Recycled Engine Oil Bottoms as Asphalt Binder Additive

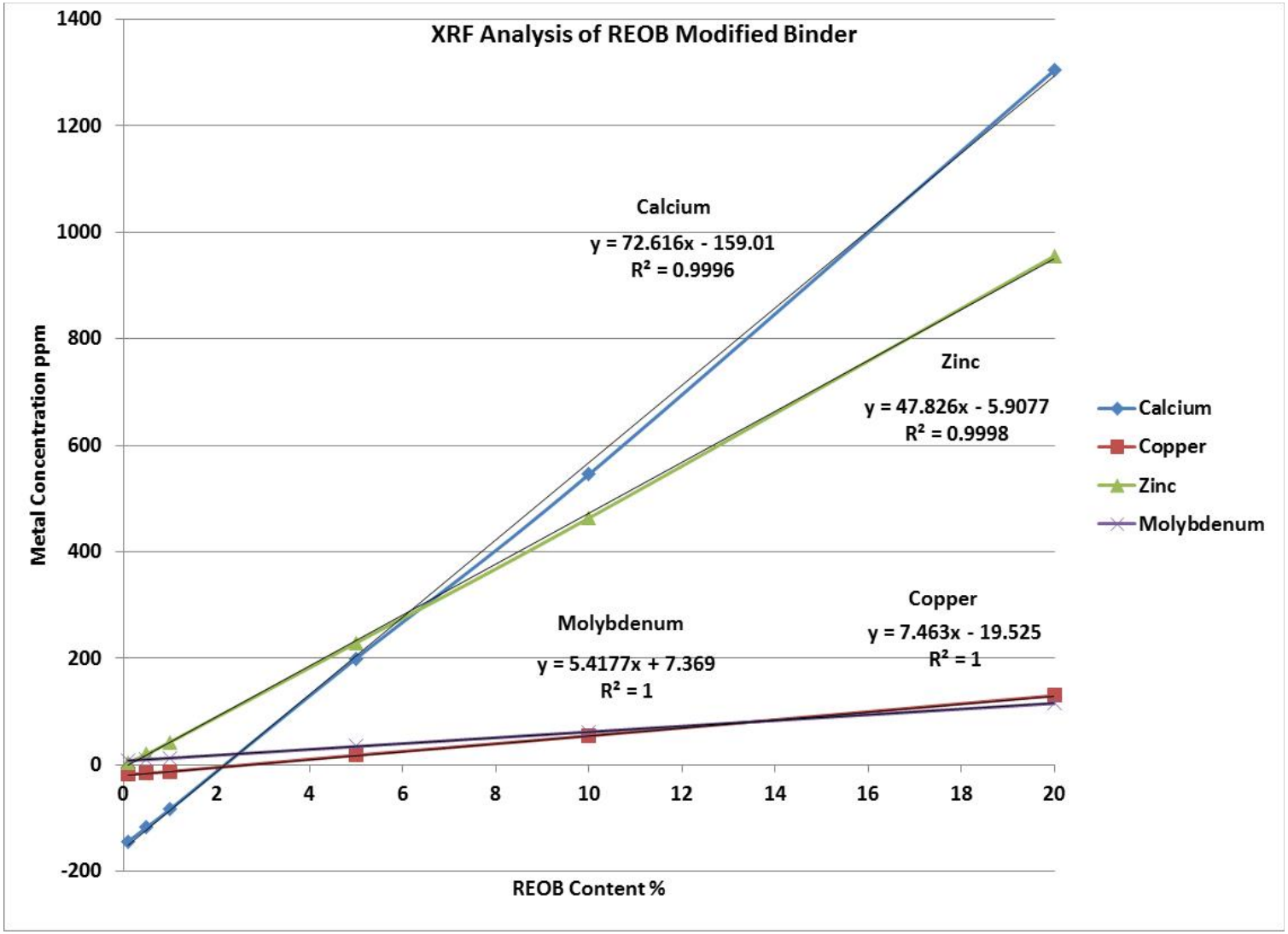
Spring 2015 Expert Task Group

Recycled Engine Oil Bottoms are Liquids at Room Temperature

XRF-Spectrometer

Variation and Complications
between and within REOB Suppliers

- **Phosphorous 1.5 - 1.9%**
- **Sulfur 1.5 - 1.9%**
- **Calcium 7,204 - 10,901ppm**
- **Iron 372 - 1,838 ppm**
- **Copper 704 - 1,563 ppm**
- **Zinc 4,554 - 7,213 ppm**
- **Molybdenum 288 - 669 ppm**


XRF Analysis of REOB Modified Binder
Metal Concentration ppm
REOB Content %
1400
1200
1000
800
600
400
200
0
-200
0
2
4
6
8
10
12
14
16
18
20
Calcium
y = 72.616x - 159.01
R² = 0.9996
Zinc
y = 47.826x - 5.9077
R² = 0.9998
Molybdenum
y = 5.4177x + 7.369
R² = 1
Copper
y = 7.463x - 19.525
R² = 1
Calcium
Copper
Zinc
Molybdenum

REOB Content of Binders

1,208 binder samples received from 38 Agencies

		XRF Analysis ppm				REOB% (08-1001)				
State	Performance Grade	Calcium	Copper	Zinc	Molybdenum	Calcium ppm	Copper ppm	Zinc ppm	Molybdenum ppm	GTR %
IN	64-28	424.3	36.6	417.9	43.4	3	4	7	10	3
WA	64-22	479	48	424.5	44.4	4	5	7	10	3
AL	-	643.4	56.5	469.1	64.2	5	6	8	14	3
WA	64-28	576.6	51.9	480.2	51.8	5	6	8	11	3
IN	58-28	550.6	52.7	501.4	48.5	5	6	8	11	3
OK	70-28	478	50.6	548.1	44.4	4	5	9	10	3
OK	64-22 OK	874.1	124	576.6	32.8	8	12	9	8	4
TX	AC 15P	611.4	79.4	591.3	48.5	5	8	10	11	4
TX	AC 5	781.7	84.1	775.3	59.9	7	8	13	13	5
TX	AC20-5TR	-101.1	-8.1	794.7	-2	-1	0	13	1	5
TX	76-22T	-62.6	-8.7	837.9	0.6	-1	0	14	1	5
FL	76-22 AR	26.2	33.3	913.4	10.7	0	4	15	3	6
CFL	64-10	1255	200	933.3	42.1	11	19	15	9	6
AZ	76-22TR	0	18.5	1128.9	0.1	0	3	19	1	7
NE	58-28	-131.5	83.7	1203.8	5.9	-2	8	20	2	8
NE	64-30	-128.6	-14	1523.1	3.7	-2	0	25	2	10
CA	76-22TR	189.7	37.2	1761.7	10.6	1	4	29	3	11
AZ	58-22	1737.3	141	2452.4	64.1	15	14	41	14	16
TX	64-22	34.7	42.9	2558.4	-6.1	0	5	43	0	16
CA	64-28TR	782.5	145	2653.7	45.8	7	14	44	10	17

Updated Activities

- Increased accuracy of quantification
- Ongoing round-robin for detection and quantification
- Currently testing LTPP samples

