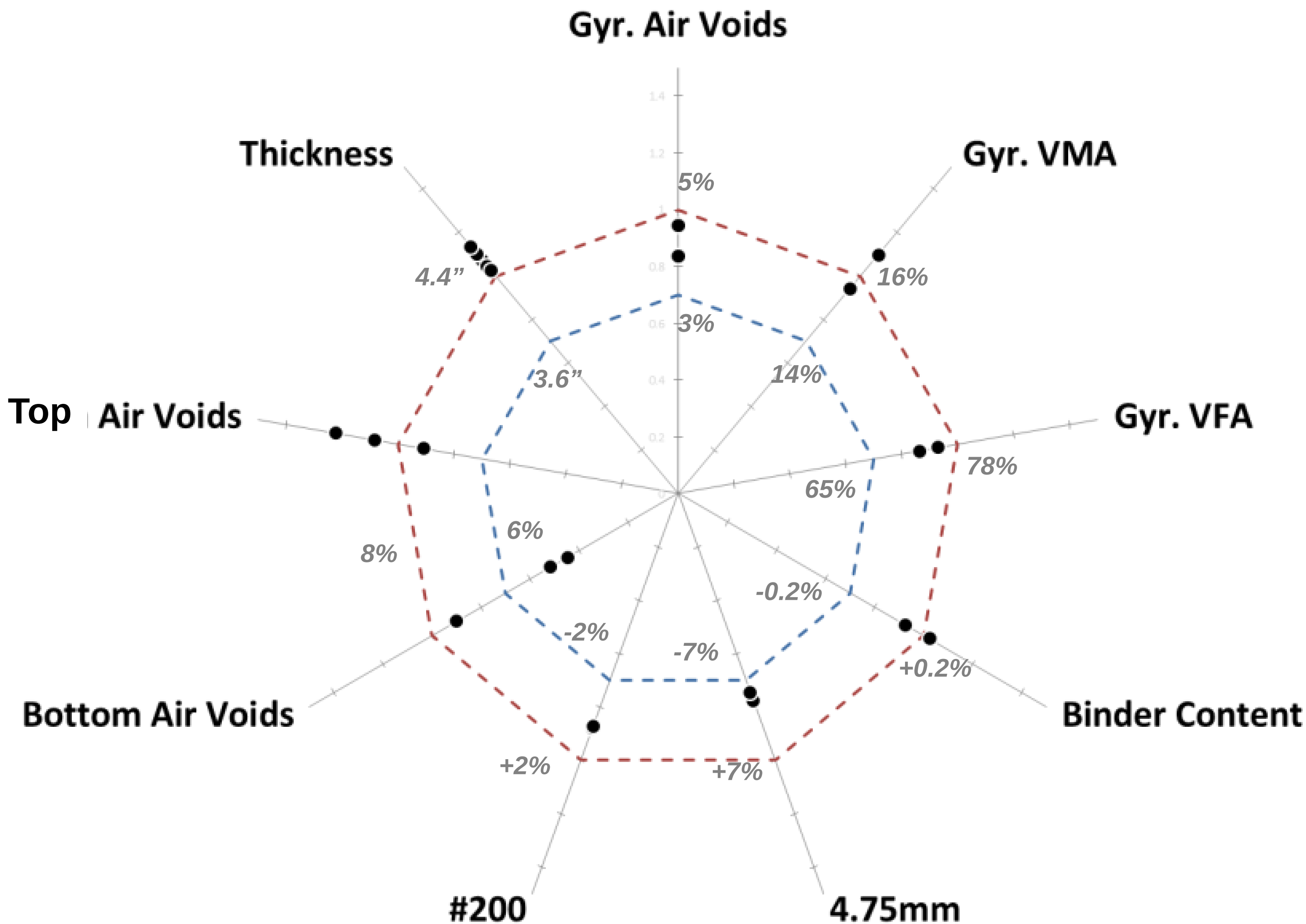
Tests

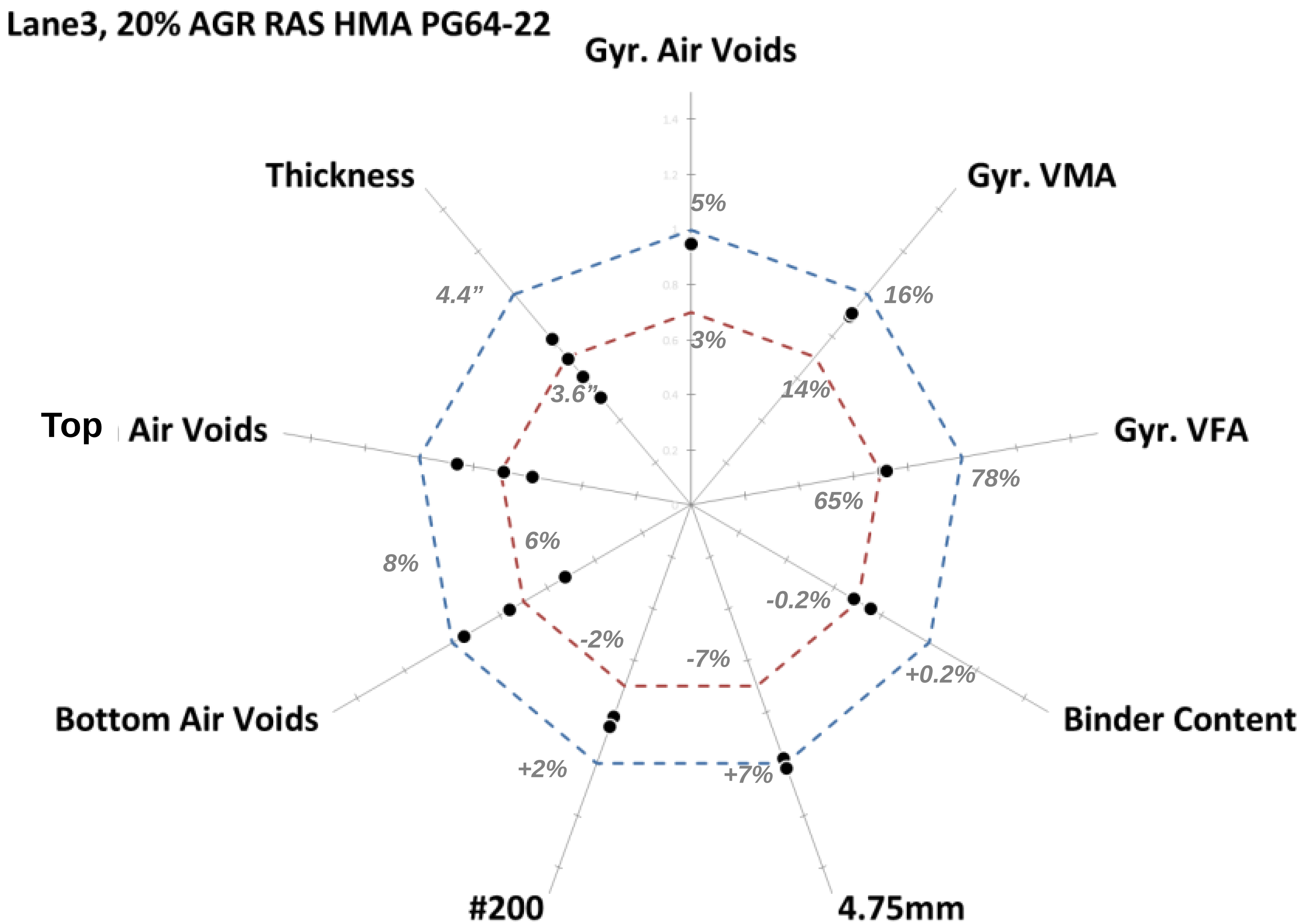
									Air Voids	Pass?
								…ll	7.16	Yes
									7.89	Yes
								…m	5.98	NO
G_{mb}								…ll	**6.7**	Yes
G_{sb}	---	---	---	---	*2.977*	---	1	Top	6.93	Yes
P_{ba}	5.14	Yes	5.02	Yes	*5.08*	Yes		Bottom	5.7	NO
VMA	15.89	Yes	16.24	Yes	*16.07*	Yes	3	Overall	6.45	Yes
VFA	75.42	Yes	71.46	Yes	*73.44*	Yes		Top	6.86	Yes
DB Ratio	1.03	Yes	1.05	Yes	*1.04*	Yes		Bottom	5.6	NO

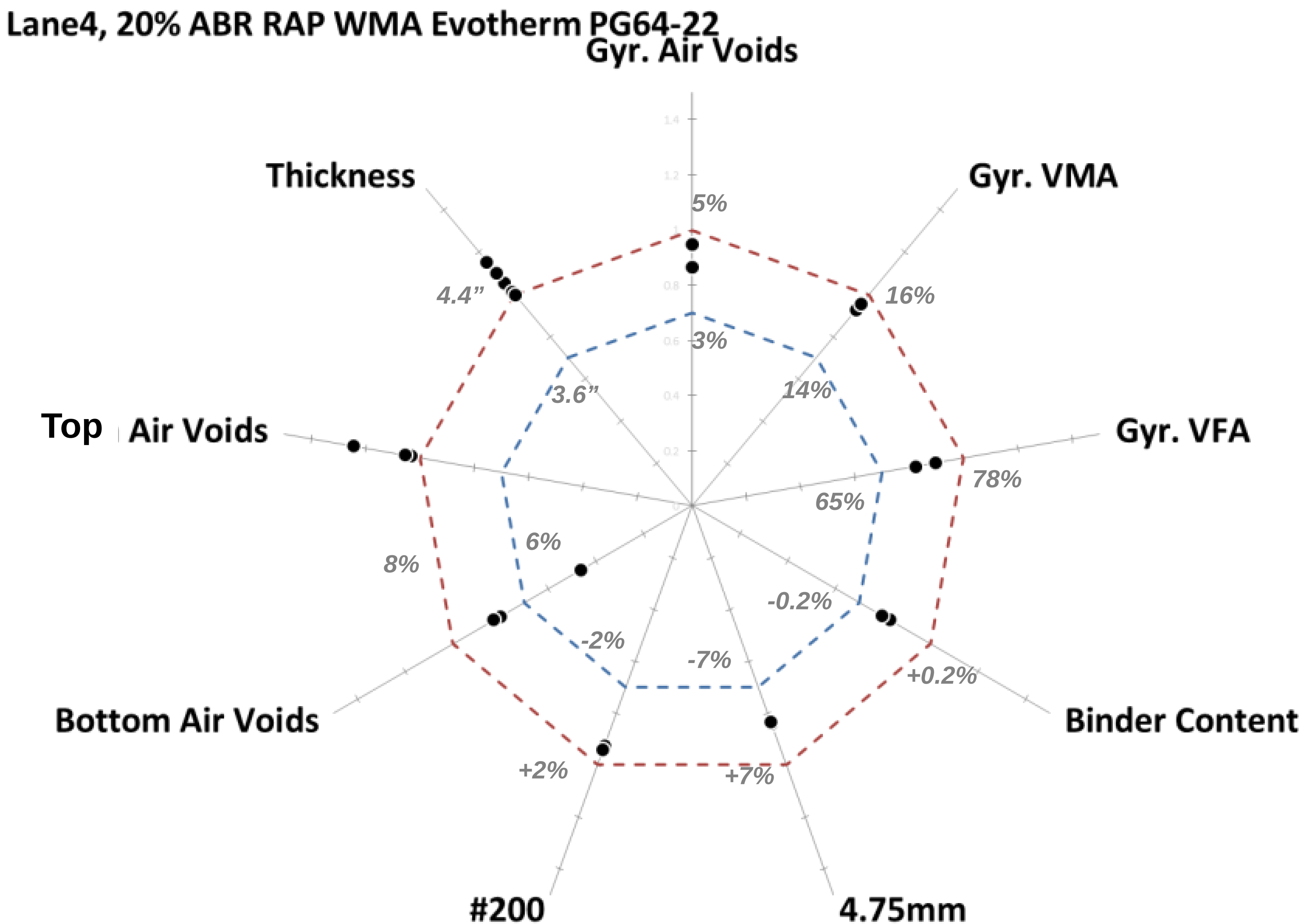


Lane1, 0% Recycle HMA PG64-22
Gyr. Air Voids
Gyr. VMA
Gyr. VFA
Binder Content
4.75mm
#200
Bottom Air Voids
Top Air Voids
Thickness
5%
3%
16%
14%
78%
65%
-0.2%
+0.2%
-7%
+7%
-2%
+2%
6%
8%
4.4”
3.6”

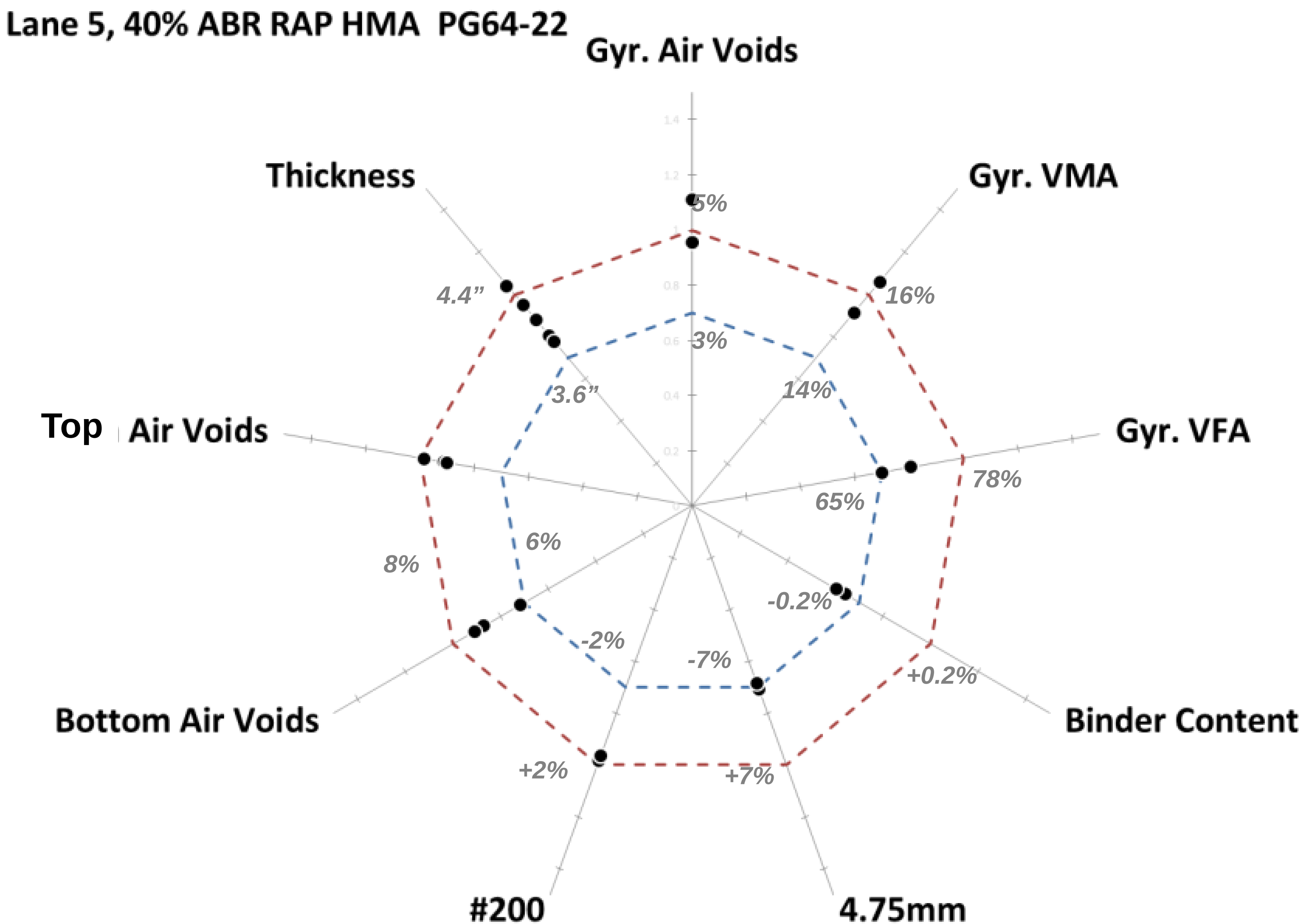
Lane2, 40% ABR RAP Foam PG58-28



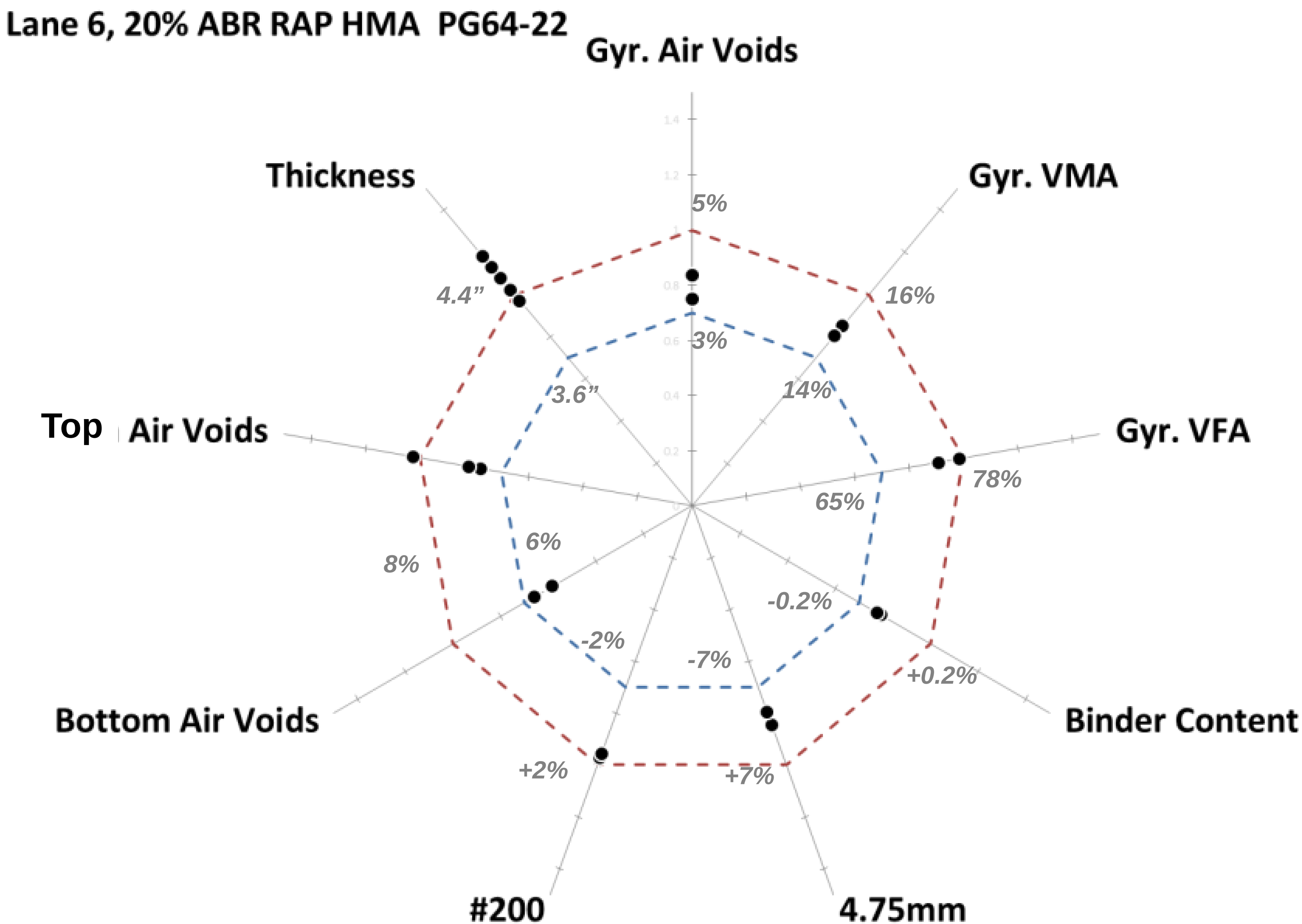

Lane3, 20% AGR RAS HMA PG64-22
Gyr. Air Voids
5%
3%
Gyr. VMA
16%
14%
Gyr. VFA
78%
65%
Binder Content
-0.2%
+0.2%
4.75mm
-7%
+7%
#200
-2%
+2%
Bottom Air Voids
6%
8%
Top Air Voids
Thickness
4.4”
3.6”



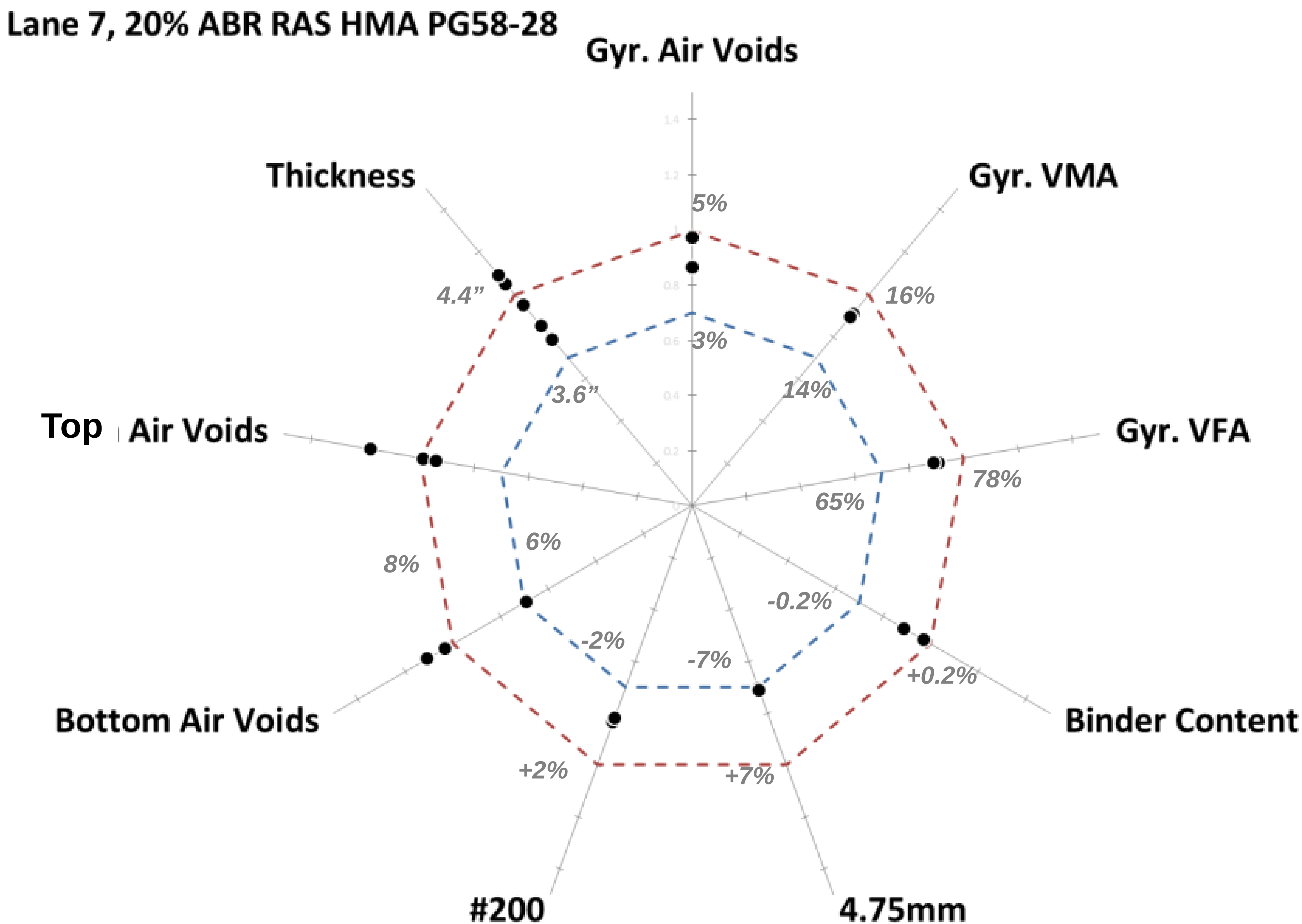
Lane4, 20% ABR RAP WMA Evotherm PG64-22
Gyr. Air Voids
Gyr. VMA
Gyr. VFA
Binder Content
4.75mm
#200
Bottom Air Voids
Top Air Voids
Thickness
5%
3%
16%
14%
78%
65%
-0.2%
+0.2%
-7%
+7%
-2%
+2%
6%
8%
4.4”
3.6”

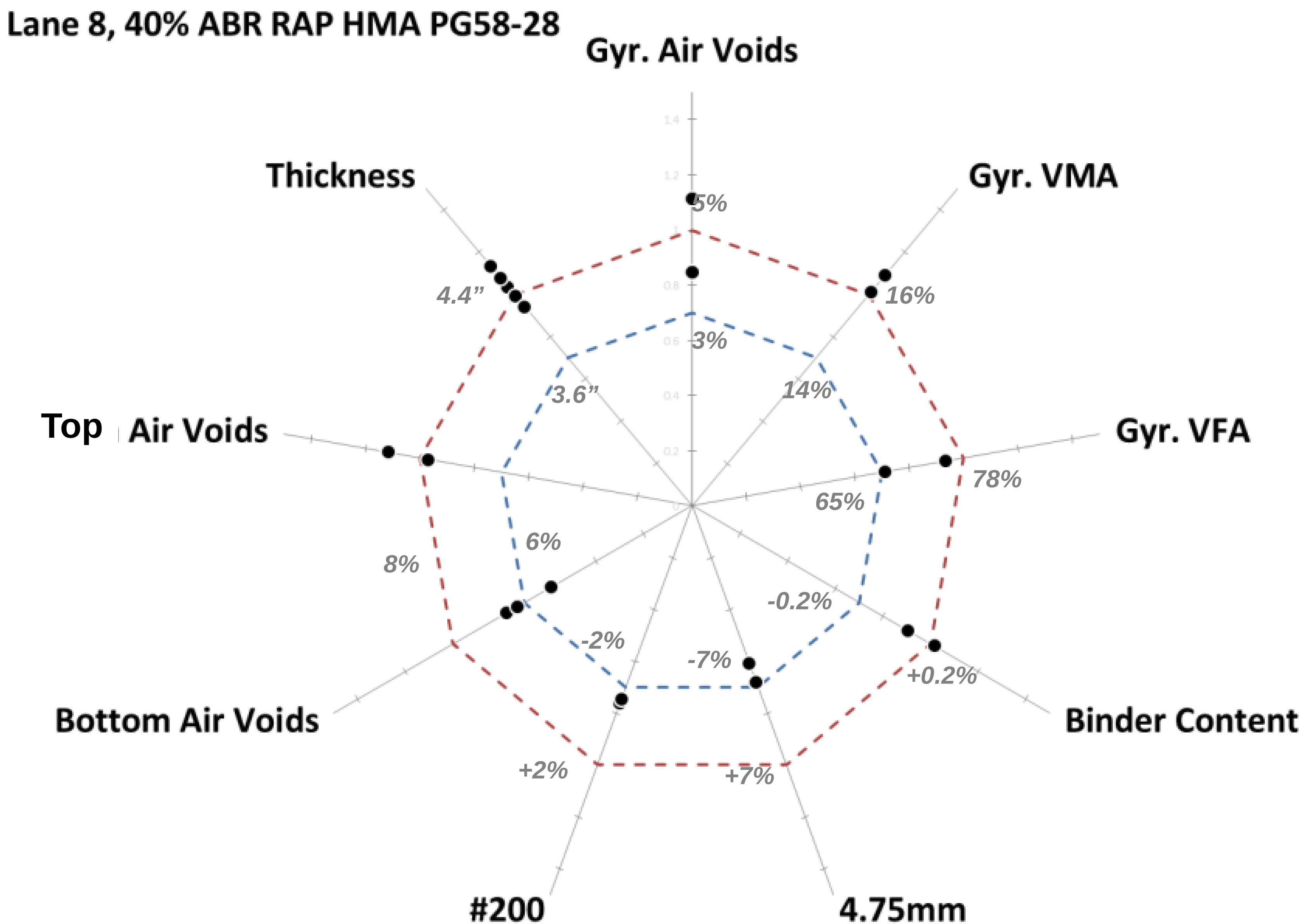


Lane 5, 40% ABR RAP HMA PG64-22
Gyr. Air Voids
Gyr. VMA
Gyr. VFA
Binder Content
4.75mm
#200
Bottom Air Voids
Top Air Voids
Thickness
5%
3%
16%
14%
78%
65%
-0.2%
+0.2%
-7%
+7%
-2%
+2%
6%
8%
4.4"
3.6"

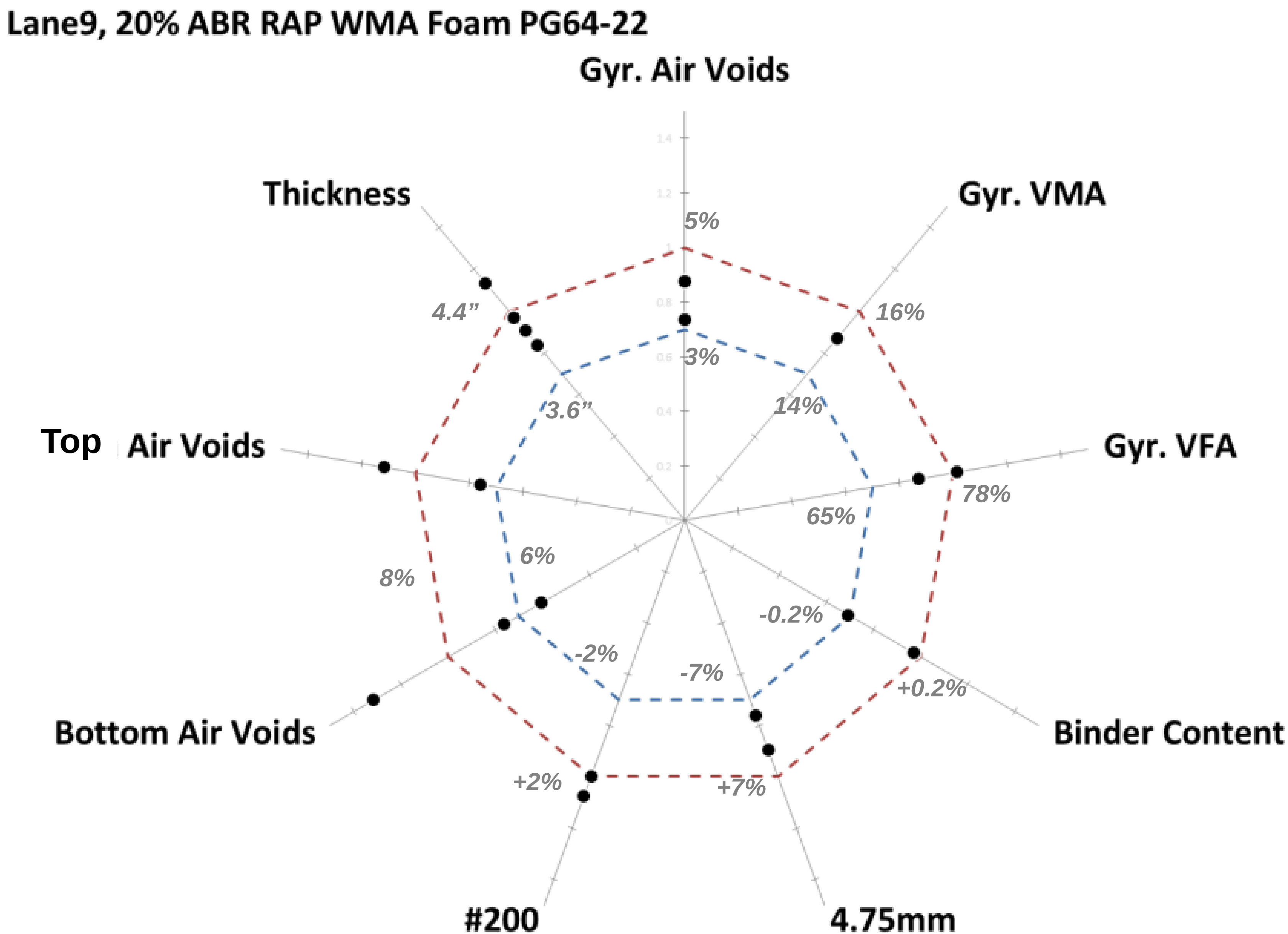


Lane 6, 20% ABR RAP HMA PG64-22
Gyr. Air Voids
Gyr. VMA
Gyr. VFA
Binder Content
4.75mm
#200
Bottom Air Voids
Top Air Voids
Thickness
5%
3%
16%
14%
78%
65%
-0.2%
+0.2%
-7%
+7%
-2%
+2%
6%
8%
4.4"
3.6"

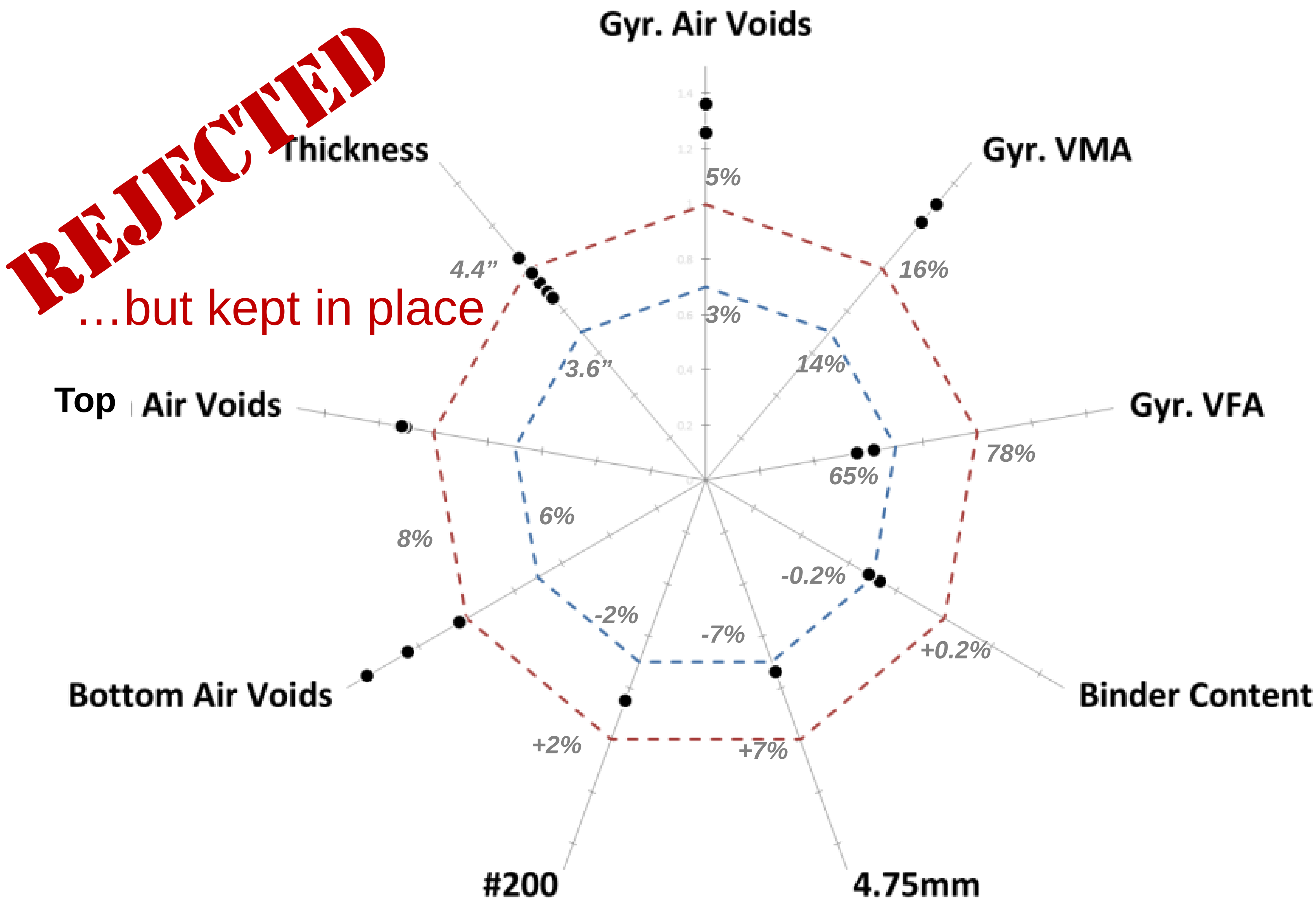

Lane 7, 20% ABR RAS HMA PG58-28
Gyr. Air Voids
Gyr. VMA
Gyr. VFA
Binder Content
4.75mm
#200
Bottom Air Voids
Top Air Voids
Thickness
5%
3%
16%
14%
78%
65%
-0.2%
+0.2%
-7%
+7%
-2%
+2%
6%
8%
4.4”
3.6”