Binders' and Mixtures' Engineering Properties

Two Modification Approaches

- **Softening an unmodified PG to another PG**

PG64-22

6% REOB*

PG58-28

**with a single REOB sample*

Two Modification Approaches

- Softening an unmodified PG to another PG

PG64-22

*6% REOB**

PG58-28

- **Diluting a unmodified PG**

PG69-24

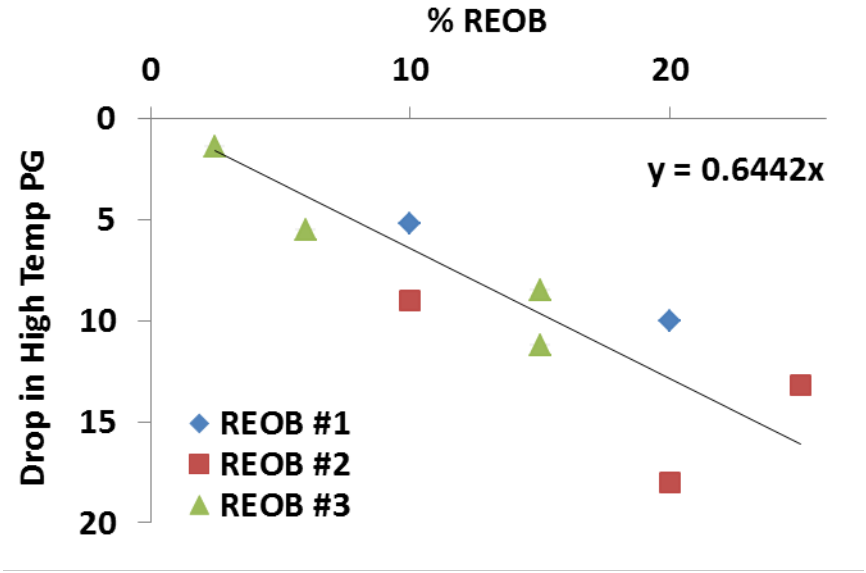
+20% PG100-0 ***+15% REOB****

PG58-28 **PG58-28**

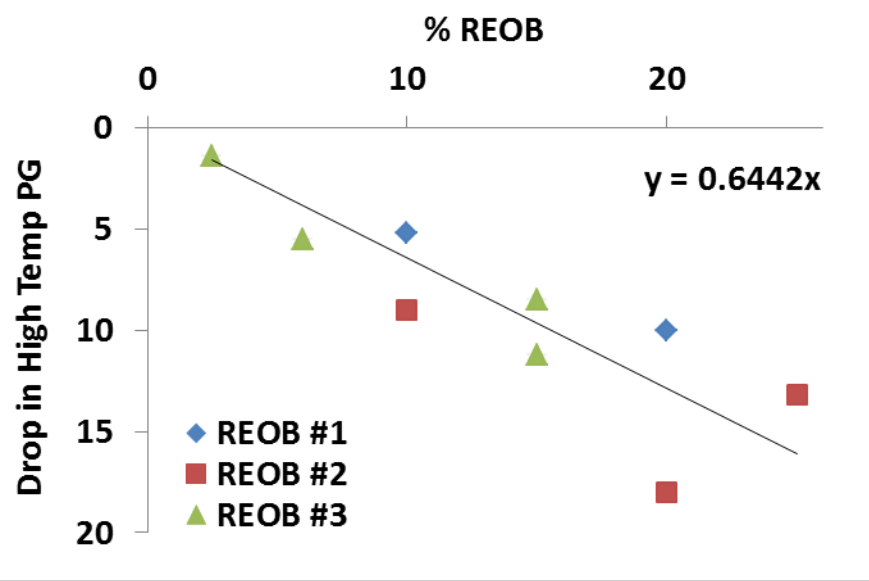
PG58-28 **PG58-28**

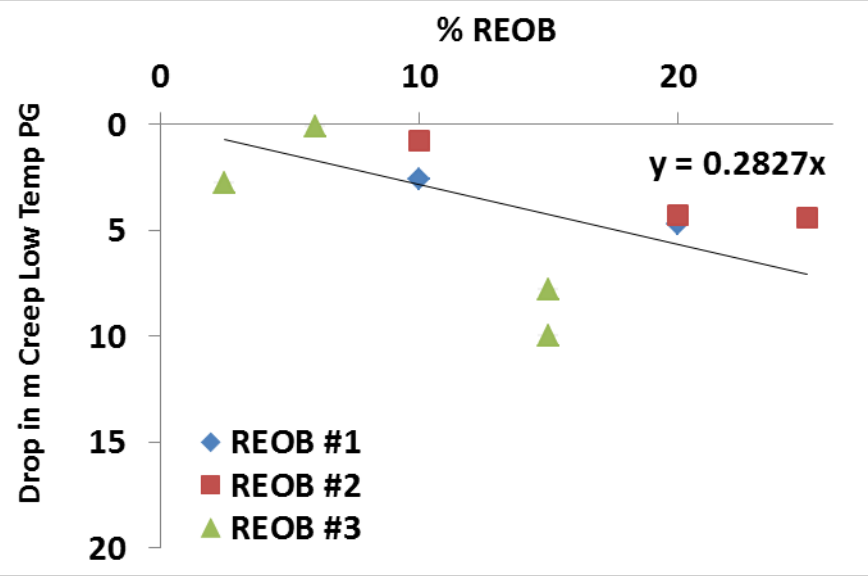
+2.5% REOB*

PG58-28* *with a single REOB sample*

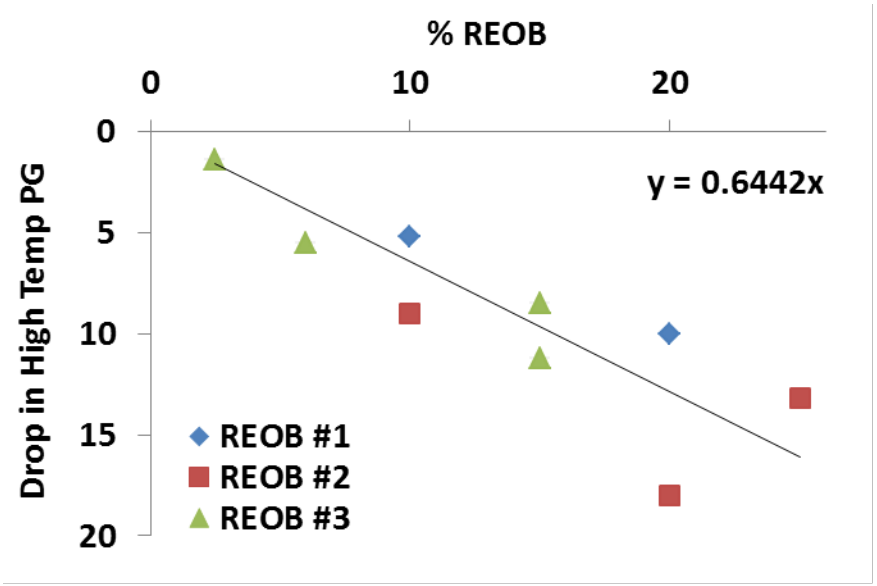


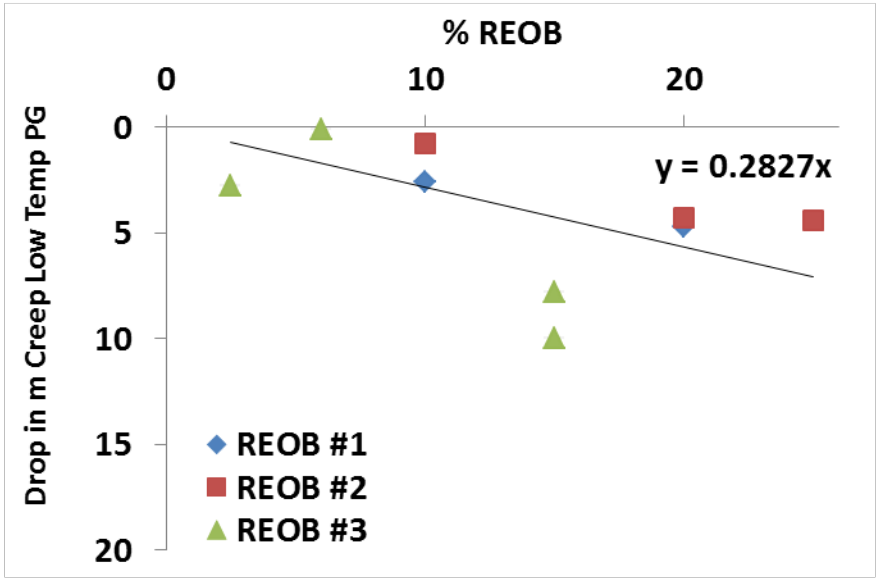
- **DSR High Temp**
  - **~9% REOB per PG Grade Drop**



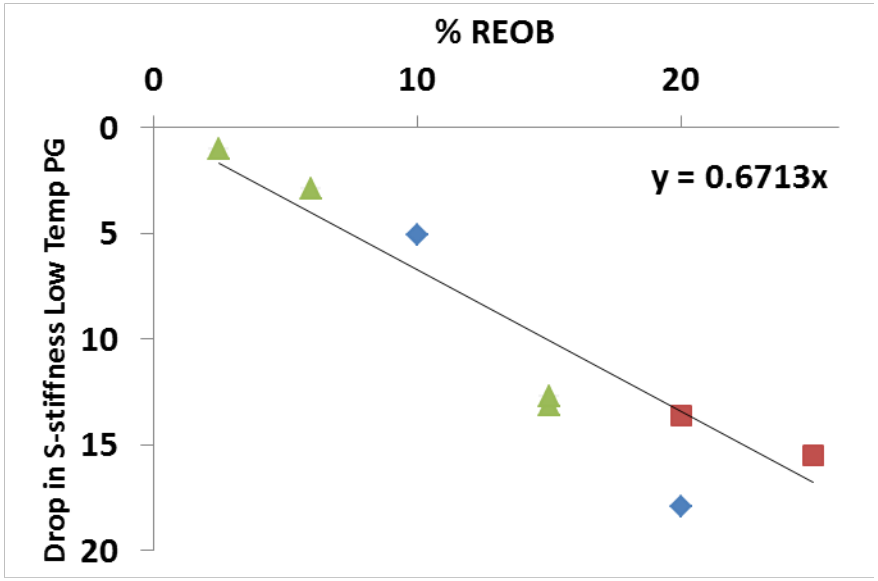


- **DSR High Temp**
  - **~9% REOB per PG Grade Drop**
- **BBR m-Value**
  - **~21% REOB per PG Grade Drop**





- **DSR High Temp**
  - **~9% REOB per PG Grade Drop**
- **BBR m-Value**
  - **~21% REOB per PG Grade Drop**
- **BBR Stiffness**
  - **~9% REOB per PG Grade Drop**



BBR $\Delta T_{critical}$ Spread: $PG_{(S)tiffness} - PG_{(m)\text{-}creep}$

	Base	*Exploratory Blends*			**Final Blends**
		+PG100-0	*+REOB Source 1*	*+REOB Source 2*	**+REOB Source 3**
	PAV				**PAV**
Holly 58-28	**-2.0°C** **60-30**				

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	PAV				**PAV**
Holly 58-28	**-2.0°C** **60-30**	*-0.8°C* *0% / 20%* *69-24*			
		-1.6°C *0% / 30%* *72-20*			

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		-1.6°C *0% / 30%* *72-20*	*-13°C* *25% / 30%* *59-25*		

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		-1.6°C *0% / 30%* *72-20*	*-13°C* *25% / 30%* *59-25*		*-5.1°C* *15% / 0%* *51-40*

BBR $\Delta T_{critical}$ Spread: $PG_{(S)tiffness} - PG_{(m)\text{-}creep}$

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		-1.6°C *0% / 30%* *72-20*	*-13°C* *25% / 30%* *59-25*		*-5.1°C* *15% / 0%* *51-40*
					-0.2°C **2.5%** **59-33**

BBR $\Delta T_{critical}$ Spread: $PG_{(S)tiffness} - PG_{(m)\text{-}creep}$

	Base	Exploratory Blends			Final Blends
		+PG100-0	+REOB Source 1	+REOB Source 2	+REOB Source 3
	PAV				PAV
Holly 58-28	**-2.0°C** **60-30**	*-0.8°C* *0% / 20%* *69-24*	*-10°C* *20% / 20%* *59-28*	*-14°C* *20% / 20%* *51-28*	**-5.7°C** **15% / 20%** **58-33**
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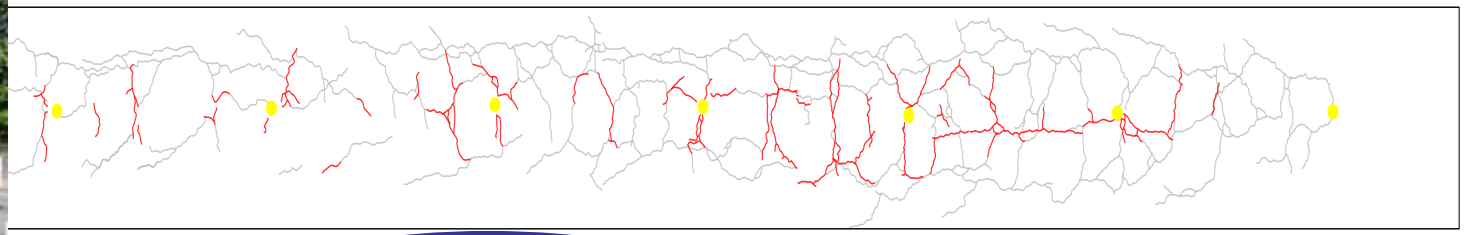
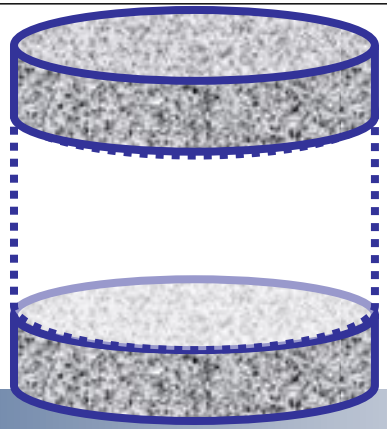
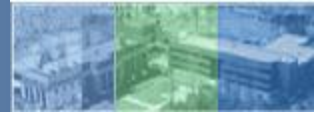
					-0.2°C **2.5%** **59-33**
BP 64-22	+0.8°C 67-27		*-1.7°C* *10%* *61-31*	*-4.0°C* *10%* *58-29*	**-2.2°C** **6%** **61-28**

Awareness of long-term performance

- Utility of PAV to approximate 5-years age
- Poor performance after 5-years ***anecdotally*** attributed to REOB
- Data from FHWA ALF test sections
  - Top and bottom 1-inch of core extracted & recovered binder