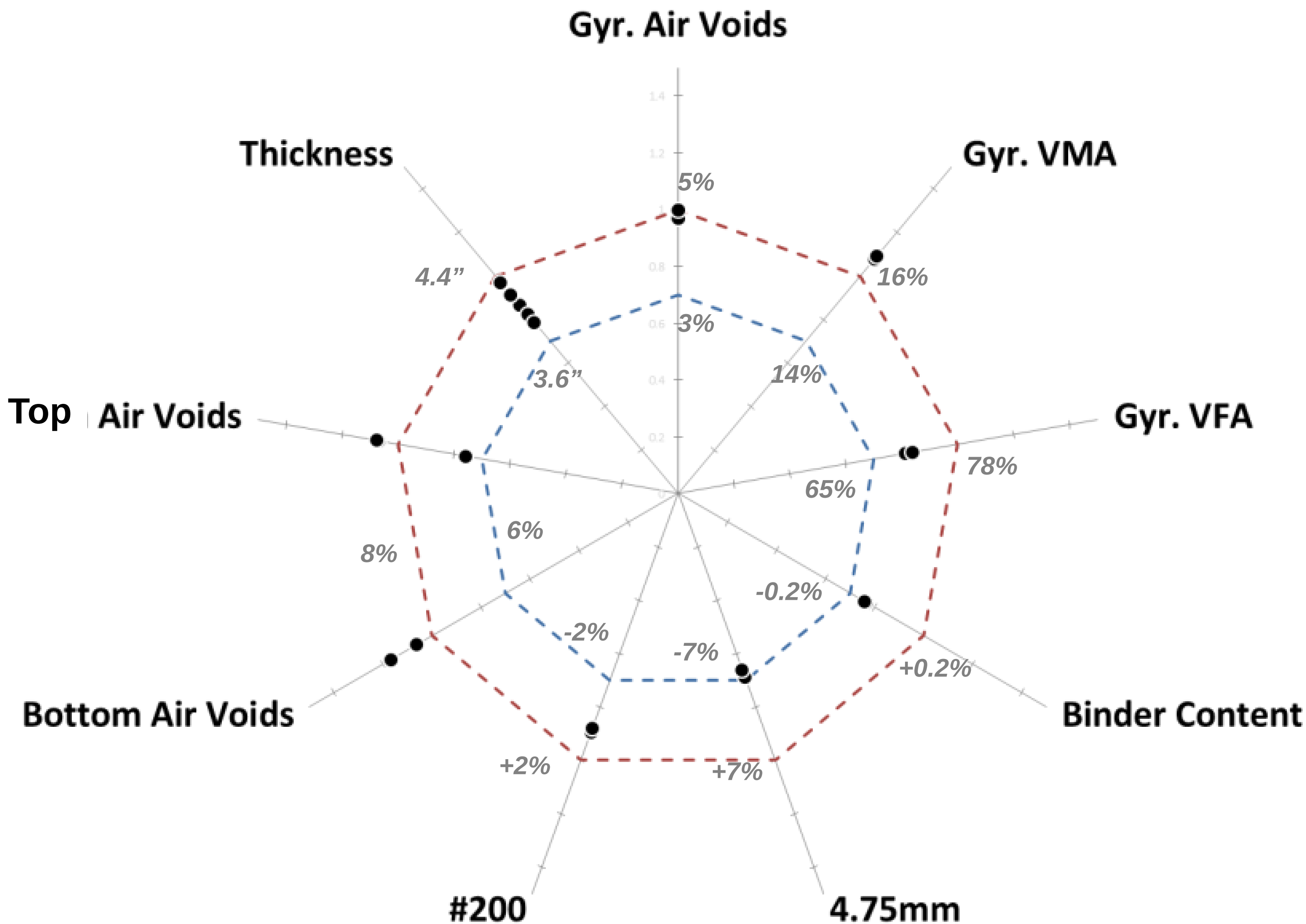
Lane 8, 40% ABR RAP HMA PG58-28
Gyr. Air Voids
Gyr. VMA
Gyr. VFA
Binder Content
4.75mm
#200
Bottom Air Voids
Top Air Voids
Thickness
5%
3%
16%
14%
78%
65%
-0.2%
+0.2%
-7%
+7%
-2%
+2%
6%
8%
3.6”
4.4”


Lane9, 20% ABR RAP WMA Foam PG64-22
Gyr. Air Voids
5%
3%
Gyr. VMA
16%
14%
Gyr. VFA
78%
65%
Binder Content
-0.2%
+0.2%
4.75mm
-7%
+7%
#200
-2%
+2%
Bottom Air Voids
Top Air Voids
8%
6%
Thickness
4.4"
3.6"

Lane 10, 40% ABR RAP WMA Evotherm PG58-28



Lane 11, 40% ABR RAP WMA Evotherm PG58-28 (#2)

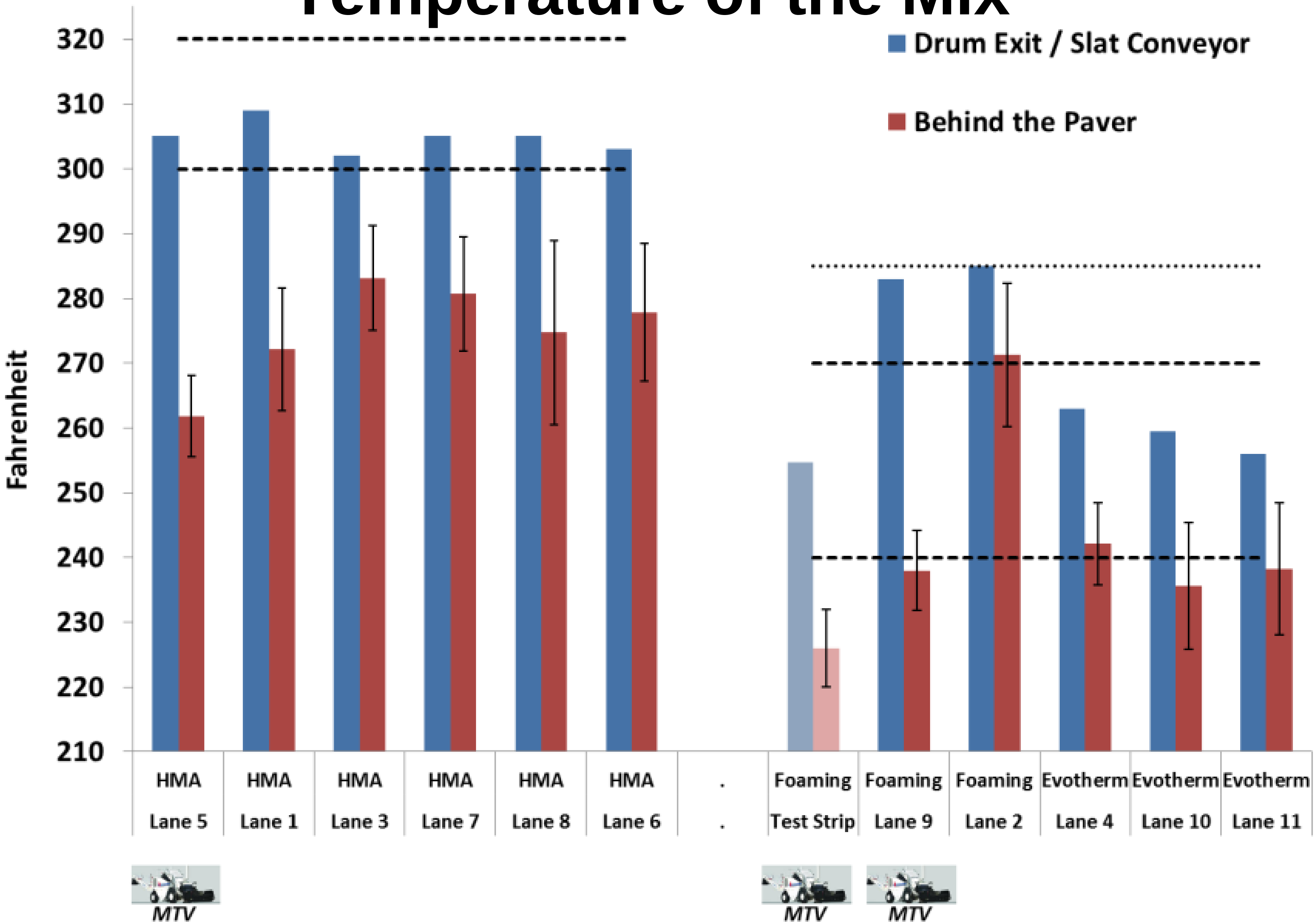


Temperature of the Mix

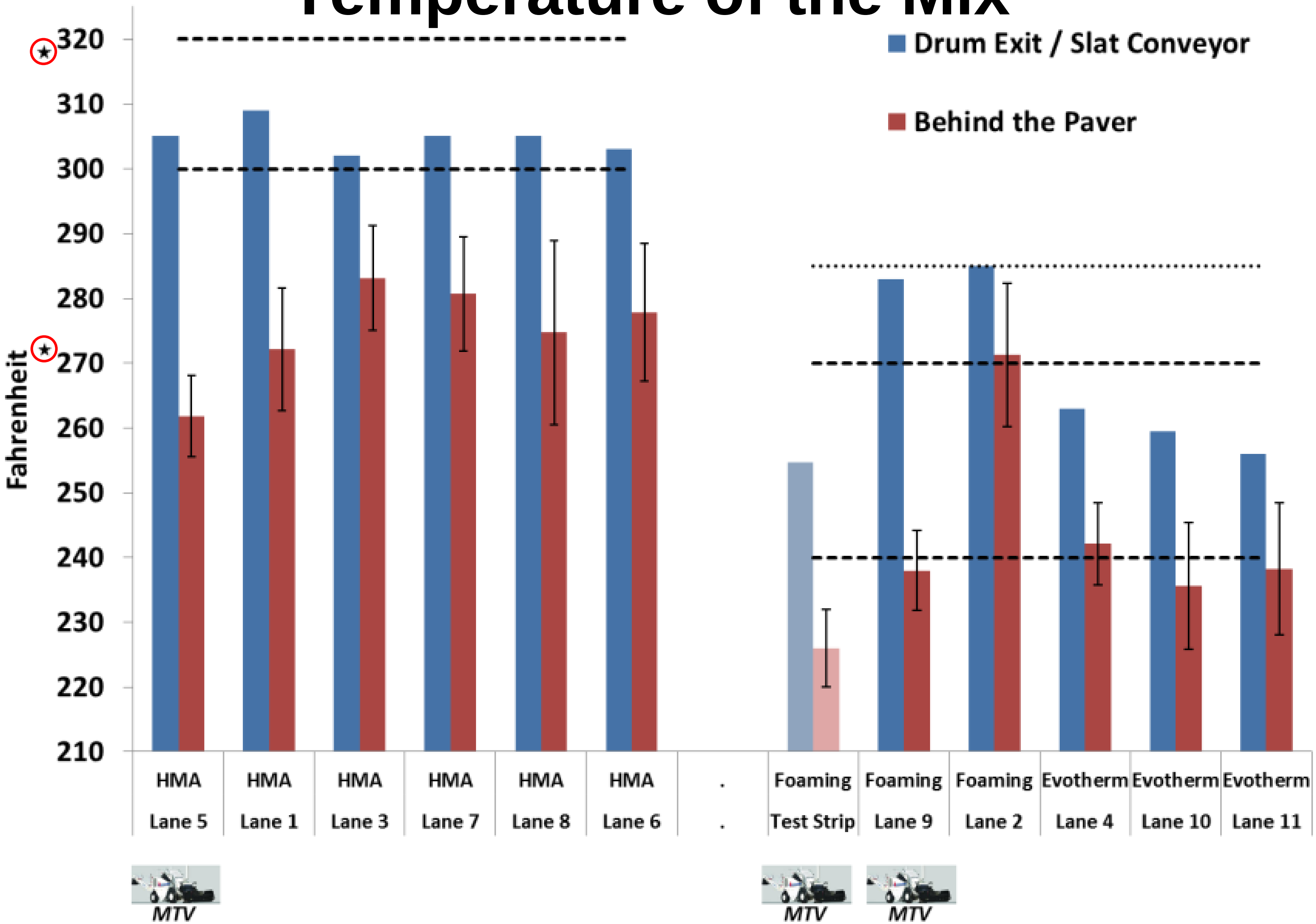
Drum Exit / Slat Conveyor

Behind the Paver

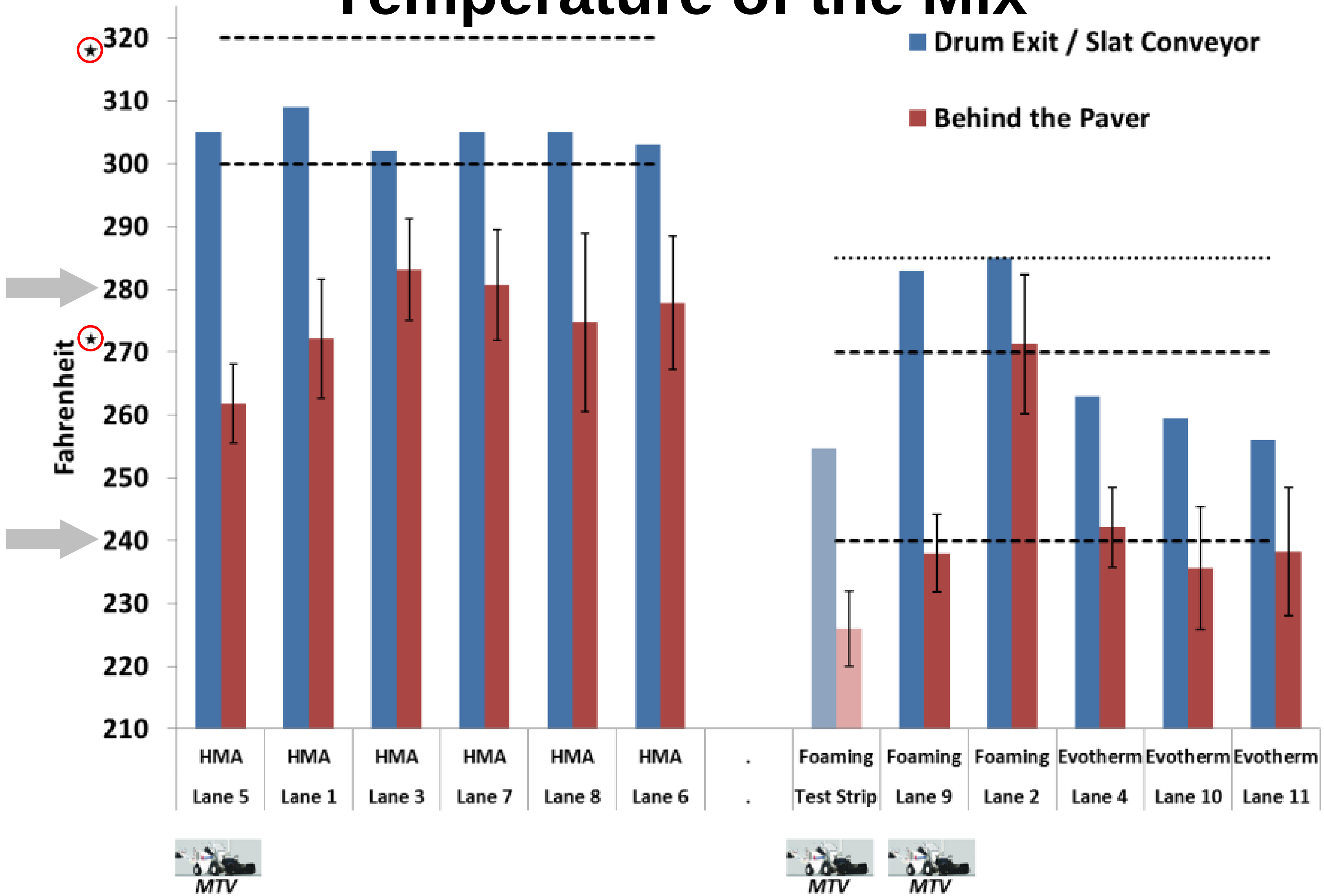
Temperature of the Mix



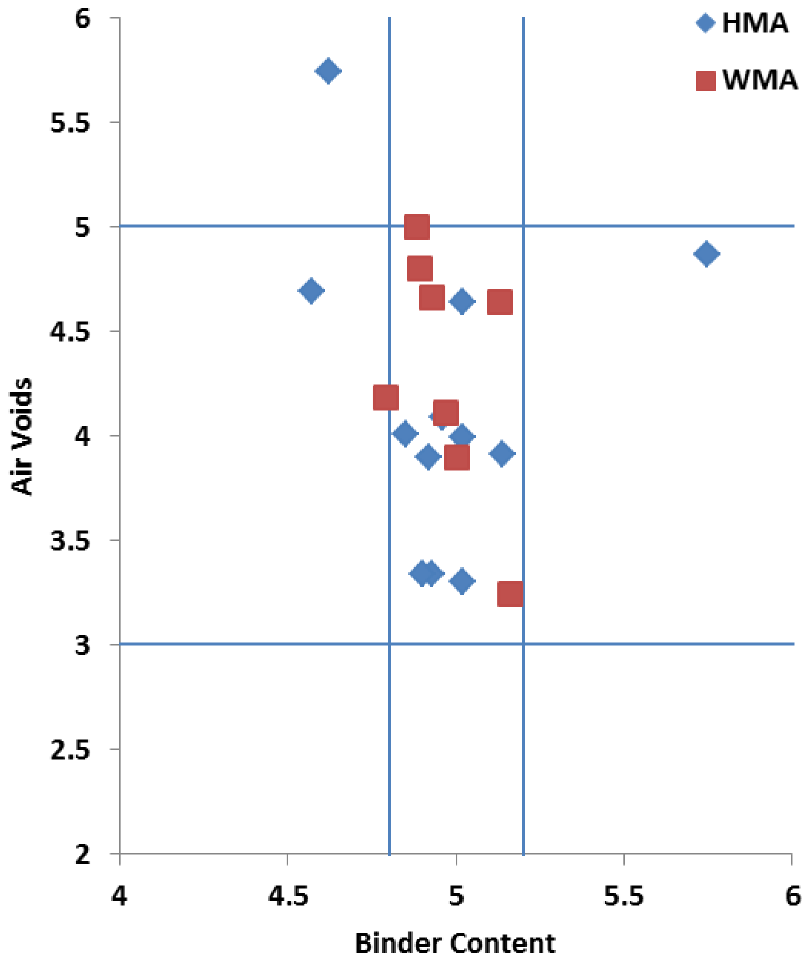
Temperature of the Mix

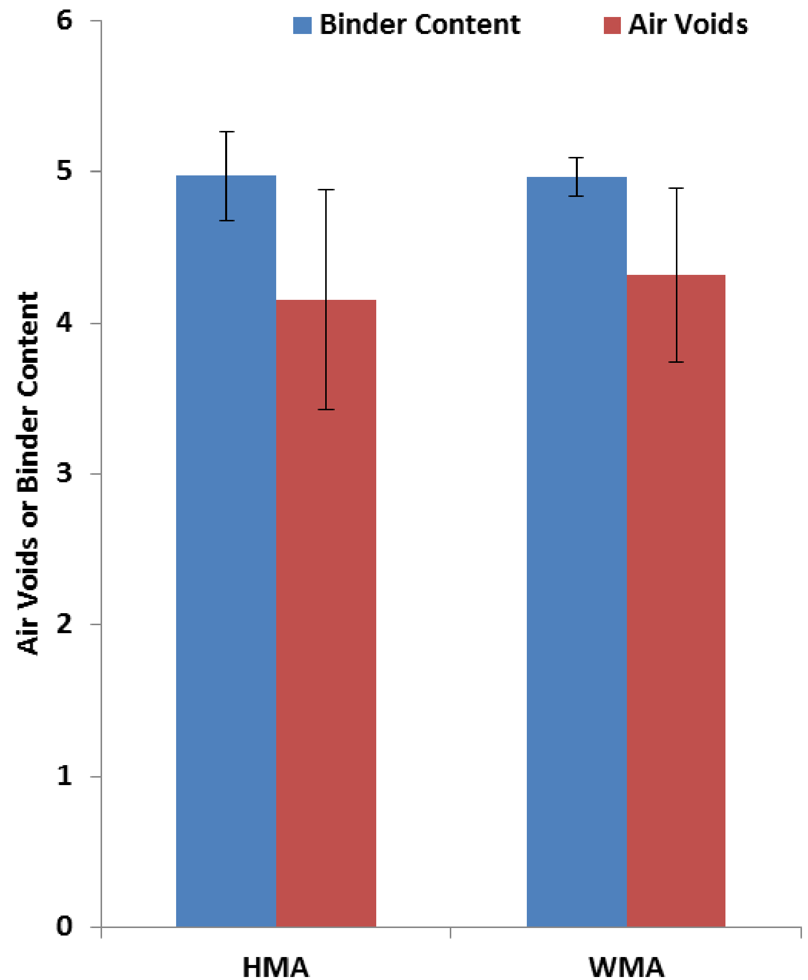


Temperature of the Mix



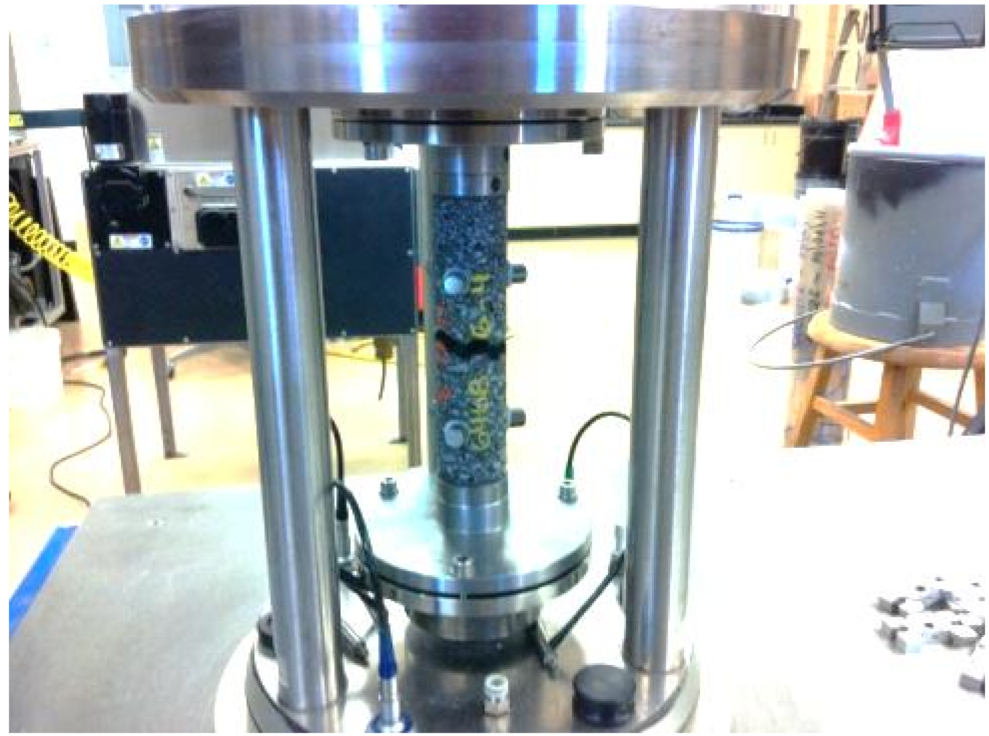
Consequence of WMA "Drop-In" to HMA Design





** Local Diabase Aggregate Water Absorption: 0.3% Coarse Stockpiles
0.5% & 1.4% Fine Stockpiles

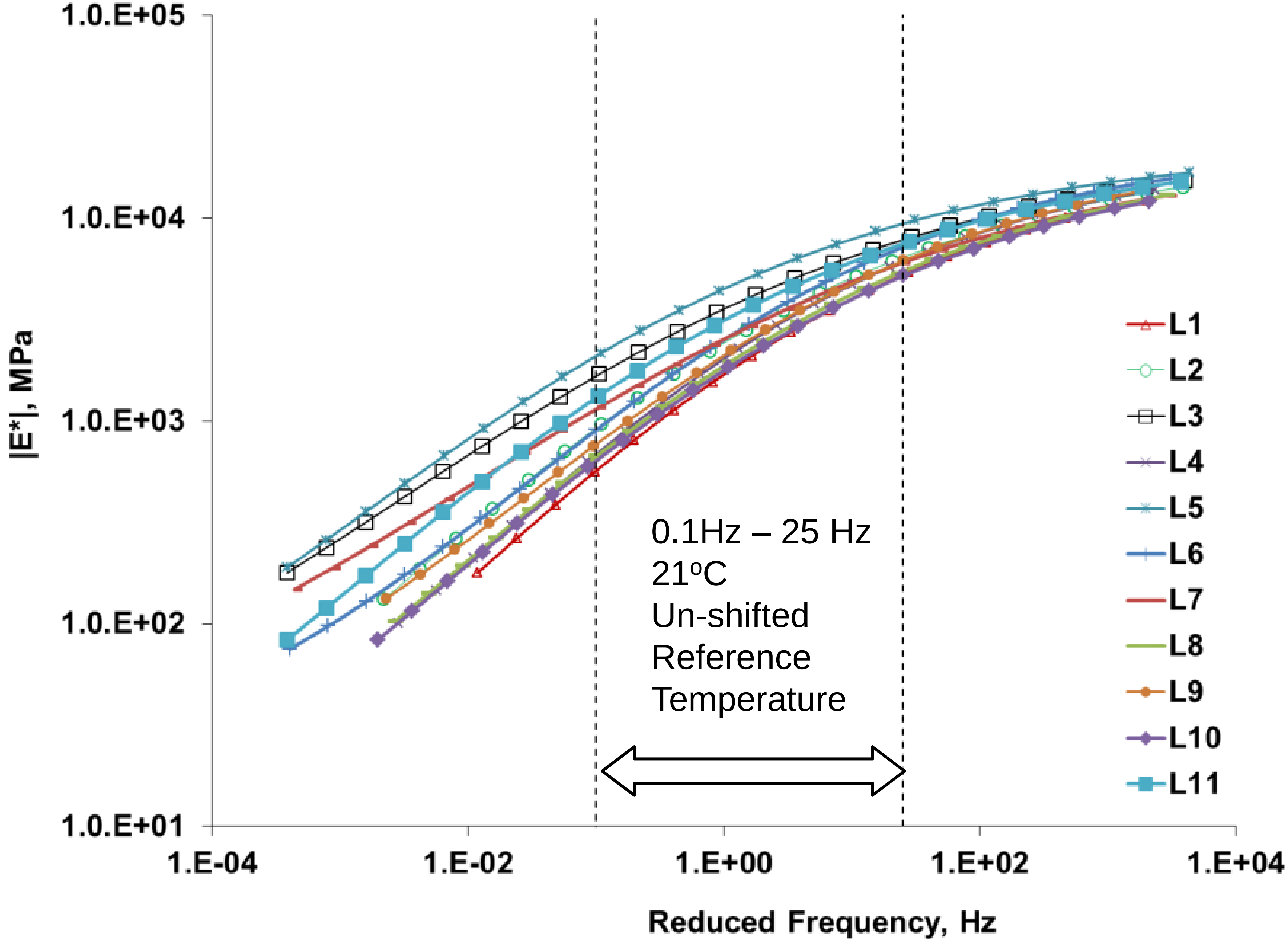
Post Construction, As-built |E*| and Fatigue Using Reduced-Scale Specimens



- **See**

  Kutay et al. (2009), Transportation Research Record TRR # 2127

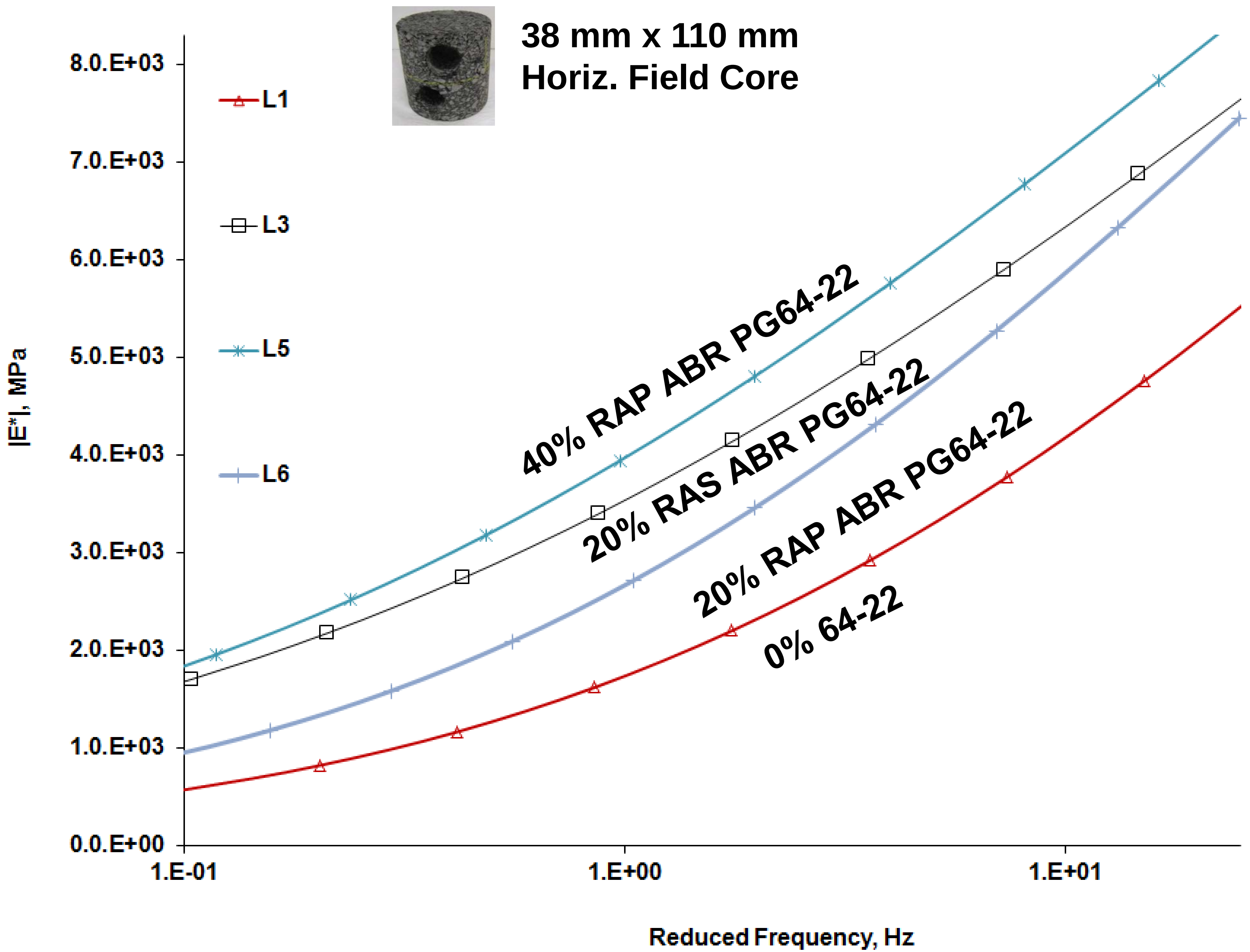
  Li & Gibson (2013), Journal of the Assoc. of Asphalt Paving Tech., Vol. 82

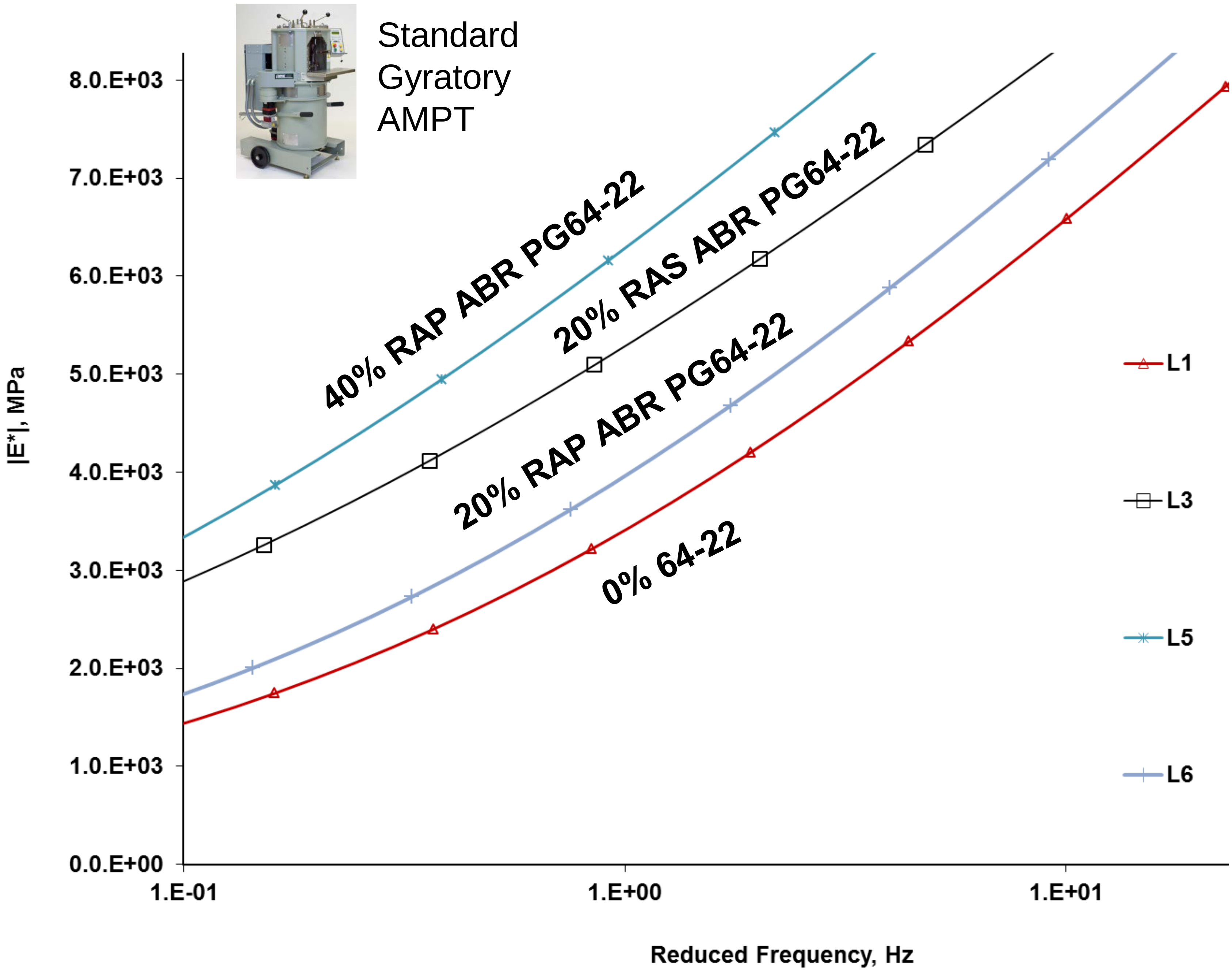


1.0.E+05
1.0.E+04
1.0.E+03
1.0.E+02
1.0.E+01
|E*|, MPa
1.E-04
1.E-02
1.E+00
1.E+02
1.E+04
Reduced Frequency, Hz
0.1Hz – 25 Hz
21°C
Un-shifted
Reference
Temperature
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11