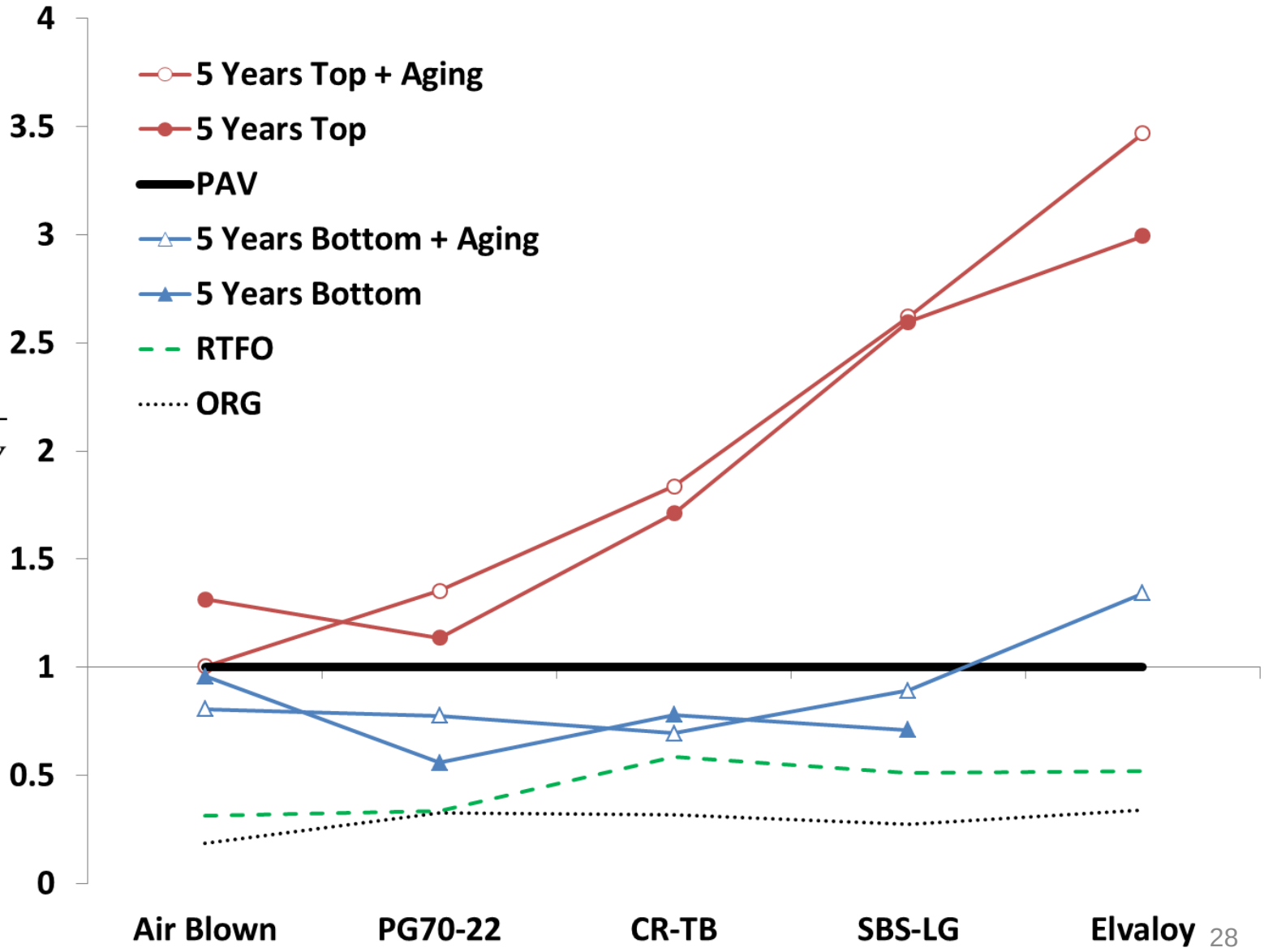


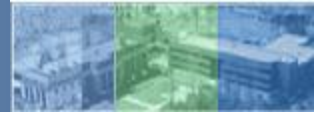


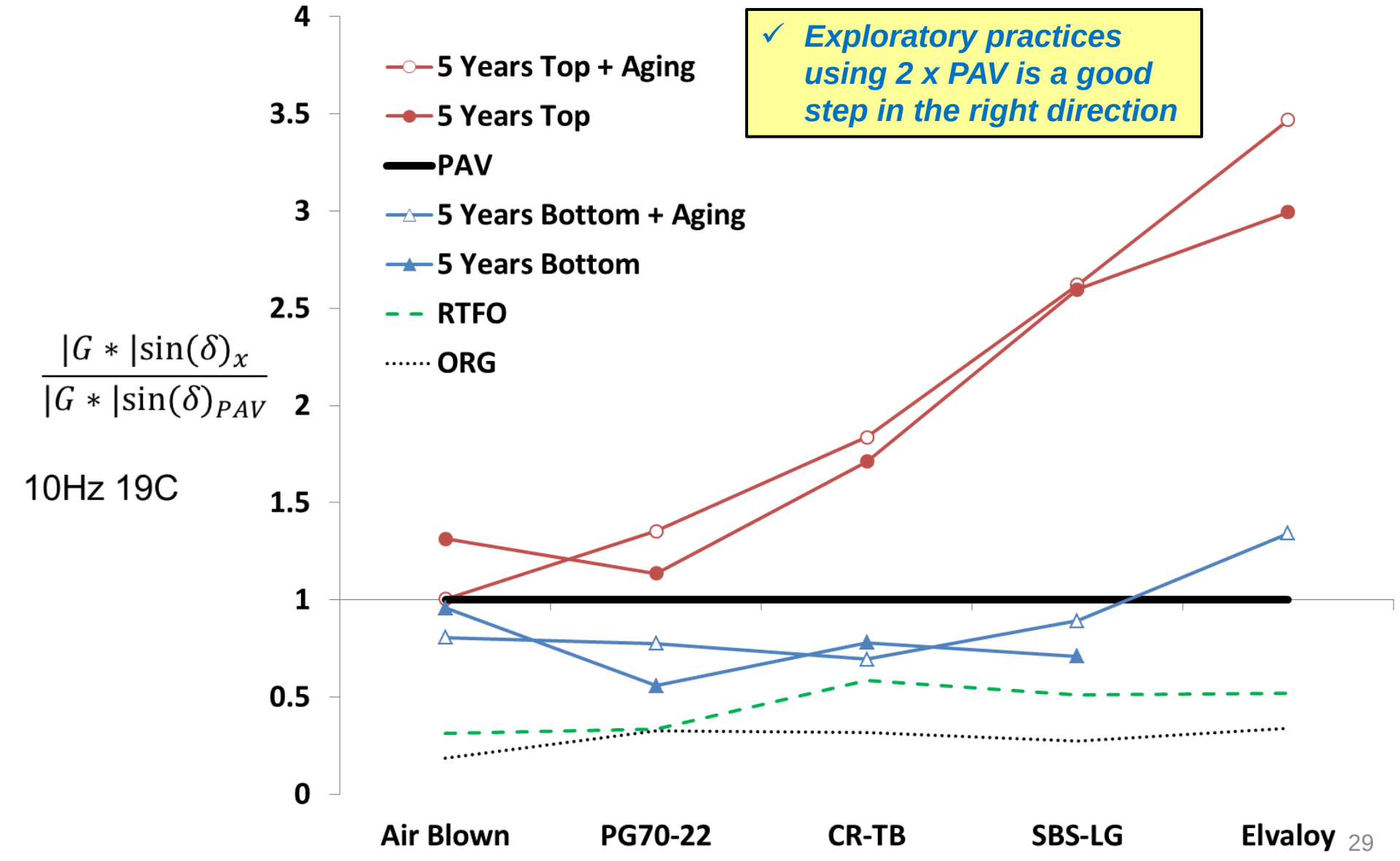


$$\frac{|G * |\sin(\delta)_x}{|G * |\sin(\delta)_{PAV}}$$

10Hz 19C



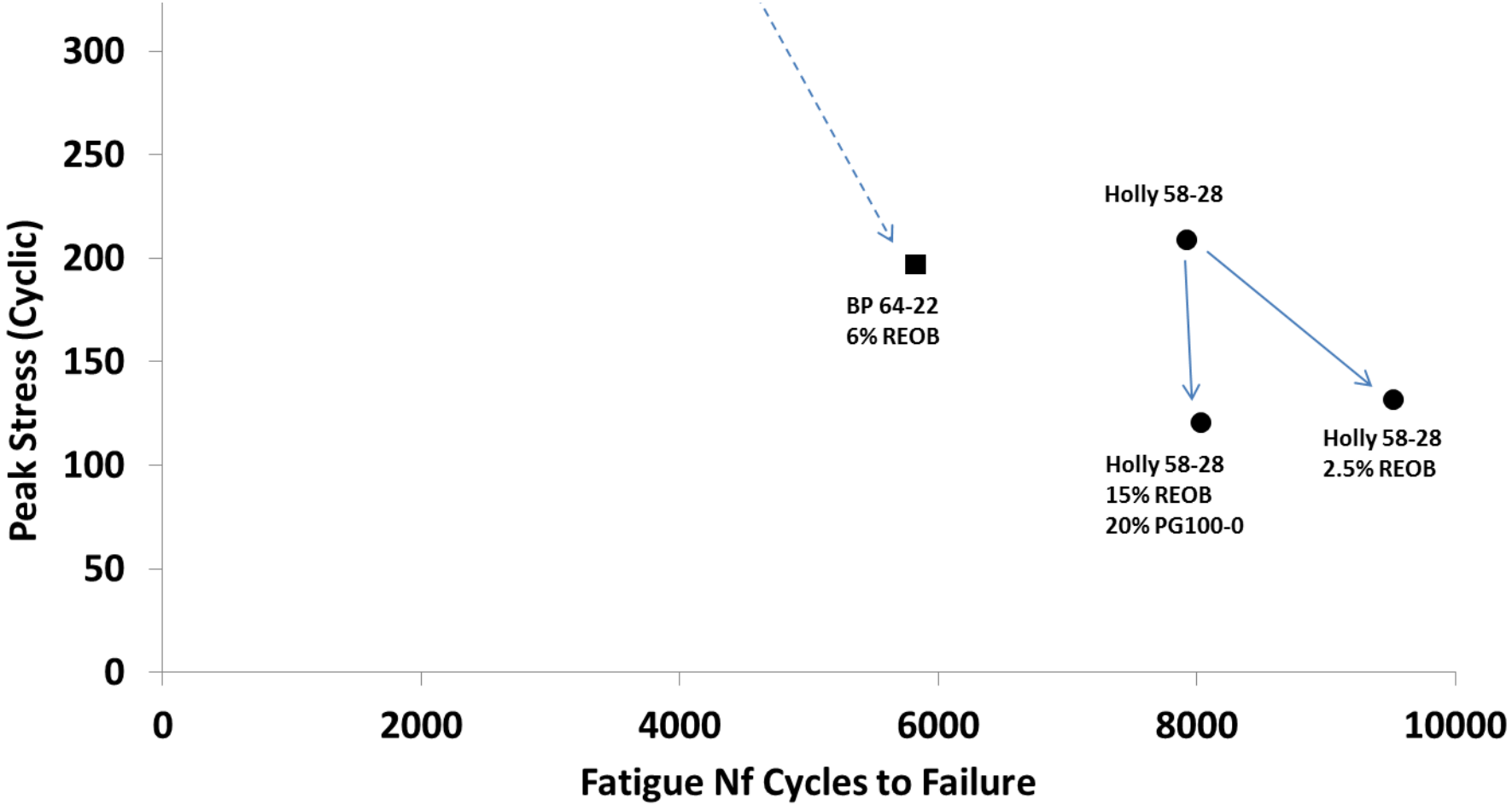


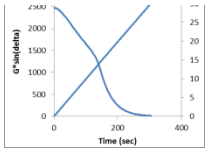

✓ Exploratory practices using 2 x PAV is a good step in the right direction
5 Years Top + Aging
5 Years Top
PAV
5 Years Bottom + Aging
5 Years Bottom
RTFO
ORG
$\frac{|G * |\sin(\delta)_x}{|G * |\sin(\delta)_{PAV}}$
10Hz 19C
4
3.5
3
2.5
2
1.5
1
0.5
0
Air Blown
PG70-22
CR-TB
SBS-LG
Elvaloy

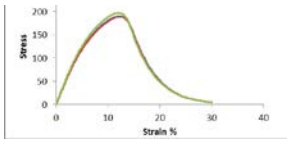
BBR $\Delta T_{critical}$ Spread: $PG_{(S)tiffness} - PG_{(m)\text{-}creep}$

	Base		*Exploratory Blends*			**Final Blends**	
			+PG100-0	*+REOB Source 1*	*+REOB Source 2*	**+REOB Source 3**	
	PAV	**2 X PAV**				**PAV**	**2 X PAV**
Holly 58-28	**-2.0°C** **60-30**	**-1.1°C** **□-29**	*-0.8°C* *0% / 20%* *69-24*	*-10°C* *20% / 20%* *59-28*	*-14°C* *20% / 20%* *51-28*	**-5.7°C** **15% / 20%** **58-33**	**-10°C** **15% / 20%** **□-26**
			-1.6°C *0% / 30%* *72-20*	*-13°C* *25% / 30%* *59-25*		*-5.1°C* *15% / 0%* *51-40*	*-10°C* *15% / 0%* *□-34*
						-0.2°C **2.5%** **59-33**	**-2.8°C** **2.5%** **□-29**
BP 64-22	+0.8°C 67-27	-1.9°C □-23		*-1.7°C* *10%* *61-31*	*-4.0°C* *10%* *58-29*	**-2.2°C** **6%** **61-28**	**-2.9°C** **6%** **□-23**