Effect of Recycle Content

HMA / WMA Production Temperature	300^{o}F - 320^{o}F		240^{o}F - 270^{o}F	
Warm Mix Technology **Recycle Content**	-		Foam	Chem.
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28

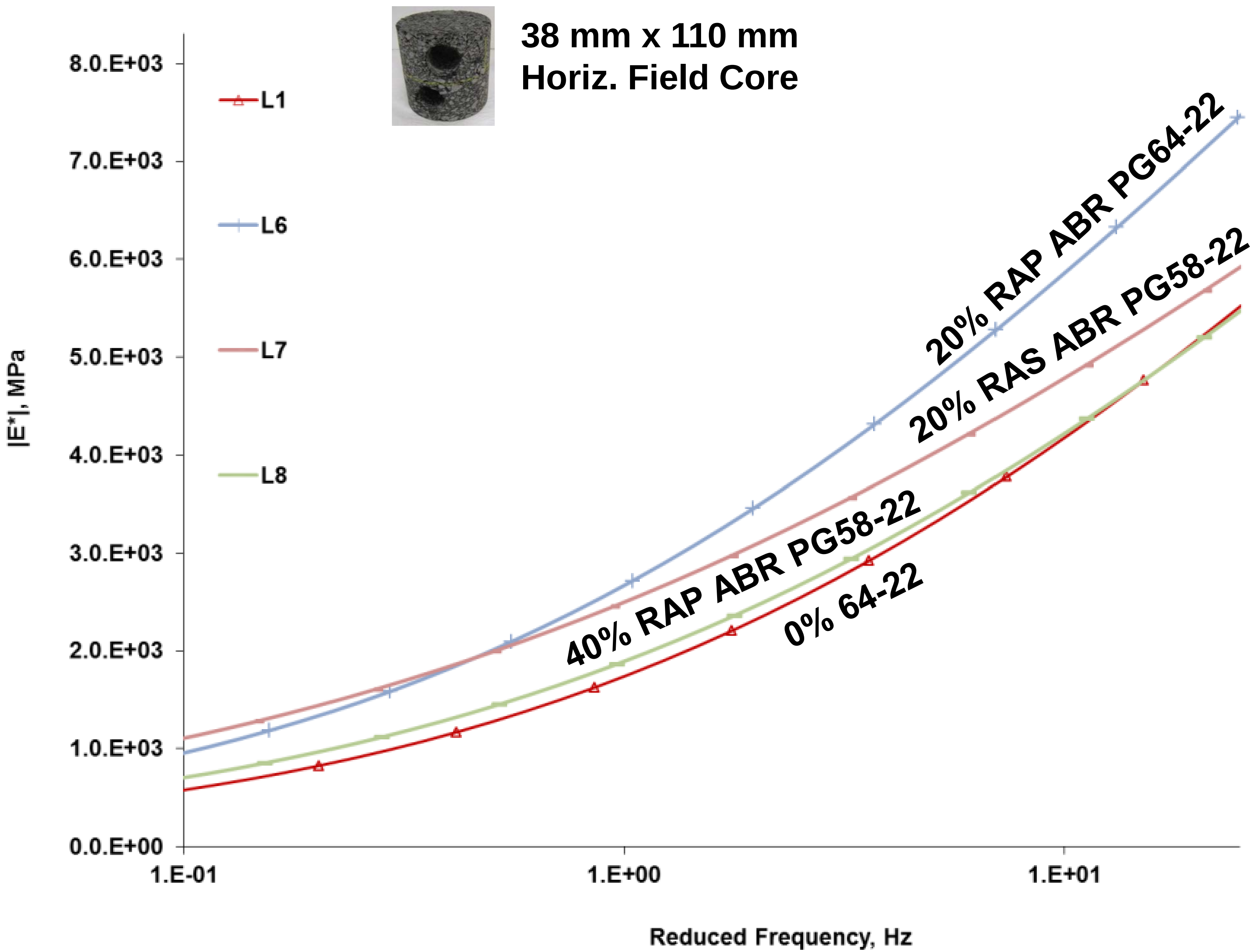

38 mm x 110 mm
Horiz. Field Core
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L1
L3
L5
L6
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

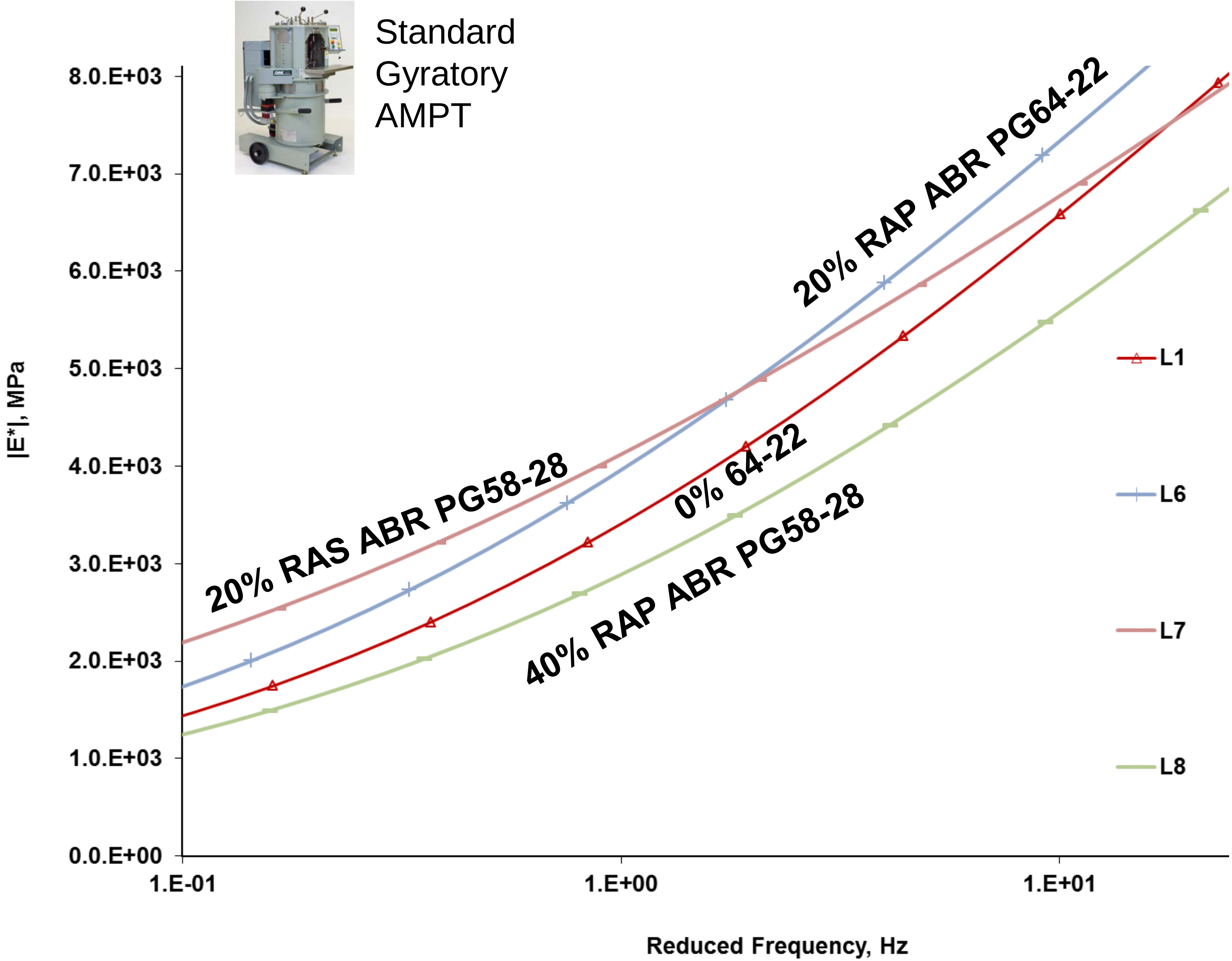


Standard
Gyratory
AMPT
40% RAP ABR PG64-22
20% RAS ABR PG64-22
20% RAP ABR PG64-22
0% 64-22
L1
L3
L5
L6
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

Effect of Offset with Softer Binder PG

HMA / WMA — Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
Recycle Content				
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28

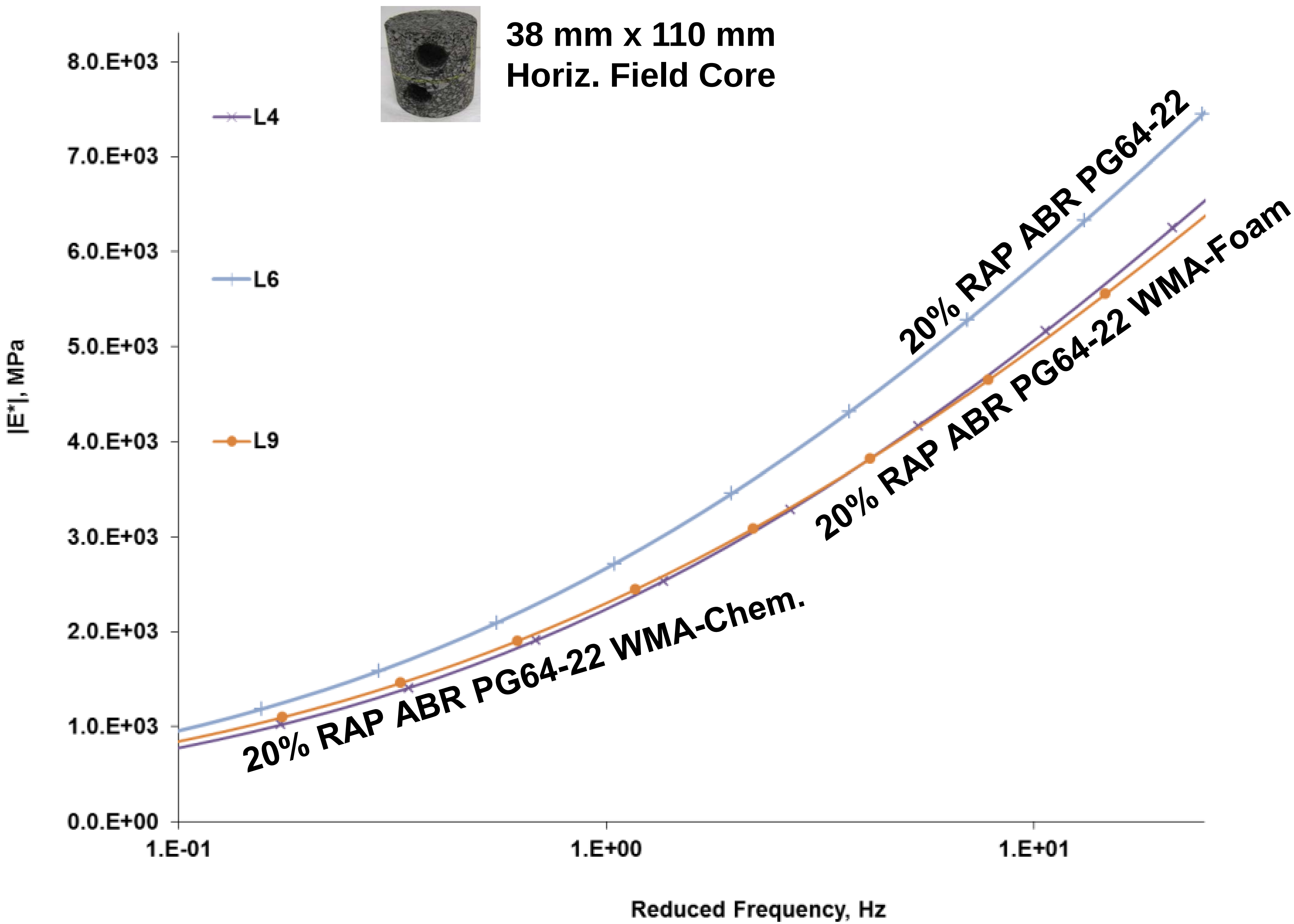

38 mm x 110 mm
Horiz. Field Core
L1
L6
L7
L8
20% RAP ABR PG64-22
20% RAS ABR PG58-22
40% RAP ABR PG58-22
0% 64-22
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



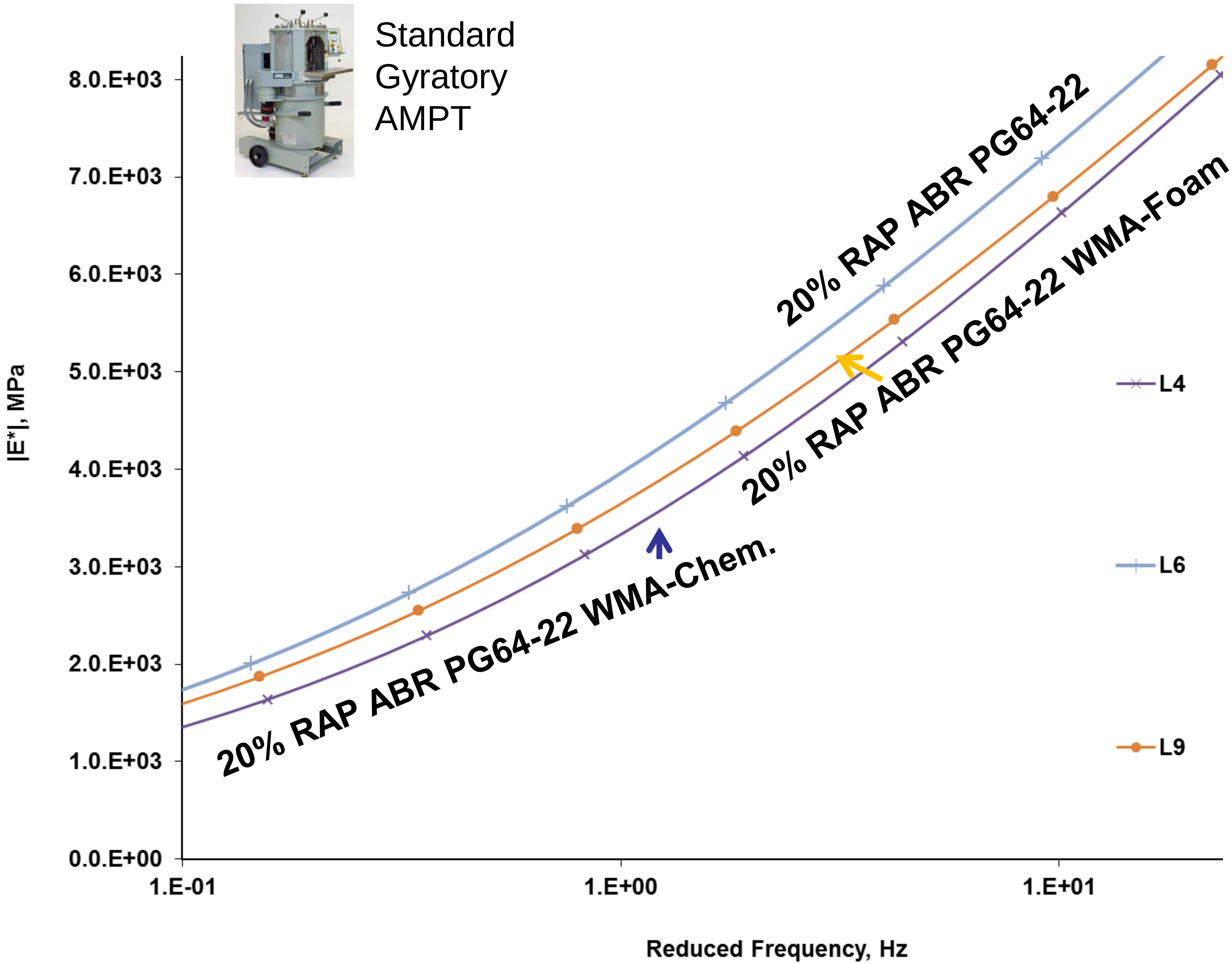
Standard
Gyratory
AMPT
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
20% RAP ABR PG64-22
20% RAS ABR PG58-28
0% 64-22
40% RAP ABR PG58-28
L1
L6
L7
L8

Effect of WMA (1 of 2)

Recycle Content				
HMA / WMA Production Temperature	300°F - 320°F		240°F - 270°F	
Warm Mix Technology	-		Foam	Chem.
0%	✔ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✔ PG64-22		✔ PG64-22	✔ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✔ PG64-22	✔ PG58-28		
40% ABR RAP ≈ 44% by weight	✔ PG64-22	✔ PG58-28	✔ PG58-28	✔ PG58-28



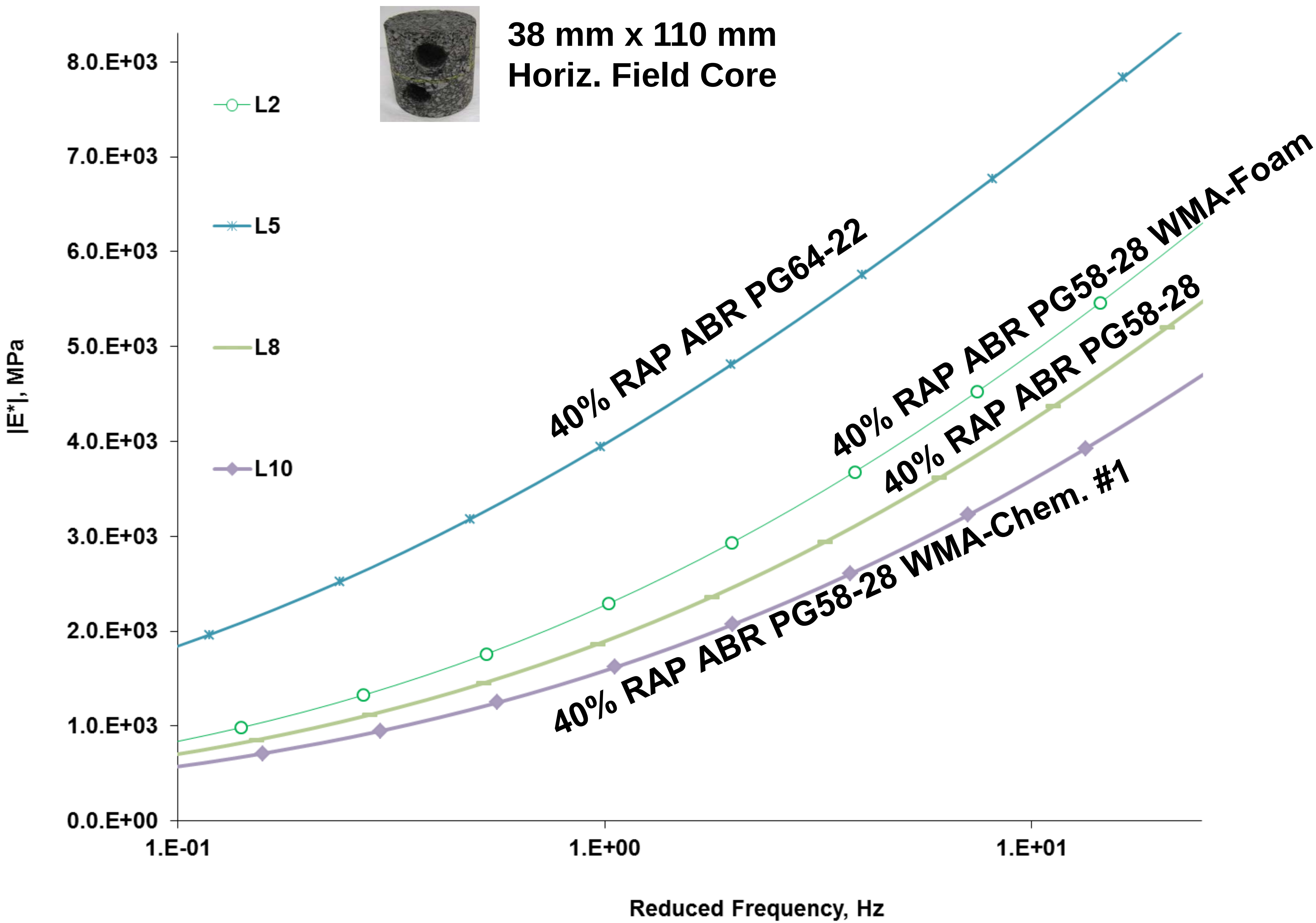
38 mm x 110 mm
Horiz. Field Core
L4
L6
L9
20% RAP ABR PG64-22
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

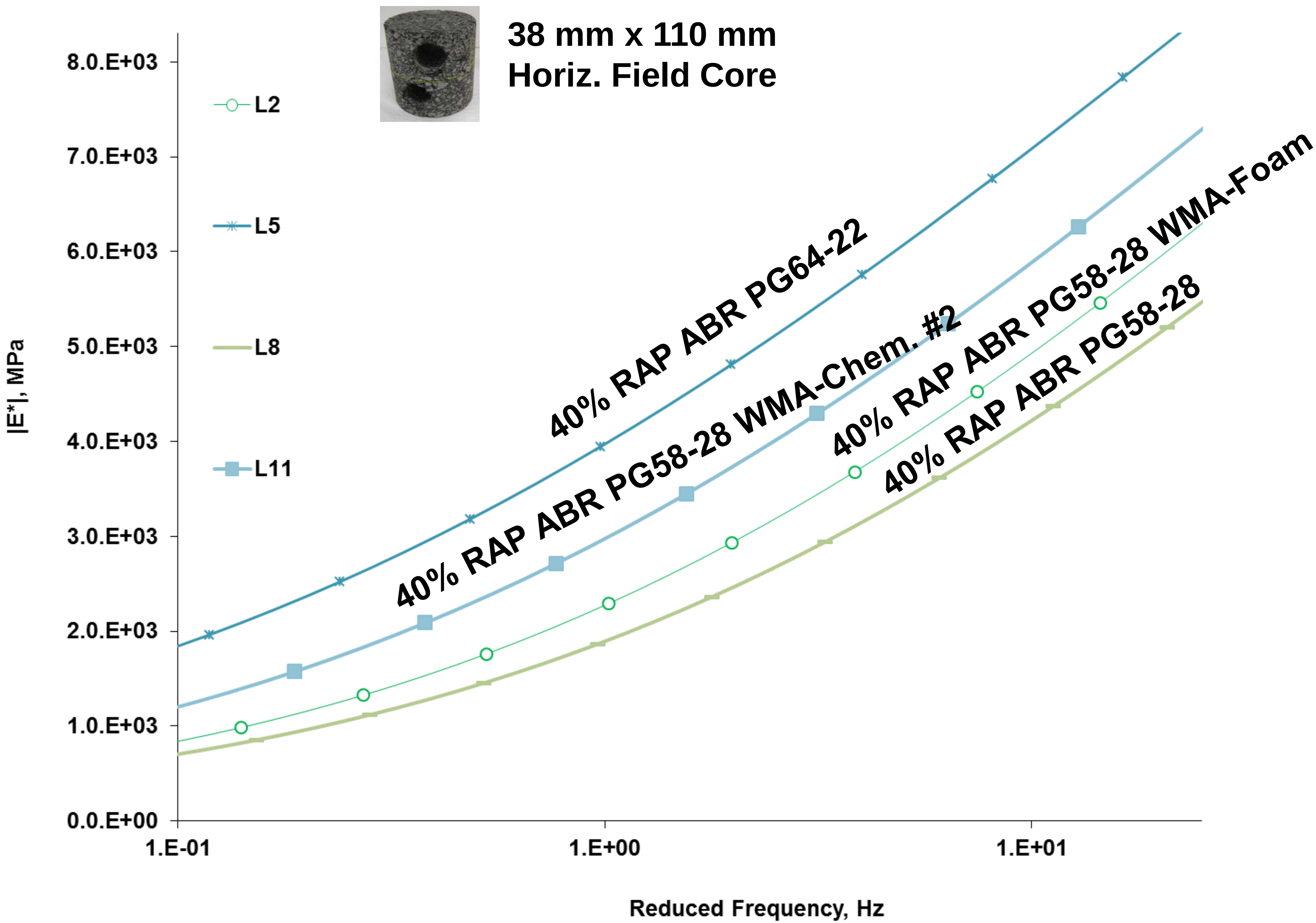


Standard
Gyratory
AMPT
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
20% RAP ABR PG64-22
20% RAP ABR PG64-22 WMA-Foam
20% RAP ABR PG64-22 WMA-Chem.
L4
L6
L9

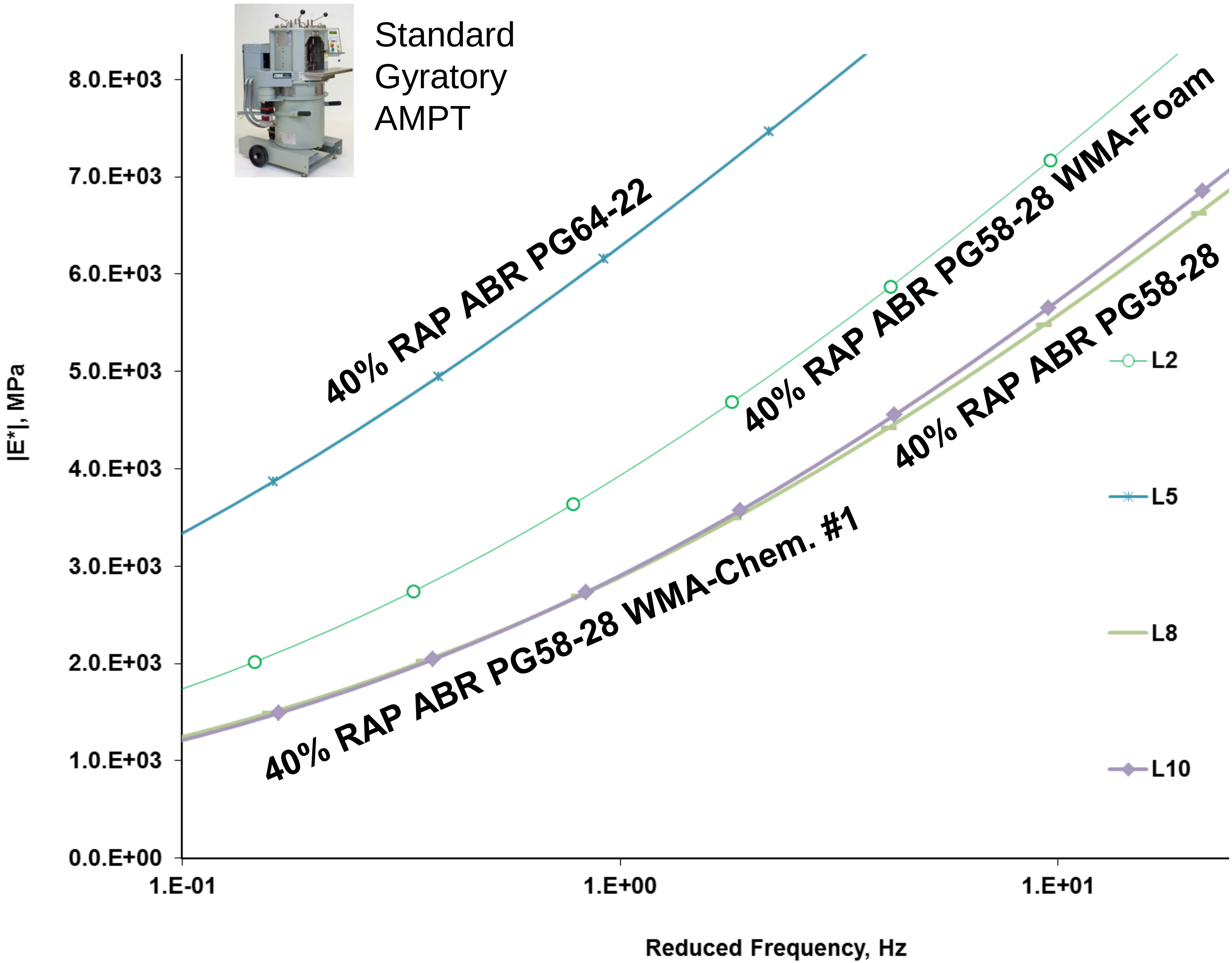
Effect of WMA (2 of 2)

HMA / WMA Production Temperature Warm Mix Technology Recycle Content	300°F - 320°F		240°F - 270°F	
	-		Foam	Chem.
0%	✓ PG64-22		-	-
20% ABR RAP ≈ 23% by weight	✓ PG64-22		✓ PG64-22	✓ PG64-22
20% ABR RAS ≈ 6% Shingle by weight	✓ PG64-22	✓ PG58-28		
40% ABR RAP ≈ 44% by weight	✓ PG64-22	✓ PG58-28	✓ PG58-28	✓ PG58-28

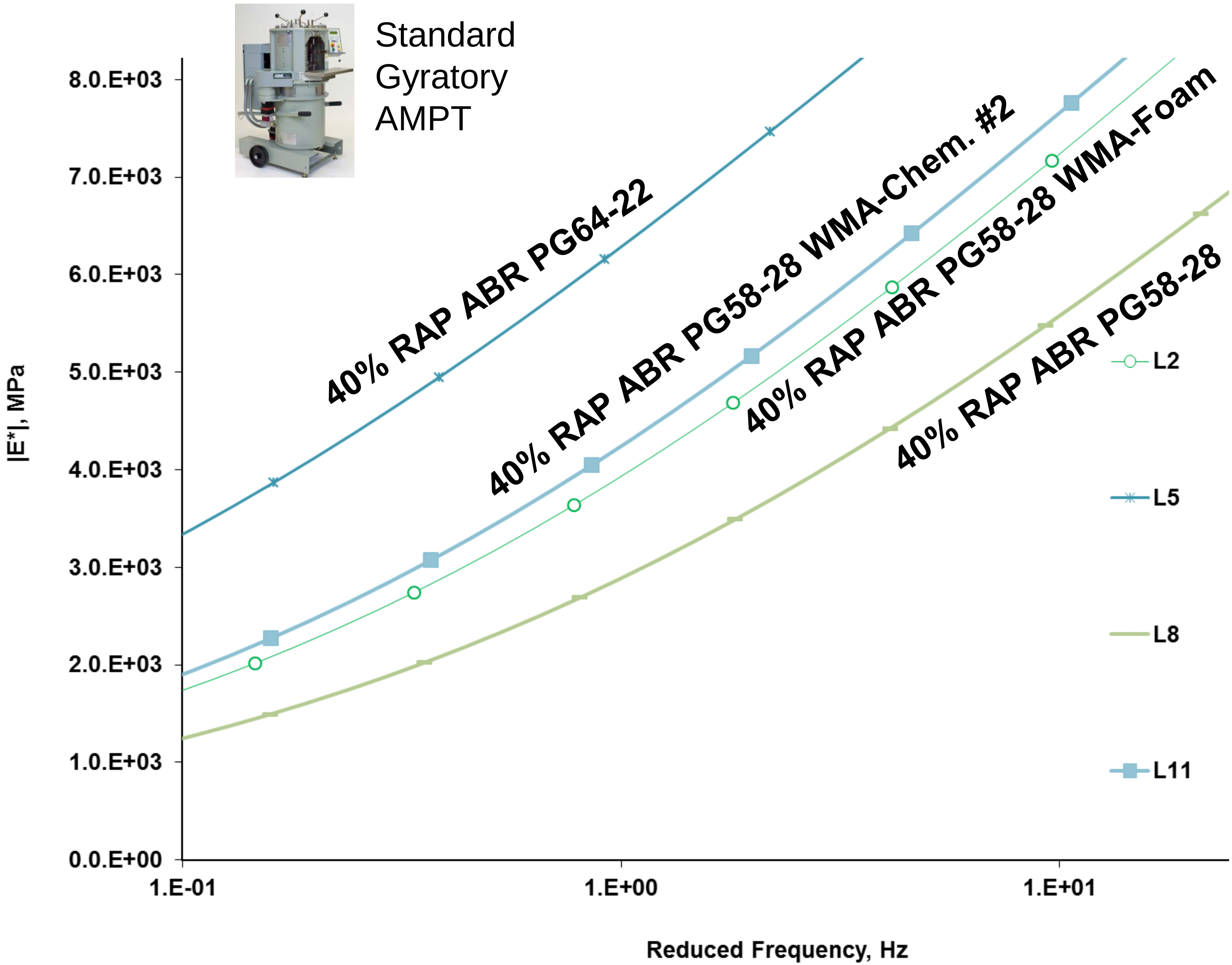

38 mm x 110 mm
Horiz. Field Core
L2
L5
L8
L10
40% RAP ABR PG64-22
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
40% RAP ABR PG58-28 WMA-Chem. #1
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