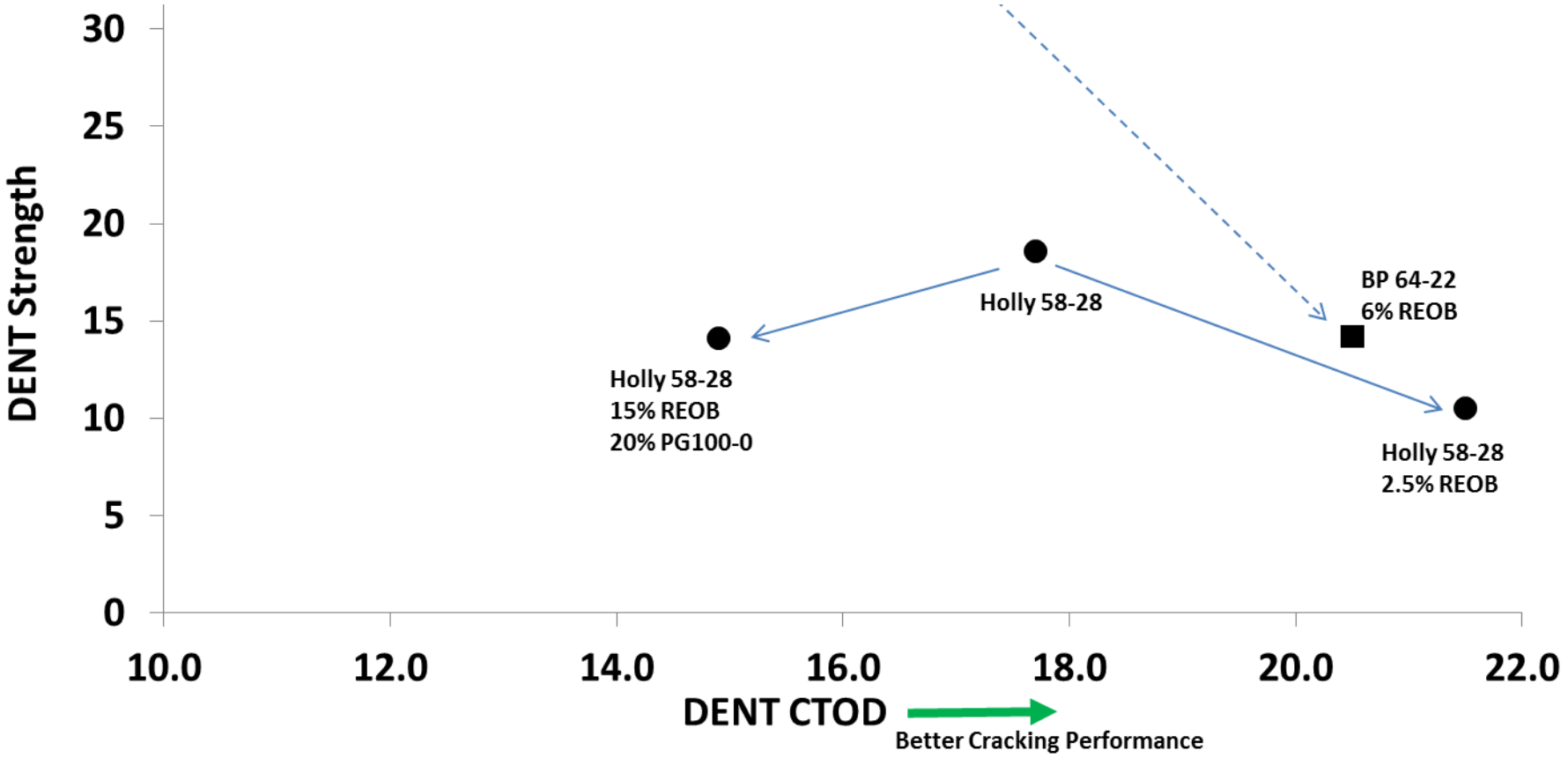
DSR Fatigue: Linear Amplitude Sweep (LAST)