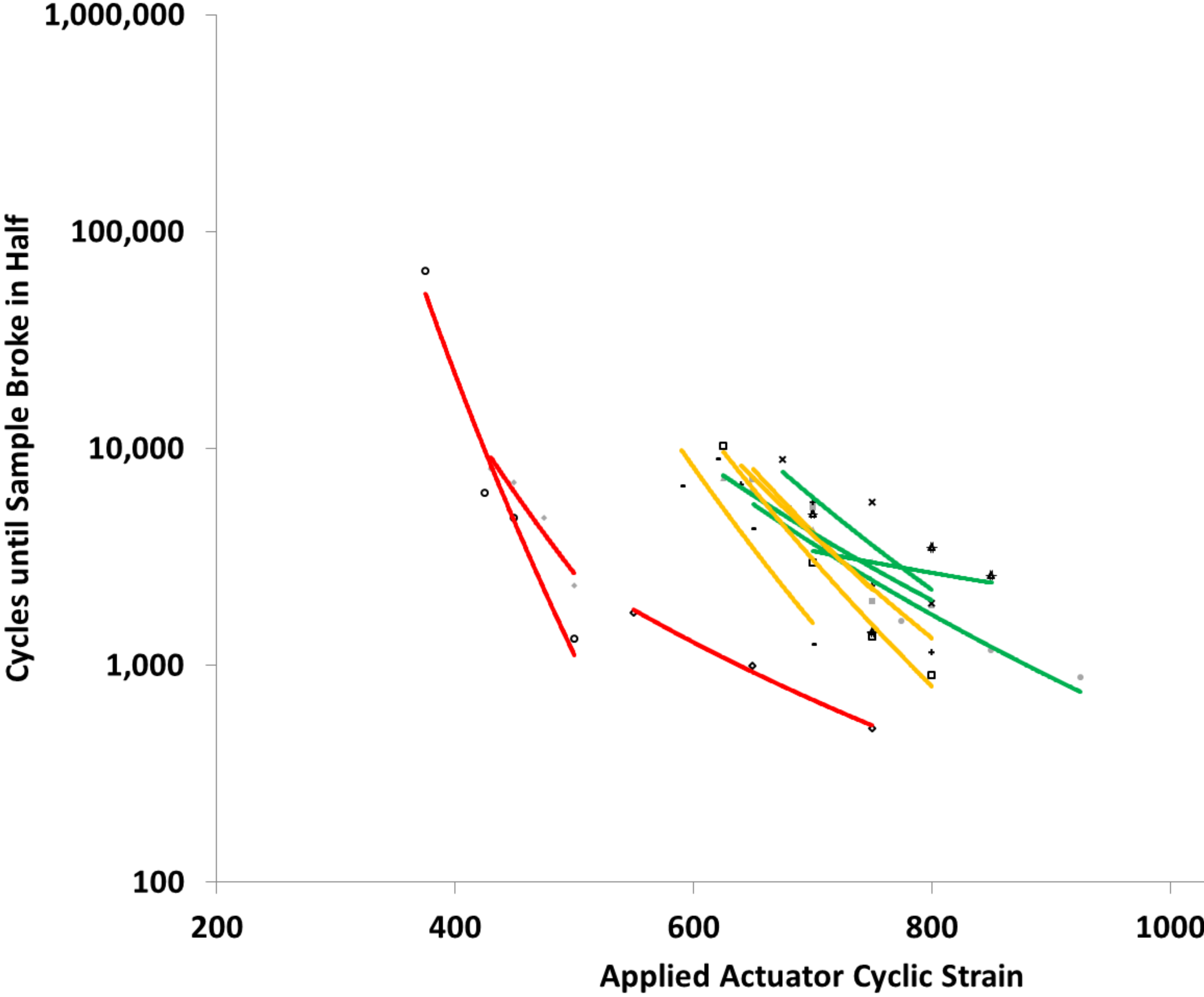
38 mm x 110 mm
Horiz. Field Core
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
L2
L5
L8
L11
40% RAP ABR PG64-22
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz



Standard
Gyratory
AMPT
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
|E*|, MPa
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz
40% RAP ABR PG64-22
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
40% RAP ABR PG58-28 WMA-Chem. #1
L2
L5
L8
L10


Standard
Gyratory
AMPT
40% RAP ABR PG64-22
40% RAP ABR PG58-28 WMA-Chem. #2
40% RAP ABR PG58-28 WMA-Foam
40% RAP ABR PG58-28
L2
L5
L8
L11
|E*|, MPa
8.0.E+03
7.0.E+03
6.0.E+03
5.0.E+03
4.0.E+03
3.0.E+03
2.0.E+03
1.0.E+03
0.0.E+00
1.E-01
1.E+00
1.E+01
Reduced Frequency, Hz

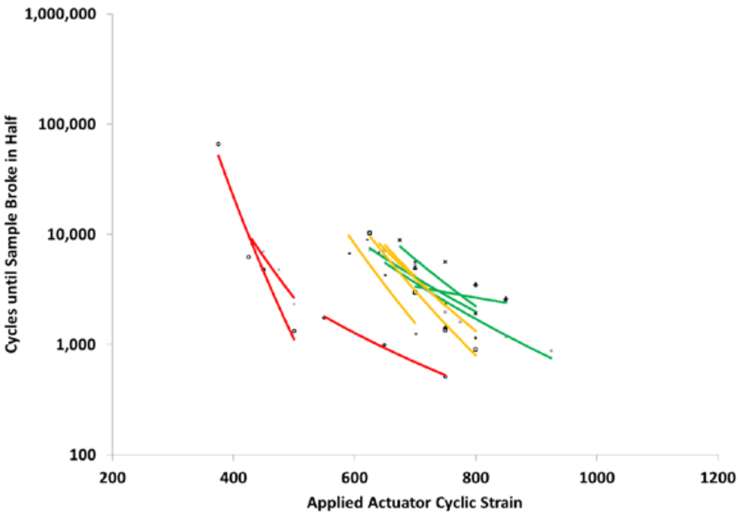
AMPT Fatigue before VECD Analysis



Standard Gyratory AMPT

AMPT Fatigue before VECD Analysis

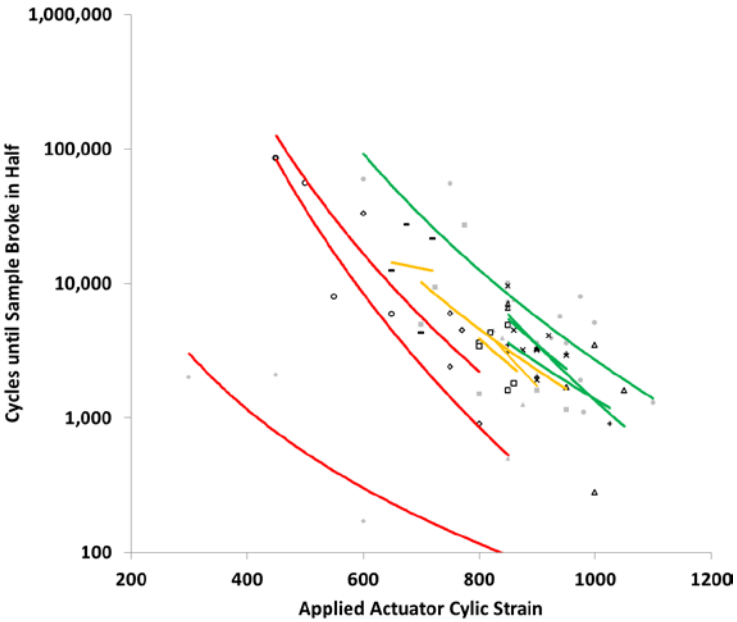
Standard
Gyratory
AMPT



GREEN	0% Control PG64-22 40% ABR RAP ***PG58-28*** 20% ABR RAP PG64-22 WMA Chem. 40% ABR RAP ***PG58-28*** WMA Chem. #1
YELLOW	40% ABR RAP ***PG58-28*** WMA Foam 20% ABR RAP PG64-22 WMA Foam 20% ABR RAP PG64-22 40% ABR RAP ***PG58-28*** WMA Chem. #2
RED	20% ABR RAS PG64-22 20% ABR RAS ***PG58-28*** 40% ABR RAP PG64-22

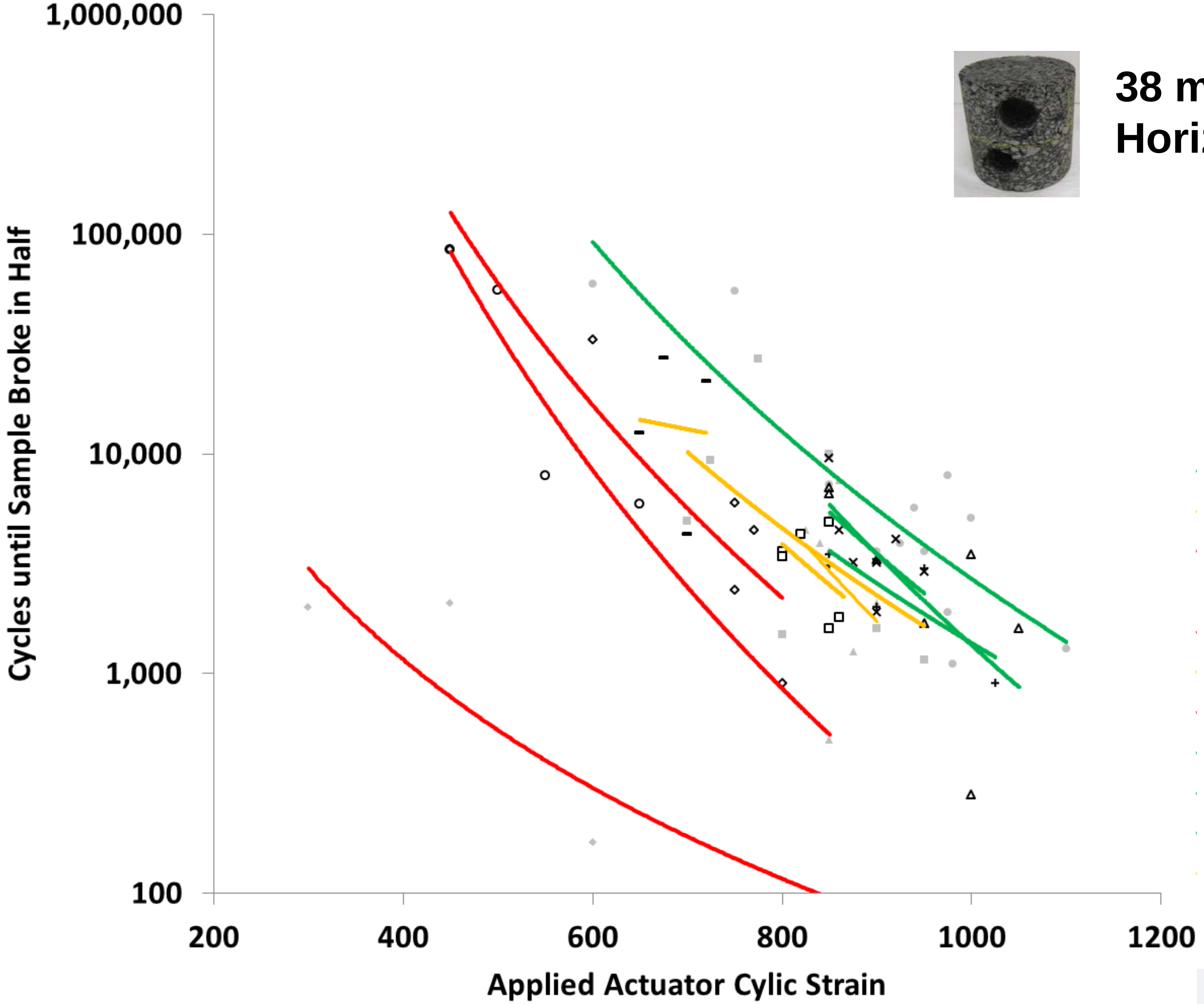
AMPT Fatigue before VECD Analysis

38 mm x 110 mm
Horiz. Field Core



GREEN	0% Control PG64-22 40% ABR RAP ***PG58-28*** 20% ABR RAP PG64-22 WMA Foam 40% ABR RAP ***PG58-28*** WMA Chem. #1
YELLOW	40% ABR RAP ***PG58-28*** WMA Foam 20% ABR RAP PG64-22 WMA Chem. 20% ABR RAP PG64-22 40% ABR RAP ***PG58-28*** WMA Chem. #2
RED	20% ABR RAS PG64-22 20% ABR RAS ***PG58-28*** 40% ABR RAP PG64-22

AMPT Fatigue before VECD Analysis



38 mm x 110 mm
Horiz. Field Core

AMPT Fatigue without VECD Analysis

	 **Horizontal Field Core** **In-Place Density**	 **Standard Gyratory AMPT** **Controlled 7% air voids**
GREEN	0% Control PG64-22 40% ABR RAP ***PG58-28*** 20% ABR RAP PG64-22 WMA Foam 40% ABR RAP ***PG58-28*** WMA Chem. #1	0% Control PG64-22 40% ABR RAP ***PG58-28*** 20% ABR RAP PG64-22 WMA Chem. 40% ABR RAP ***PG58-28*** WMA Chem. #1
YELLOW	40% ABR RAP ***PG58-28*** WMA Foam 20% ABR RAP PG64-22 WMA Chem. 20% ABR RAP PG64-22 40% ABR RAP ***PG58-28*** WMA Chem. #2	40% ABR RAP ***PG58-28*** WMA Foam 20% ABR RAP PG64-22 WMA Foam 20% ABR RAP PG64-22 40% ABR RAP ***PG58-28*** WMA Chem. #2
RED	20% ABR RAS PG64-22 20% ABR RAS ***PG58-28*** 40% ABR RAP PG64-22	20% ABR RAS PG64-22 20% ABR RAS ***PG58-28*** 40% ABR RAP PG64-22

AMPT Fatigue without VECD Analysis

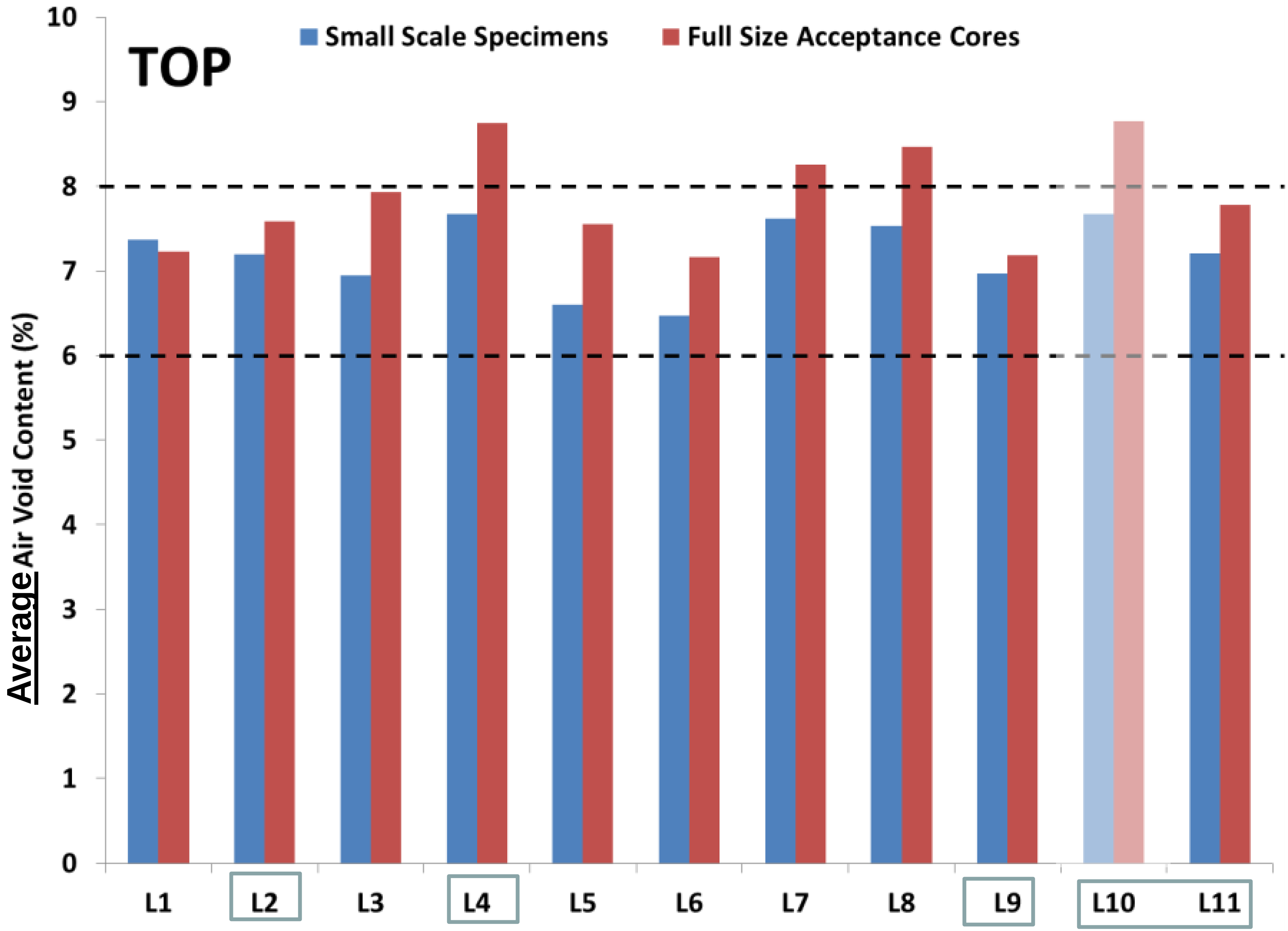
	 **Horizontal Field Core** **In-Place Density**	 **Standard Gyratory AMPT** **Controlled 7% air voids**
GREEN	0% Control PG64-22 40% ABR RAP ***PG58-28*** 20% ABR RAP PG64-22 WMA Foam 40% ABR RAP ***PG58-28*** WMA Chem. #1	0% Control PG64-22 40% ABR RAP ***PG58-28*** *20% ABR RAP PG64-22 WMA Chem.* 40% ABR RAP ***PG58-28*** WMA Chem. #1
YELLOW	40% ABR RAP ***PG58-28*** WMA Foam *20% ABR RAP PG64-22 WMA Chem.* 20% ABR RAP PG64-22 40% ABR RAP ***PG58-28*** WMA Chem. #2	40% ABR RAP ***PG58-28*** WMA Foam 20% ABR RAP PG64-22 WMA Foam 20% ABR RAP PG64-22 40% ABR RAP ***PG58-28*** WMA Chem. #2
RED	20% ABR RAS PG64-22 20% ABR RAS ***PG58-28*** 40% ABR RAP PG64-22	20% ABR RAS PG64-22 20% ABR RAS ***PG58-28*** 40% ABR RAP PG64-22

Take-Aways

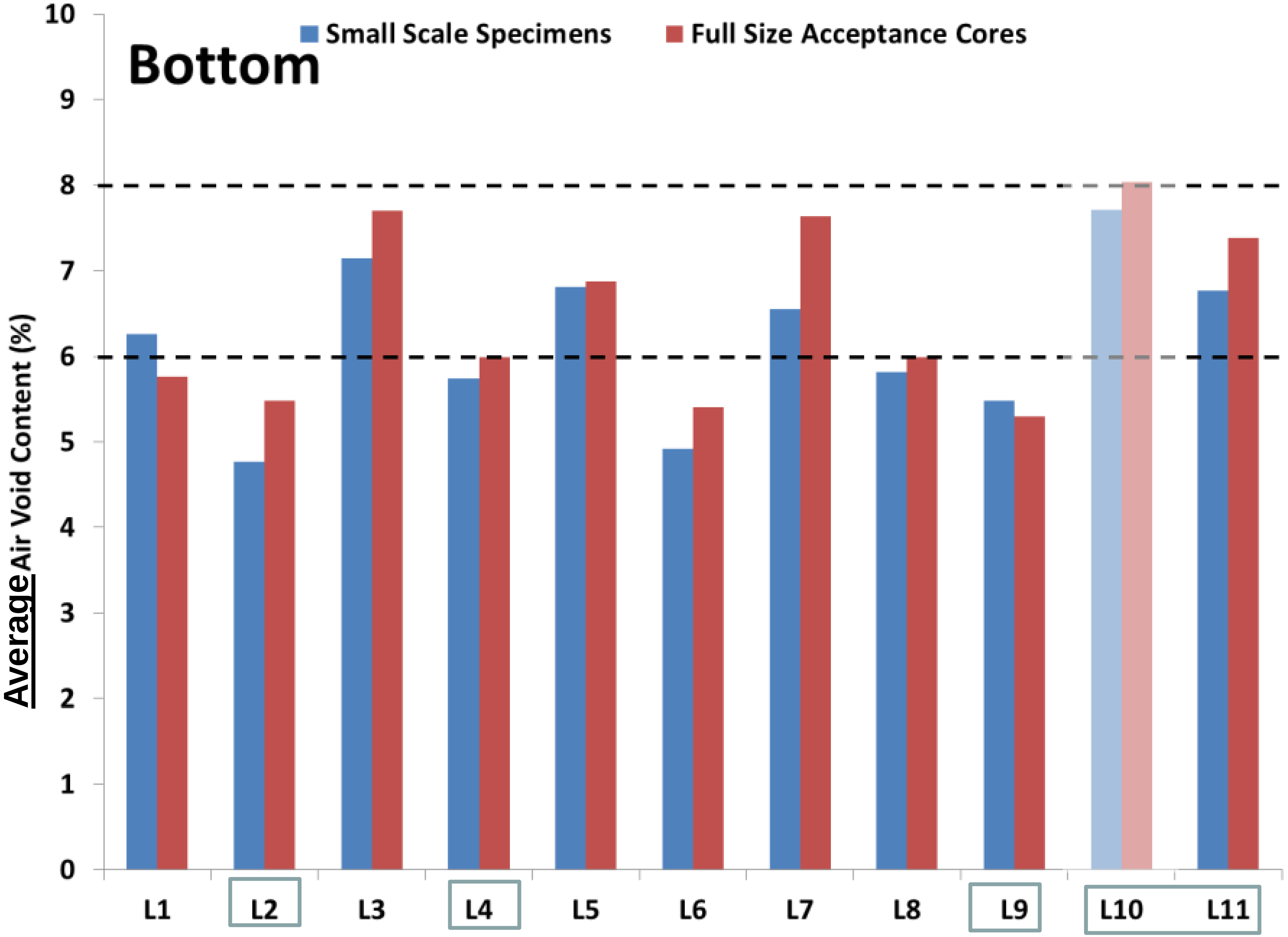
1. Production of the mixes matched the desired experimental design…small quantities
2. Specifications were tight and some mixes were rejected in order to get them produced correctly
3. High ABR mix was produced without RAP fractionation
4. No single technology (RAP, RAS, WMA) was more or less compactable than others except the WMA-foamed mix temperature needed to be increased by 15C.

Take-Aways

5. Increasing ABR stiffened the mixes
6. Softer Virgin PG that is one grade lower on both the high and low end softened the high ABR mixes and the RAS mix
7. Reduced temperature WMA production decreased the stiffness of the mix but is less clear at High ABR.
8. |E*| data support tolerance for performance test samples is adequate at +/-1% air voids (rather than +/-0.5%)



TOP
Small Scale Specimens
Full Size Acceptance Cores
Average Air Void Content (%)
0
1
2
3
4
5
6
7
8
9
10
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11

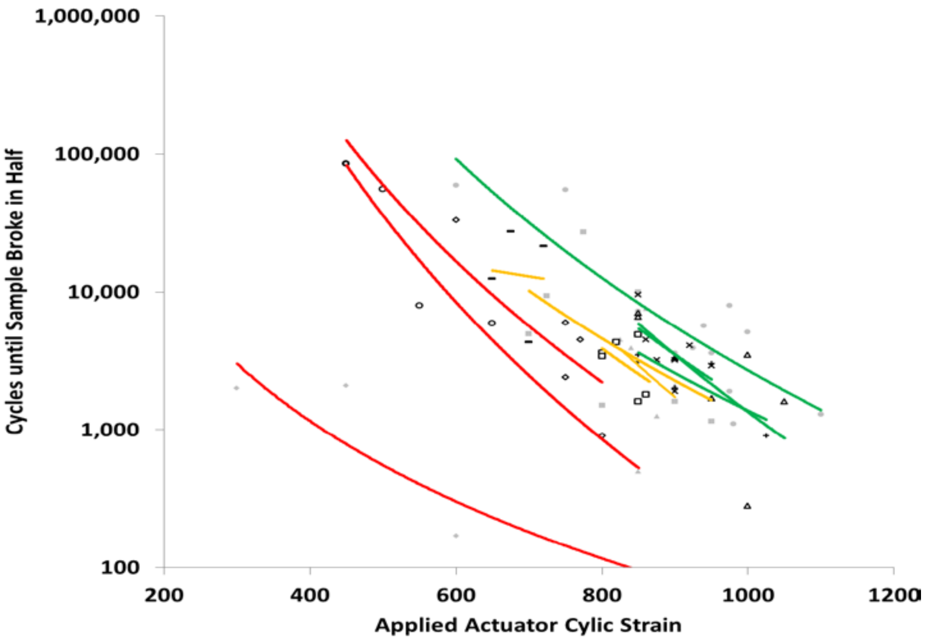


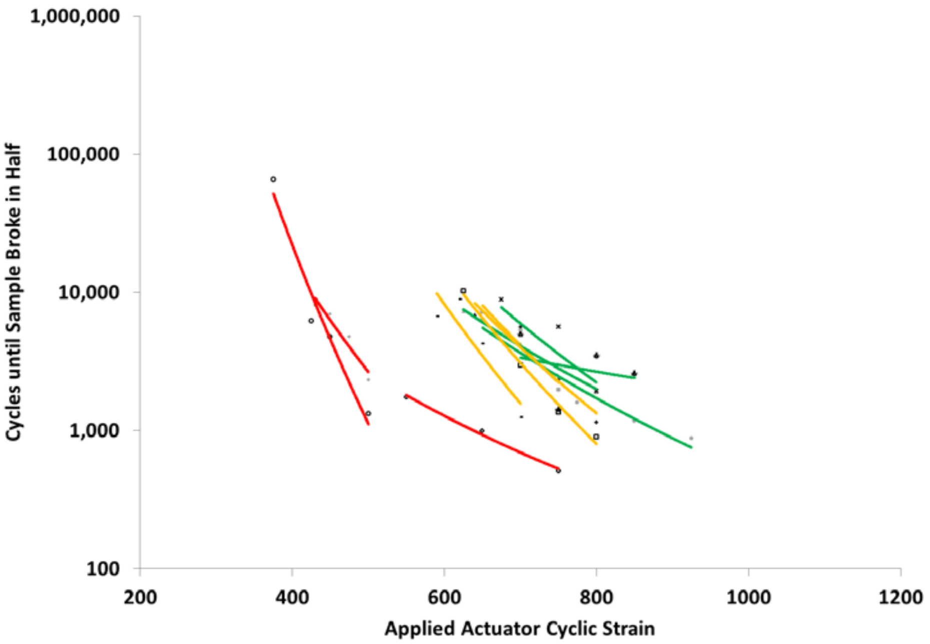
Bottom
Small Scale Specimens
Full Size Acceptance Cores
Average Air Void Content (%)
0
1
2
3
4
5
6
7
8
9
10
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11

AMPT Fatigue before VECD Analysis

As-built air void content

Controlled 7% air void content





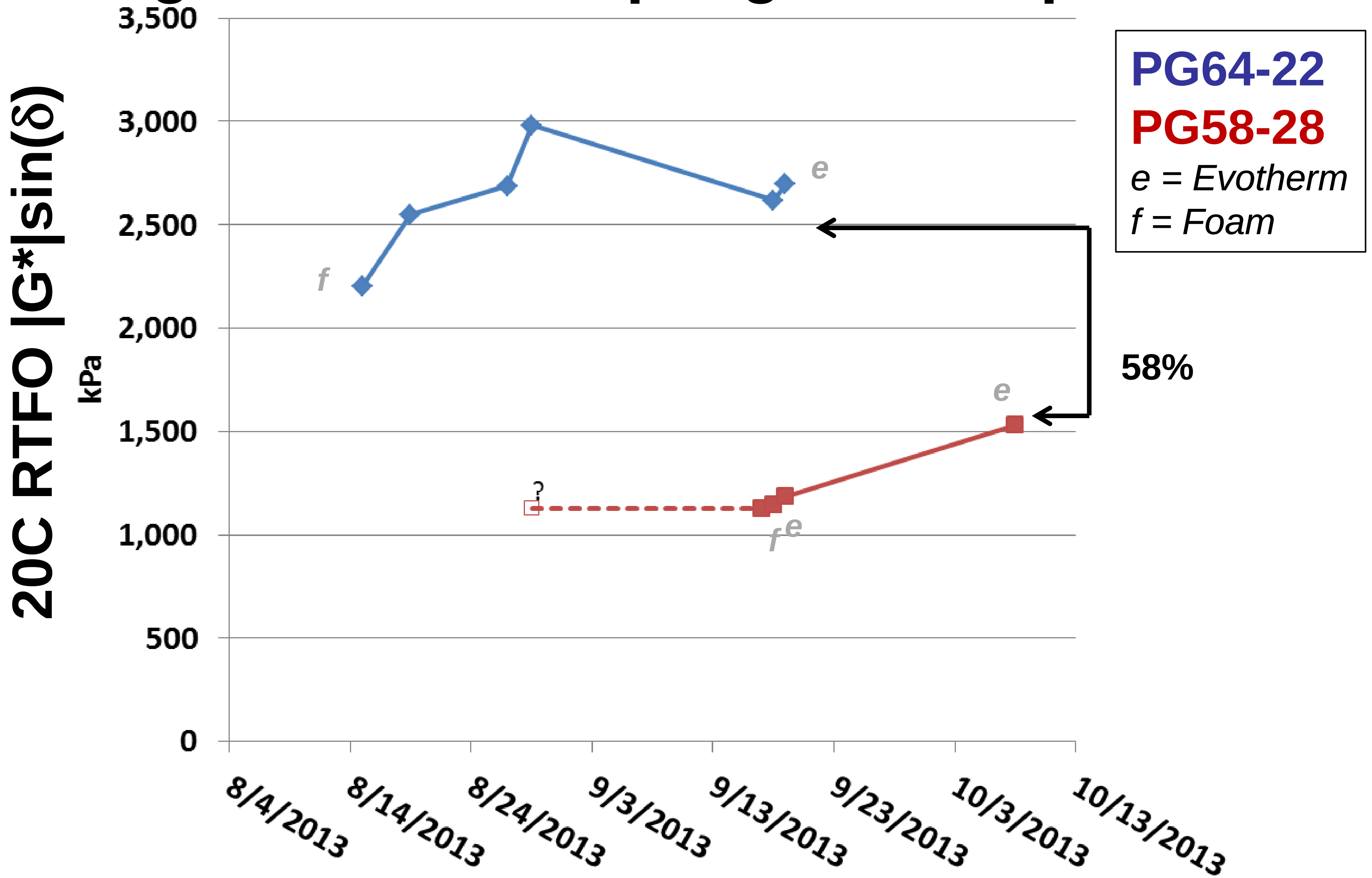
AMPT Fatigue without VECD Analysis

	 **Horizontal Field Core In-Place Density**	 **Standard Gyratory AMPT Controlled 7% air voids**
GREEN	0% Control PG64-22 (72, 13) 40% ABR RAP ***PG58-28*** (75, 15) 20% ABR RAP PG64-22 WMA Foam (77, 19) 40% ABR RAP ***PG58-28*** WMA Chem. #1 (71, 12)	0% Control PG64-22 (72, 13) 40% ABR RAP ***PG58-28*** (75, 15) *20% ABR RAP PG64-22 WMA Chem. (71, 14)* 40% ABR RAP ***PG58-28*** WMA Chem. #1 (71, 12)
YELLOW	40% ABR RAP ***PG58-28*** WMA Foam (__, __) *20% ABR RAP PG64-22 WMA Chem. (71, 14)* 20% ABR RAP PG64-22 (71, 17) 40% ABR RAP ***PG58-28*** WMA Chem. #2 (78, 16)	40% ABR RAP ***PG58-28*** WMA Foam (__, __) 20% ABR RAP PG64-22 WMA Foam (77, 19) 20% ABR RAP PG64-22 (71, 17) 40% ABR RAP ***PG58-28*** WMA Chem. #2 (78, 16)
RED	20% ABR RAS PG64-22 (91, 22) 20% ABR RAS ***PG58-28 (__,__)*** 40% ABR RAP PG64-22 (86, 22)	20% ABR RAS PG64-22 (91, 22) 20% ABR RAS ***PG58-28 (__,__)*** 40% ABR RAP PG64-22 (86, 22)

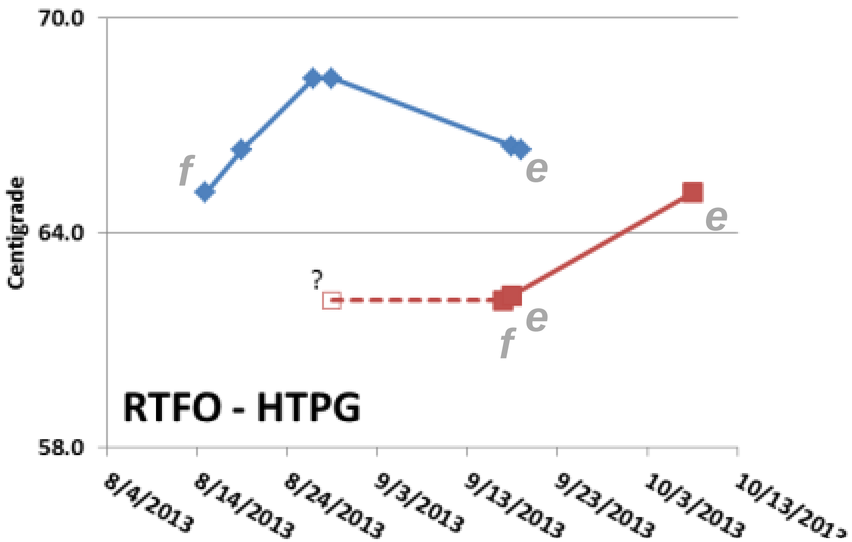
Virgin Binder Sampling and Properties

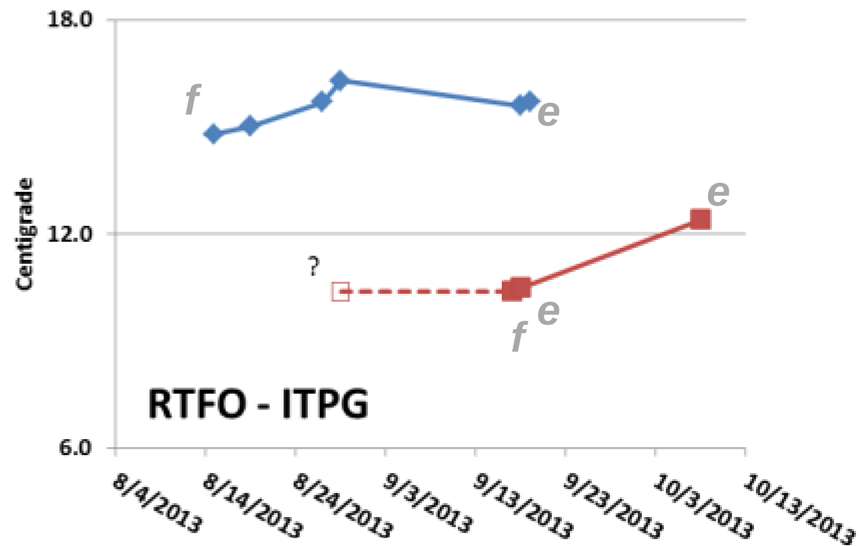
- **In-line sampling port just before entering the drum**
- **One gallon on each day of production**

Virgin Binder Sampling and Properties



Virgin Binder Sampling and Properties





PG64-22

PG58-28

e = Evotherm

f = Foam