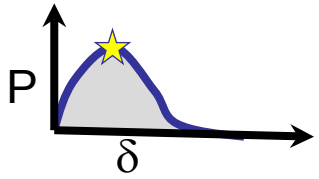


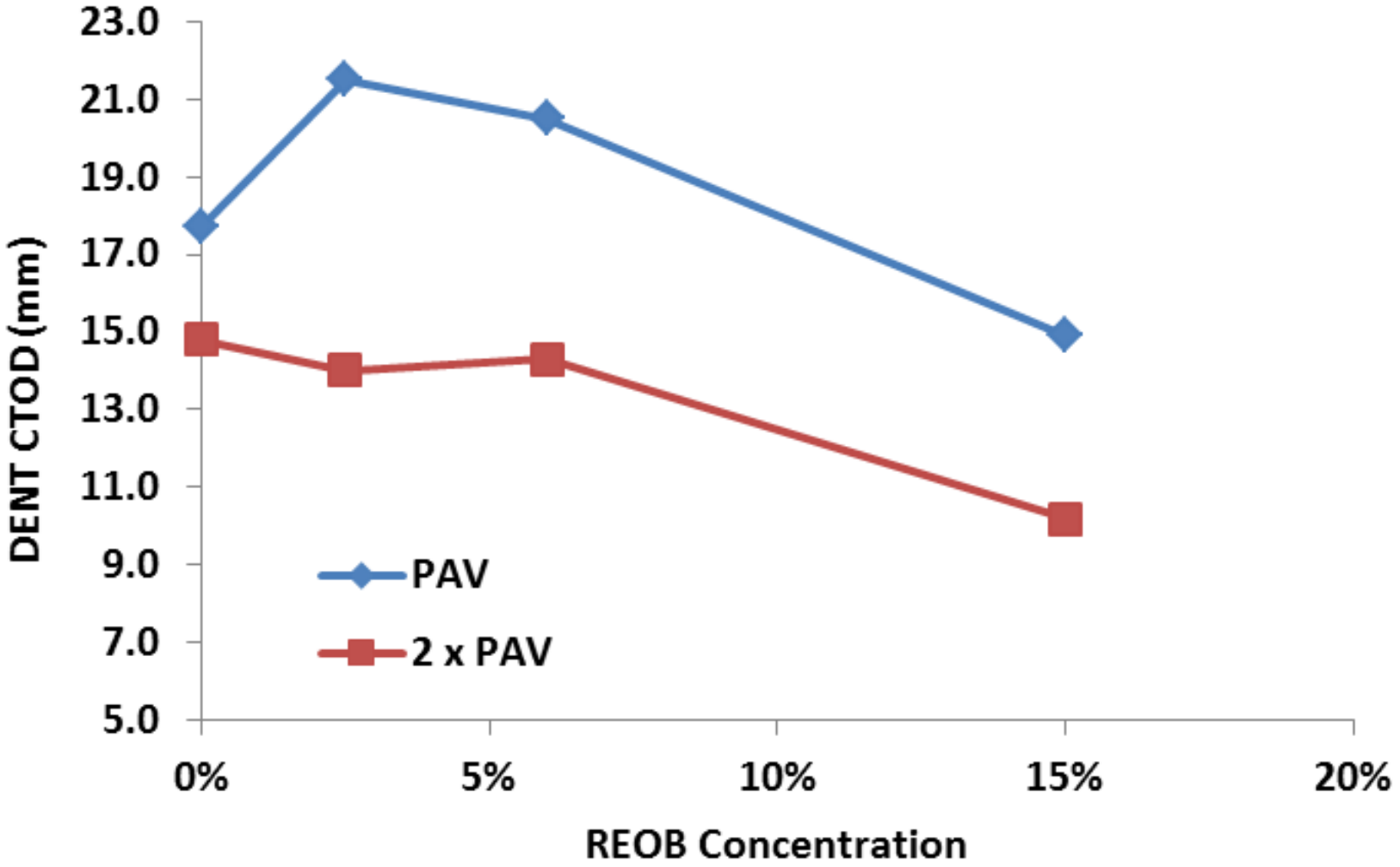




Notched Tension: Cracking Strain Tolerance

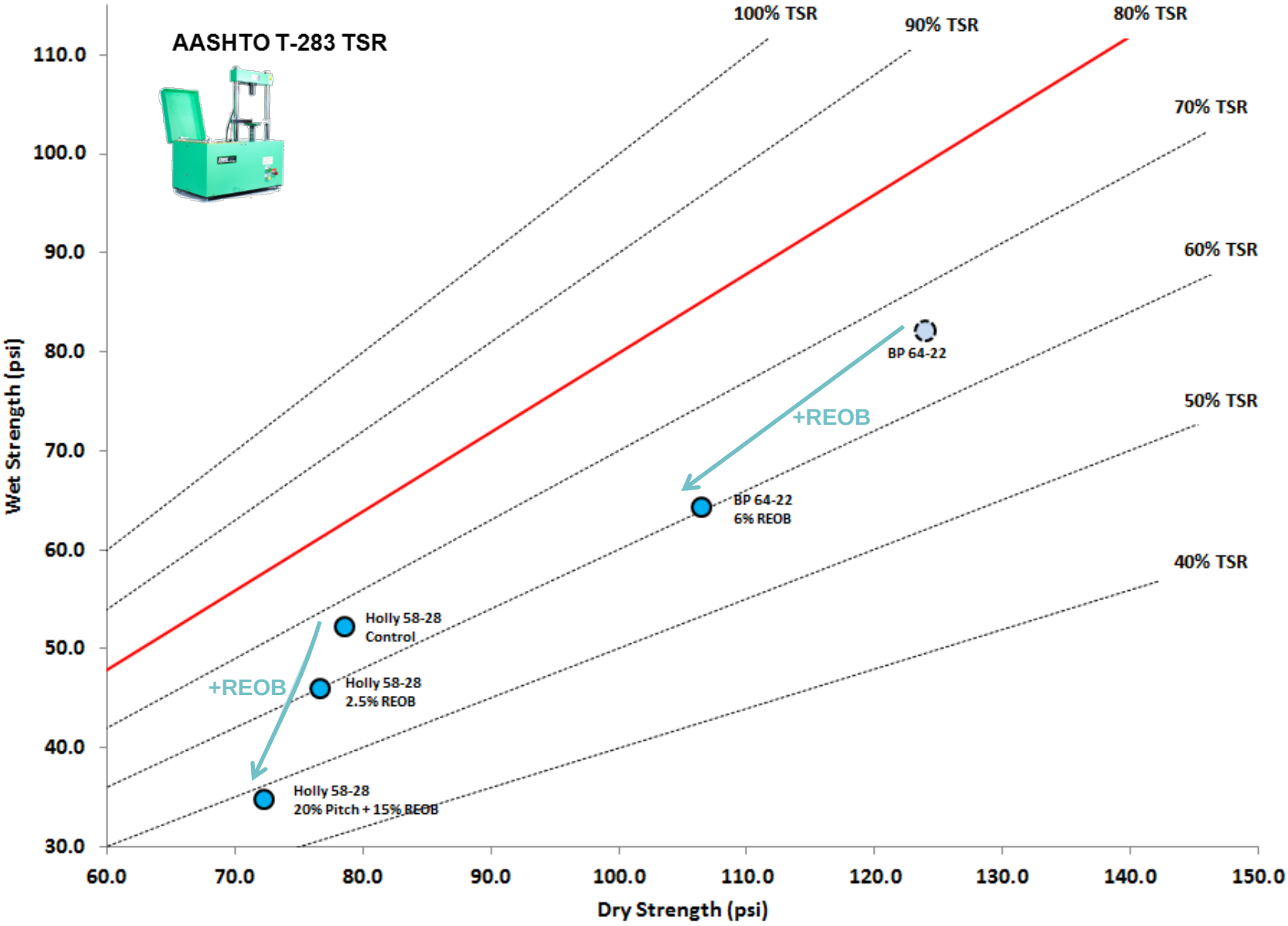


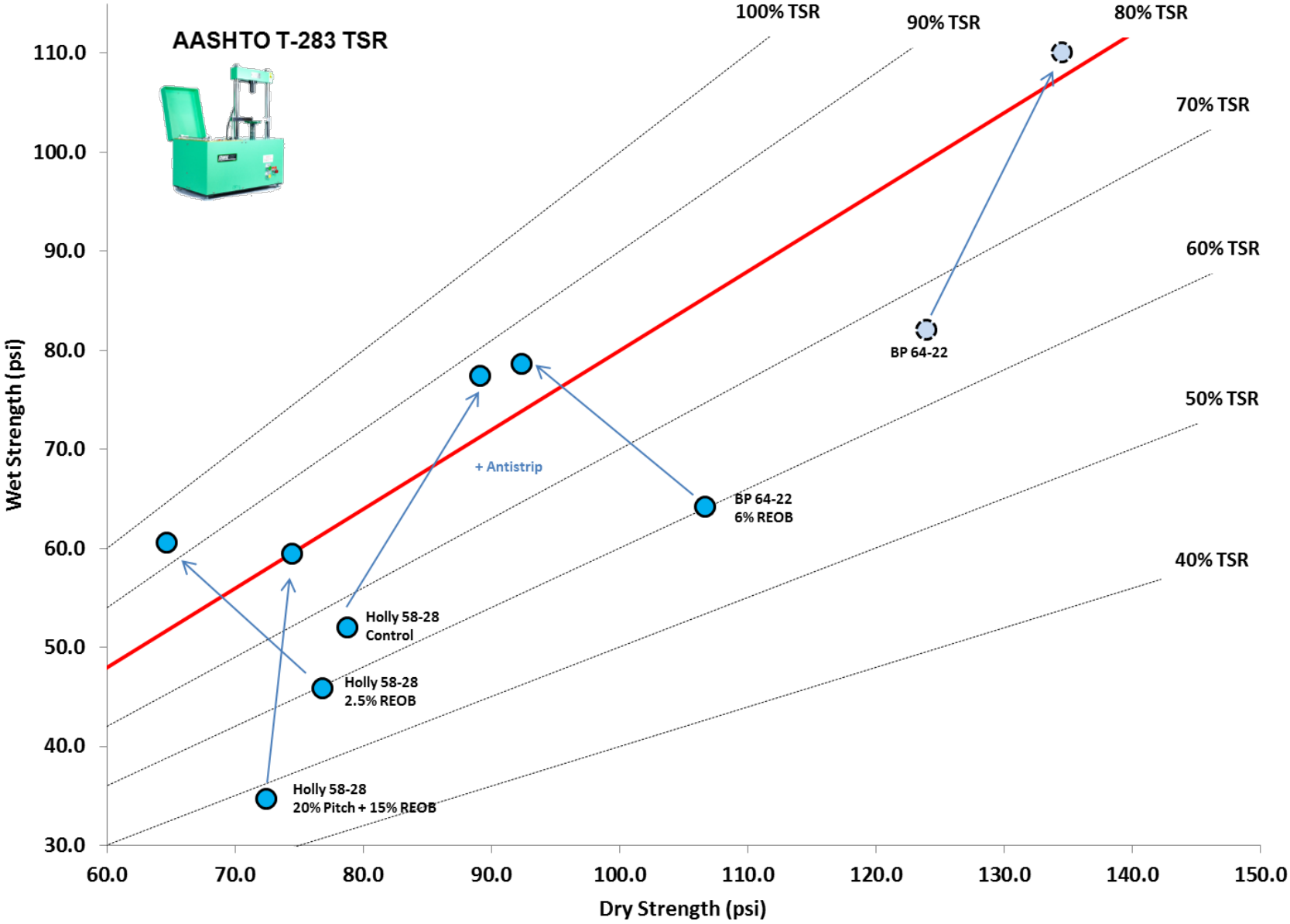


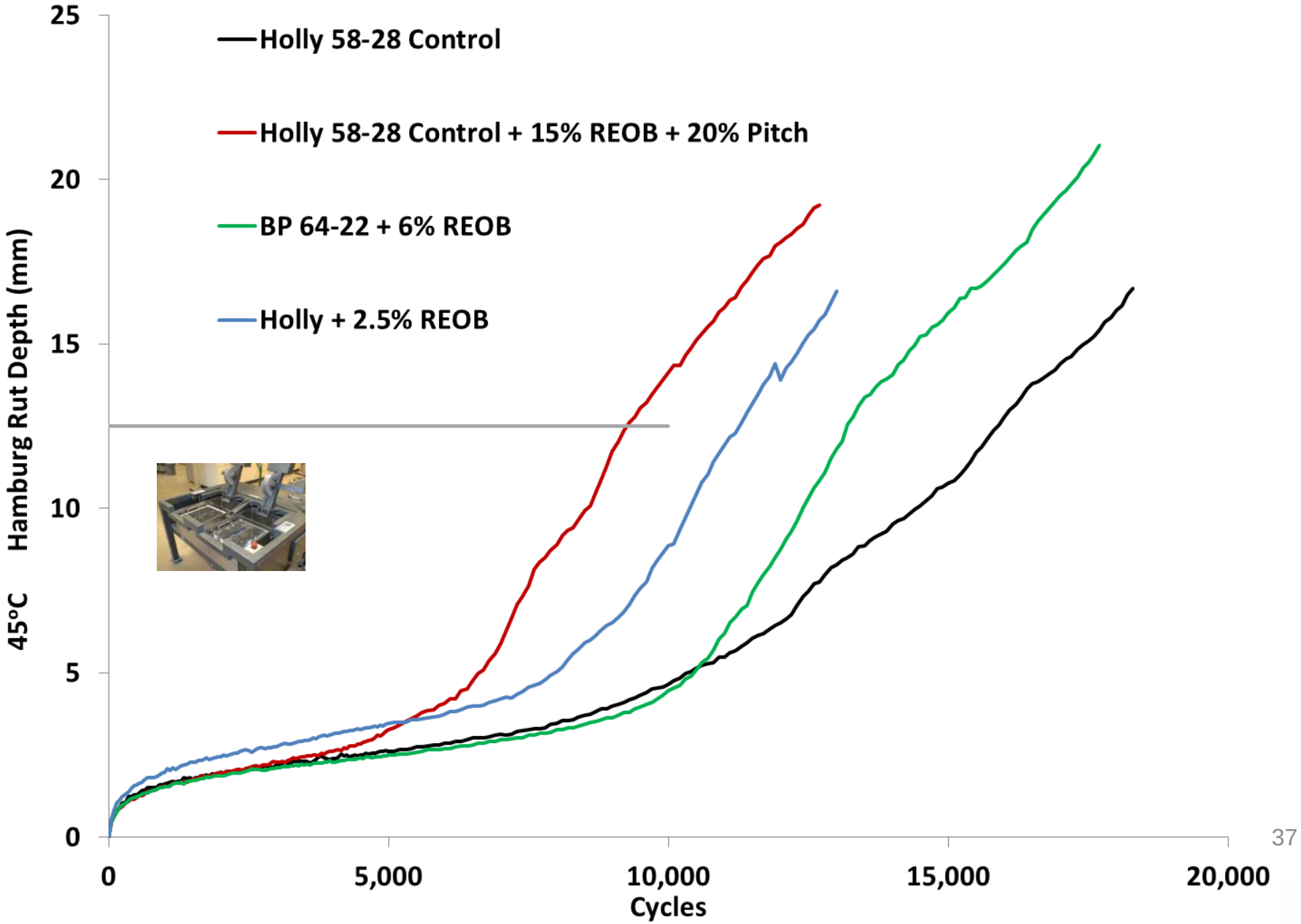

23.0
21.0
19.0
17.0
15.0
13.0
11.0
9.0
7.0
5.0
DENT CTOD (mm)
PAV
2 x PAV
0%
5%
10%
15%
20%
REOB Concentration

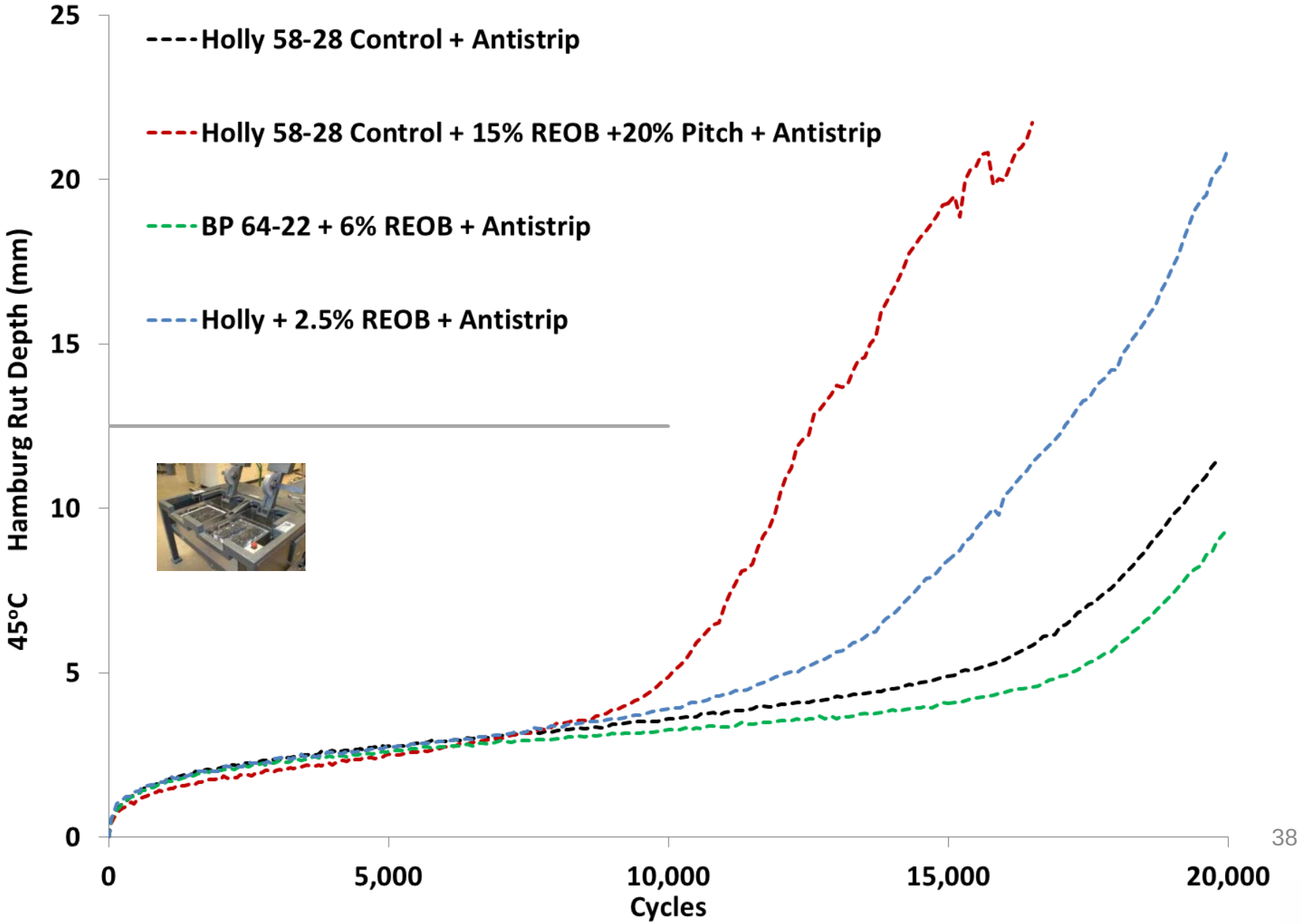
Ongoing Mixtures' Experimental Design

- **"Moisture Damage"**
  - Granite- Occoquan, VA
  - Tensile Strength Retained TSR
  - Hamburg Wheel Tracking
  - Repeated With & Without Liquid Amine Anti-strip ~~or Hydrated Lime~~
- **"Structural Performance"**
  - ALF 22% RAP Mix
  - ~~Flow Number; confined NCHRP 9-30A~~
  - Dynamic Modulus, |E*|
  - Uniaxial Fatigue - **Short and Long-Term Aged** *(loose mix 5 days @ 85°C)*
  - Thermal Stress Restrained Specimen TSRST - **Short and Long-Term Aged** *(loose mix 5 days @ 85°C)*


AASHTO T-283 TSR
100% TSR
90% TSR
80% TSR
70% TSR
60% TSR
50% TSR
40% TSR
Wet Strength (psi)
Dry Strength (psi)
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
BP 64-22
+REOB
BP 64-22
6% REOB
Holly 58-28
Control
+REOB
Holly 58-28
2.5% REOB
Holly 58-28
20% Pitch + 15% REOB

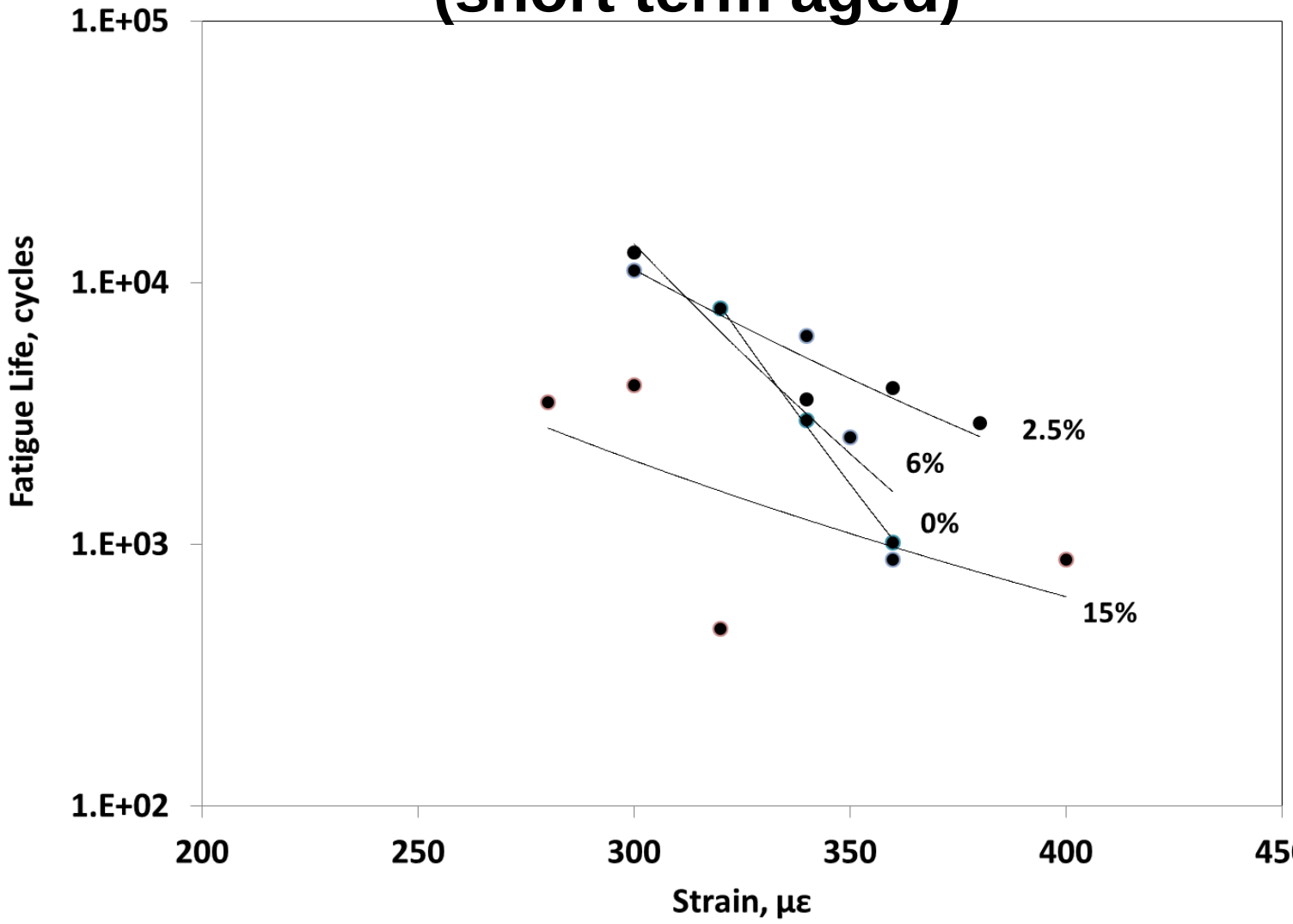

AASHTO T-283 TSR
100% TSR
90% TSR
80% TSR
70% TSR
60% TSR
50% TSR
40% TSR
Wet Strength (psi)
Dry Strength (psi)
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
BP 64-22
+ Antistrip
BP 64-22
6% REOB
Holly 58-28
Control
Holly 58-28
2.5% REOB
Holly 58-28
20% Pitch + 15% REOB


Holly 58-28 Control
Holly 58-28 Control + 15% REOB + 20% Pitch
BP 64-22 + 6% REOB
Holly + 2.5% REOB
45°C Hamburg Rut Depth (mm)
25
20
15
10
5
0
0
5,000
10,000
15,000
20,000
Cycles

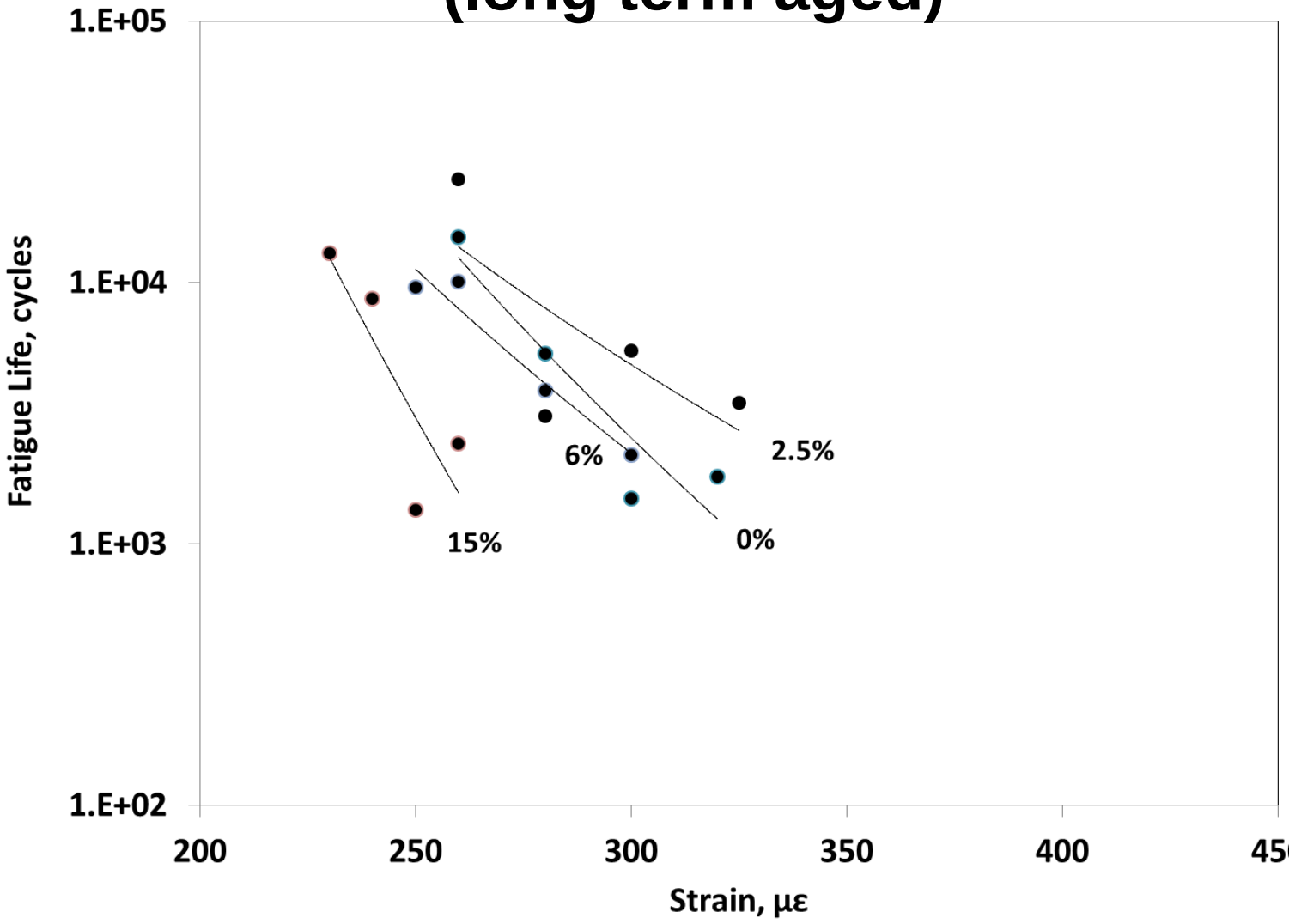

Holly 58-28 Control + Antistrip
Holly 58-28 Control + 15% REOB +20% Pitch + Antistrip
BP 64-22 + 6% REOB + Antistrip
Holly + 2.5% REOB + Antistrip
45°C Hamburg Rut Depth (mm)
25
20
15
10
5
0
0
5,000
10,000
15,000
20,000
Cycles

Fatigue – Effect of REOB

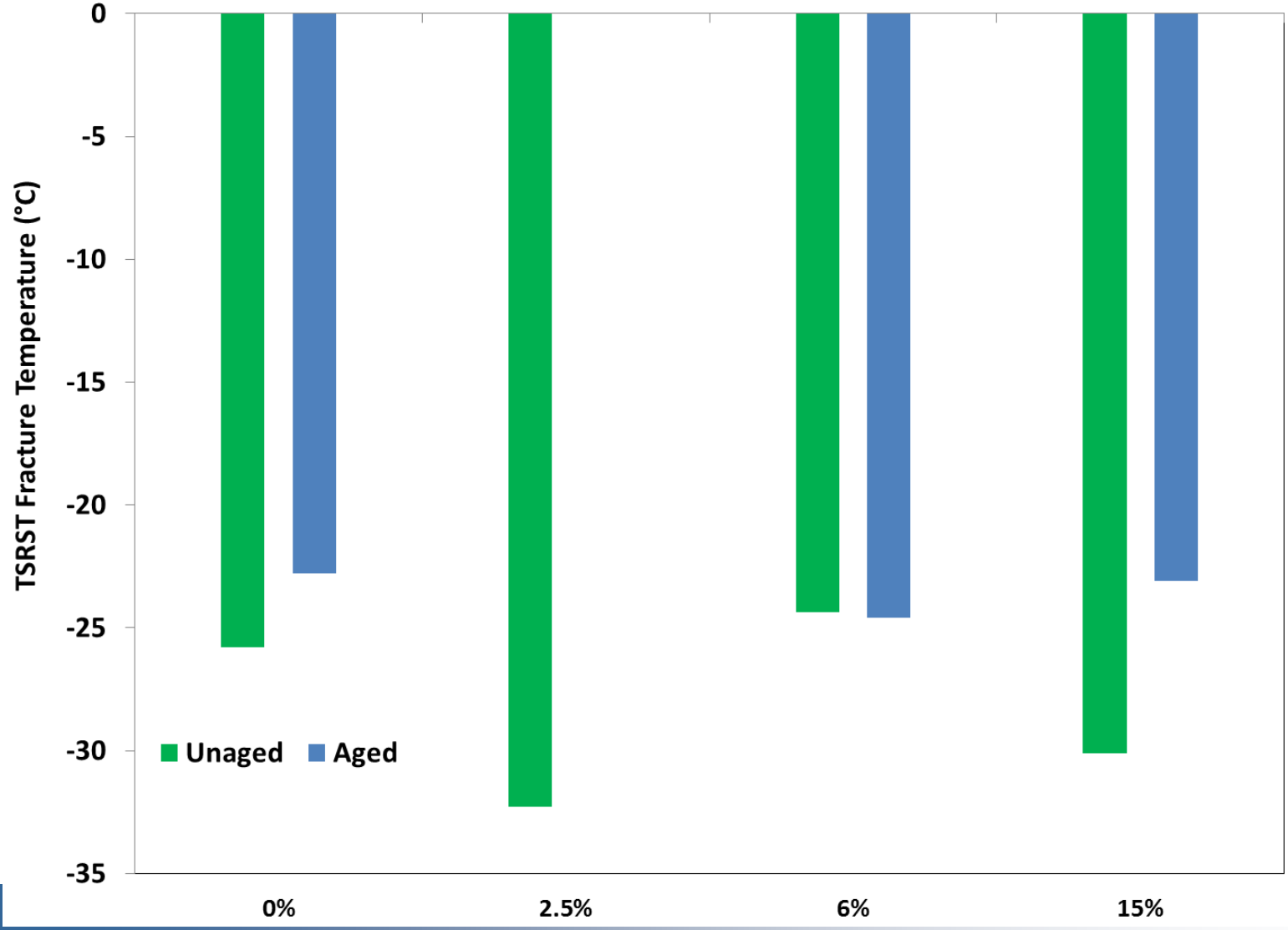
(short term aged)



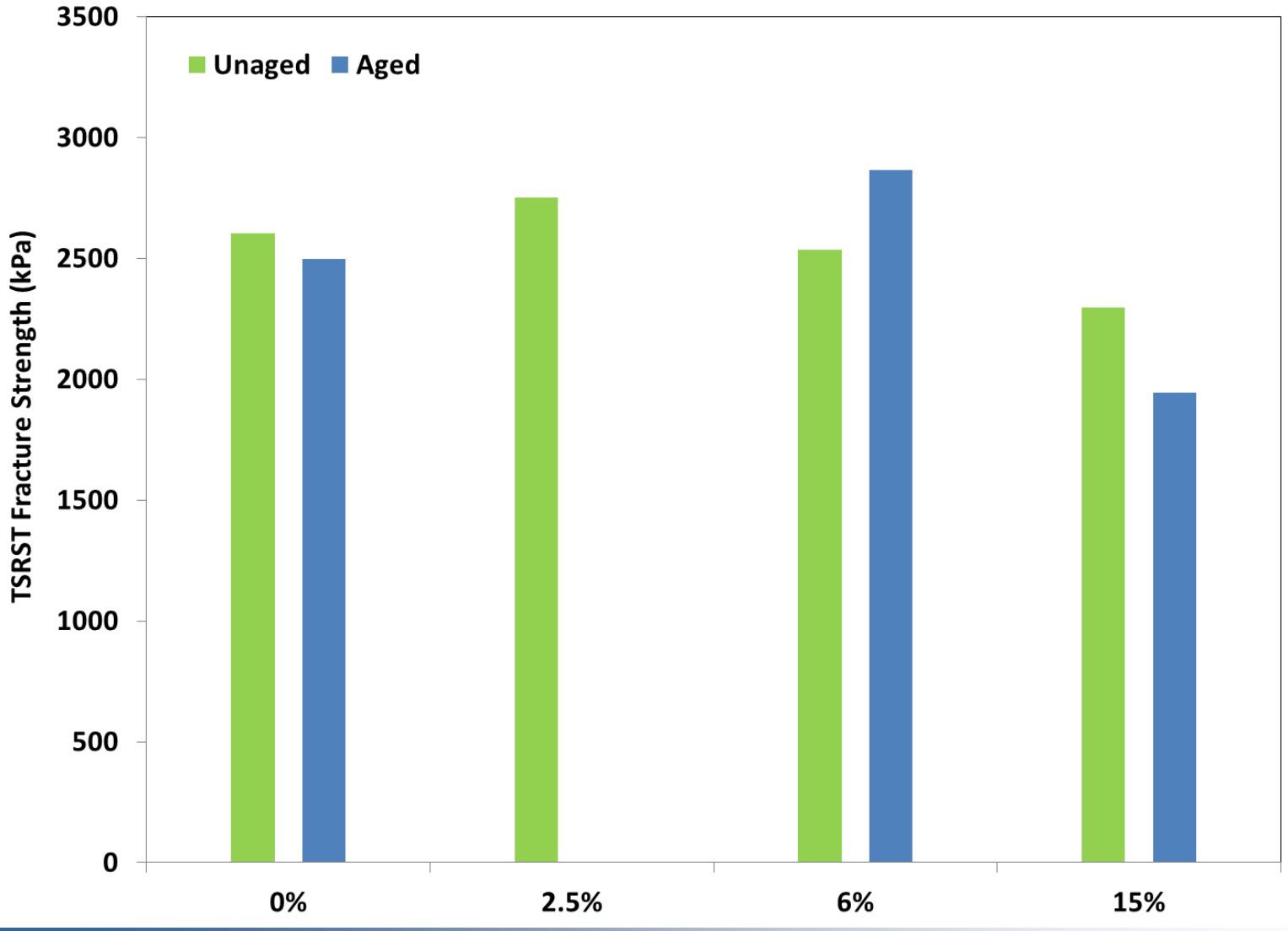
Fatigue – Effect of REOB
(long term aged)



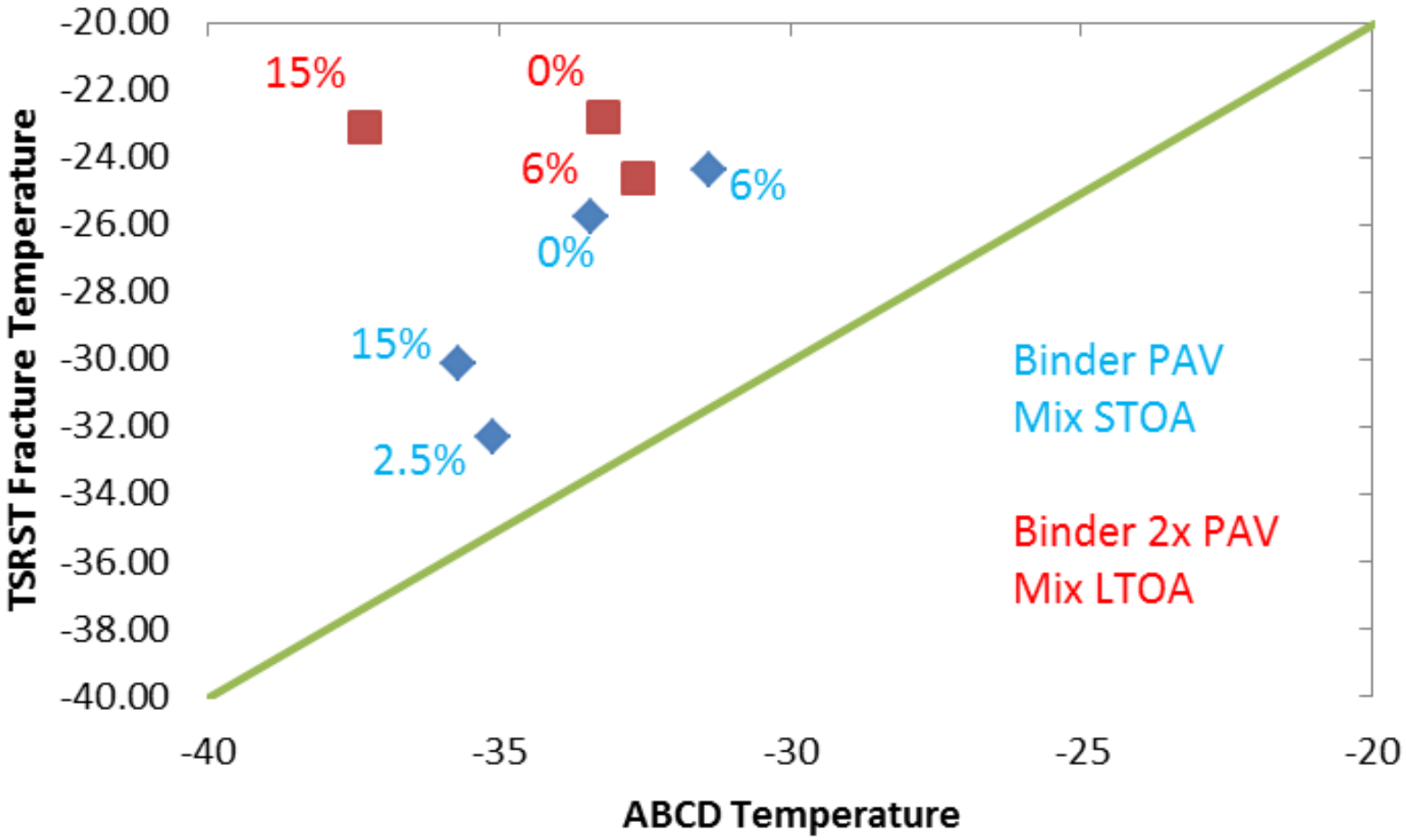
Thermal Cracking



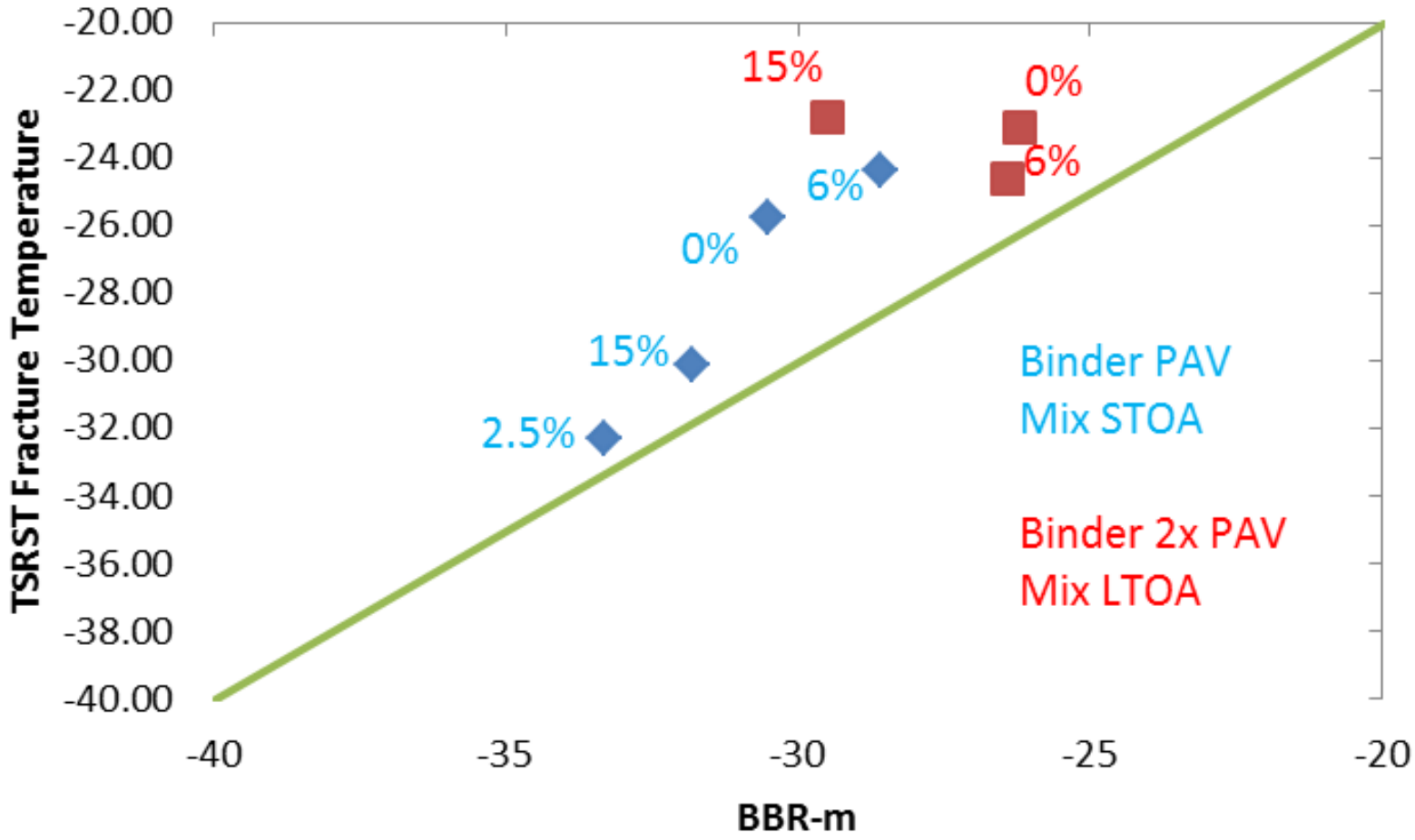
Thermal Cracking



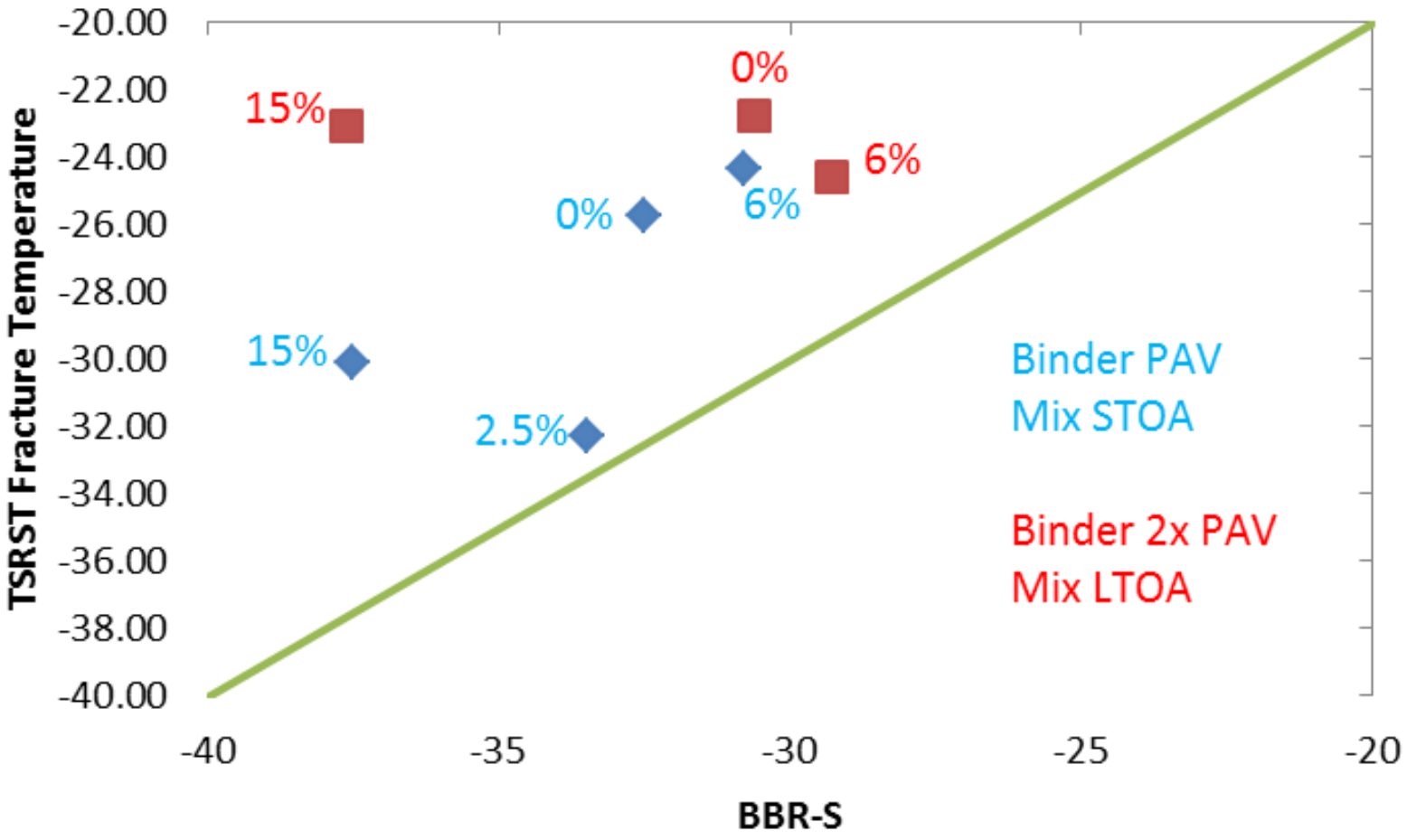
Thermal Cracking



Thermal Cracking



Thermal Cracking



Findings (1 of 5)

1. **You can readily detect REOB presence**
2. **You can tell how much is there; but you *cannot* tell *exactly* how much is there.**
   - **Round Robin XRF results may shed more light on this.**
3. **Effect of REOB depends on base binder (like PPA)**
4. **Variation between REOB suppliers & their samples**
   - **Same concentration can produce different PG grades**

Findings (2 of 5)

5. **2 X PAV is a reasonable approximation of 5 years - *where anecdotal concerns lie* (ALF Data)**

6. **REOB softens and reduces tensile strength**
   - **Binder notched tension (DENT)**
   - **Decreases mix wet and dry IDT strength**
   - **Also seen in TSRST**

7. **In 2 of 3 cases, REOB improved ***binder*** intermediate temperature parameters for fatigue / strain tolerance**
   - **6% and 2.5% REOB blends**
   - **CTOD and LAST**

Findings (3 of 5)

8. **Rheological "disruption" occurred w/ highest %REOB**
   - **Differences in Low Temperature m&S**
   - **Did Not occur in blend with PG100-0 by itself**
   - **Did occur in blends with high-REOB + PG100-0**

   - **Made worse by continued aging**
   - **Alludes to performance deterioration**

   - **Corroborated by DENT CTOD & LAST & Stripping**

   - **Forces the issue of compatibility** (extenders, rejuvenators, RAP / RAS, WMA…)

Findings (4 of 5)

9. REOB effects on Moisture Sensitivity

- TSR ratio, strength and Hamburg performance decreases with increasing REOB when no anti-strip is added
- REOB did not interfere with liquid anti-strip which improved TSR and Hamburg performance
- Liquid anti-strip (0.4%) alters IDT strength and Hamburg deterioration more than REOB (2.5%-15%)

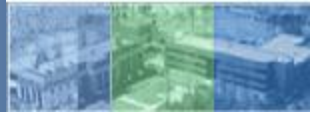
Findings (5 of 5)

10. Conclusions

- Low concentrations of REOB did not appear to adversely affect binder and mixture properties
- High concentration of REOB consistent with loss of strength in different binder and mix test methods

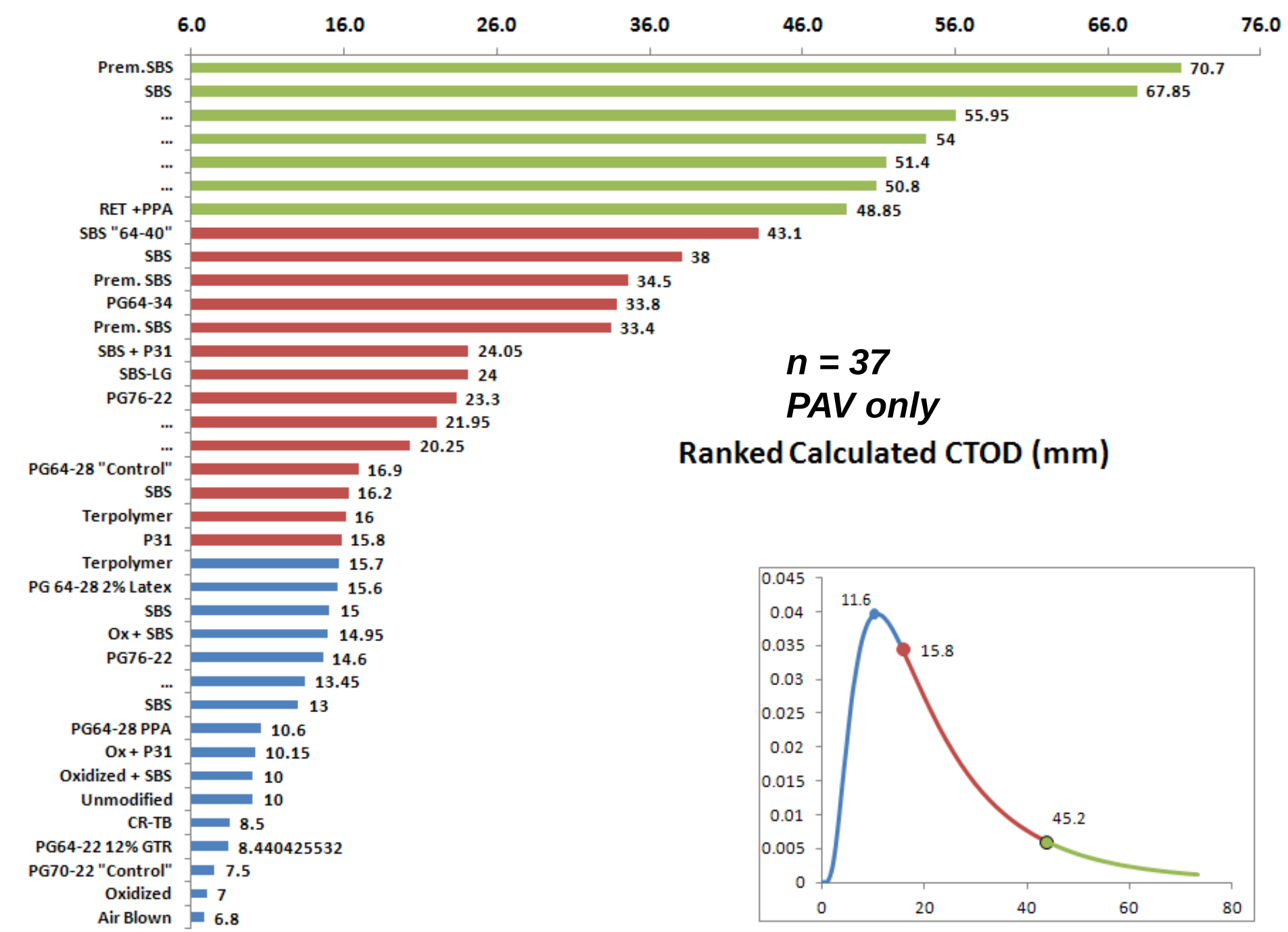
11. Recommendations

- Further examination of m & S as “flag” is warranted.
- Minimum value for S should be reexamined



Thank You.

Questions?


6.0
16.0
26.0
36.0
46.0
56.0
66.0
76.0
Prem.SBS 70.7
SBS 67.85
... 55.95
... 54
... 51.4
... 50.8
RET +PPA 48.85
SBS "64-40" 43.1
SBS 38
Prem. SBS 34.5
PG64-34 33.8
Prem. SBS 33.4
SBS + P31 24.05
SBS-LG 24
PG76-22 23.3
... 21.95
... 20.25
PG64-28 "Control" 16.9
SBS 16.2
Terpolymer 16
P31 15.8
Terpolymer 15.7
PG 64-28 2% Latex 15.6
SBS 15
Ox + SBS 14.95
PG76-22 14.6
... 13.45
SBS 13
PG64-28 PPA 10.6
Ox + P31 10.15
Oxidized + SBS 10
Unmodified 10
CR-TB 8.5
PG64-22 12% GTR 8.440425532
PG70-22 "Control" 7.5
Oxidized 7
Air Blown 6.8
n = 37
PAV only
Ranked Calculated CTOD (mm)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
11.6
15.8
45.2
0
20
40
60
80

CTOD Values - All Binders Tested Thus Far

Low Temperature Performance Grade	High Temperature Performance Grade							
	88	82	76	70	64	58	52	46
-22	37: 33.4	34	31: 23.3, 16.8	28: ***8.6***	25: 30.1, 9.7	22	19	16
-28	34	31: 34.5	28: 53.8, 46.5, 9.8	25: 27.6, 15.7, ***7.8***	22: 16.9, 15.6, 10.6	19: 38.8, 27.5, 24.1, 12.6	16	13
-34	31	28	25: 70.7	22: 49.6	19: 43.7, 33.8, 16, 15, ***12***	16: 35, ***8.1***	13: 15.3, ***10***	10: 47.3

- Extension Rate = 100mm/min, T = 25°C

CTOD Values – Polymer Modified

Low Temperature Performance Grade	High Temperature Performance Grade: 88	82	76	70	64	58	52	46
-22	37 33.4	34	31 23.3 16.8	28	25 30.1 9.7	22	19	16
-28	34	31 34.5	28 53.8 46.5 9.8	25 27.6 15.7	22 16.9 15.6 10.6	19 38.8 27.5 24.1 12.6	16	13
-34	31	28	25 70.7	22 49.6	19 43.7 33.8 16 15	16 35	13 15.3	10 47.3

- Extension Rate = 100mm/min, T = 25°C

CTOD Values – Unmodified

Low Temperature Performance Grade	High Temperature Performance Grade							
	88	82	76	70	64	58	52	46
-22	37	34	31	28 ***8.6***	25	22	19	16
-28	34	31	28	25 ***7.8***	22	19	16	13
-34	31	28	25	22	19 ***12***	16 ***8.1***	13 ***10***	10

- Extension Rate = 100mm/min, T = 25°C

CTOD Values for Various Tested Binders

PG 88-xx	PG 82-xx	PG 76-xx	PG 70-xx	PG 64-xx	PG 58-xx	PG 52-xx	PG 46-xx
33.4	34.5	53.8	49.6	43.7	38.8	15.3	47.3
		46.5	27.6	33.8	35.0	10.0	
		23.3	15.7	30.1	27.5		
		16.8	8.6	16.9	24.1		
		9.8	7.8	16.0	12.6		
				15.6	8.1		
				15.0			
				12.0			
				10.6			
				9.7			

PG xx-22	PG xx-28	PG xx-34
33.4	53.8	70.7
30.1	46.5	49.6
23.3	38.8	47.3
16.8	34.5	43.7
9.7	27.6	35.0
8.6	27.5	33.8
	24.1	16.0
	16.9	15.3
	15.6	15.0
	15.7	12.0
	12.6	10.0
	10.6	8.1
	9.8	
	7.8	

- Extension Rate = 100mm/min,
- T = 25°C

Impact of REOB on Crossover frequency and Rheological index