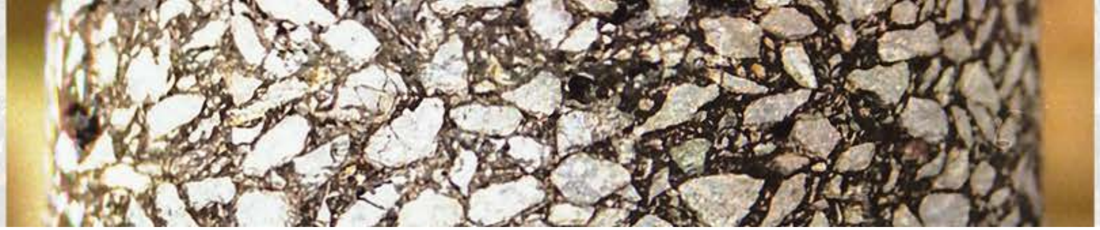
1ST INTERNATIONAL CONFERENCE ON Stone Matrix Asphalt



SMA’s Evolution: Rubber Modified SMA’s

Kamil E. Kaloush, PhD, PE, Professor, Arizona State University

November 5, 2018

Atlanta, Georgia

ASU NATIONAL CENTER of EXCELLENCE for SMART INNOVATIONS

ARIZONA STATE UNIVERSITY

Outline

- Historical perspective
- Design concepts, production and emerging technologies
- Binder and mixtures characteristics
- Laboratories studies and field performance
- Use in pavement designs

Historical Overview of Crumb Rubber in Asphalt

1960s Charles McDonald Experiments w/AR

1970s AR Field City of Phoenix and ADOT Chip Seal Coat (SAM) and patents

1985-88 AR Gap Graded & Open Graded Mixes

1994 ASTM Specification   1995 Patents expire

1997 RPA Formed

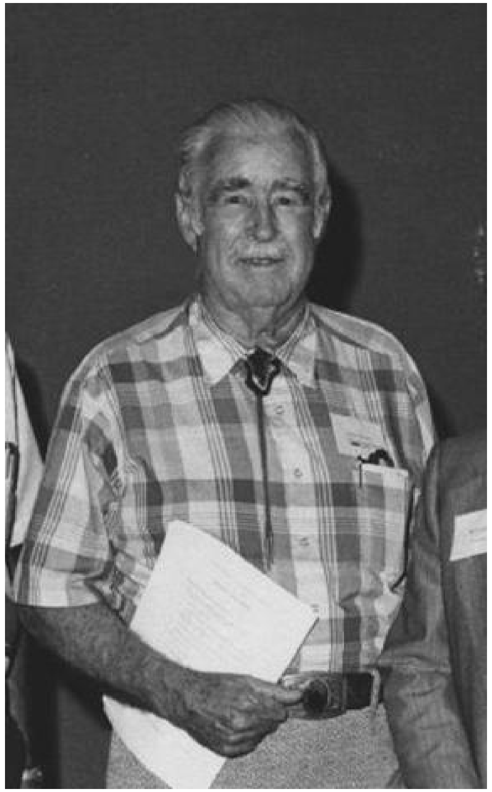
2000-2018 Seven International AR Conf.

Charlie (center) at First National A-R Conf. 1980

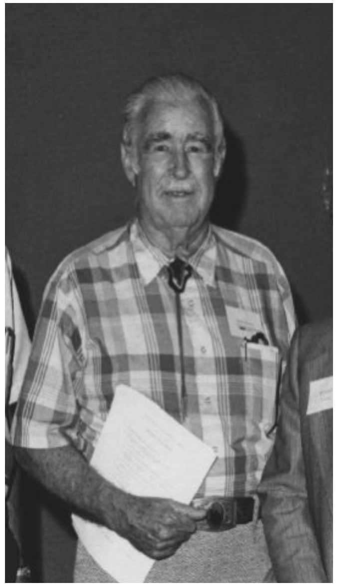
Others: Dr. J. Love FHWA, Dr. J. Epps Tex A&M, Dr. B. Galloway TTI, Gene Morris ATRC

Charles McDonald
Inventor of
Asphalt Rubber

McDonald
Applying
AR Band Aid
Patch
Circa 1966

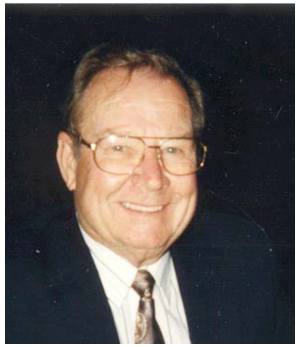


Asphalt
Rubber
Band Aid
Patch
Circa 1966



Bill Brake –
Sahuaro Asphalt
& Petroleum
/Edgington Oil

Don Nielsen,
Chairman of the Board
Arizona Refining
Company
/Union Oil Comp



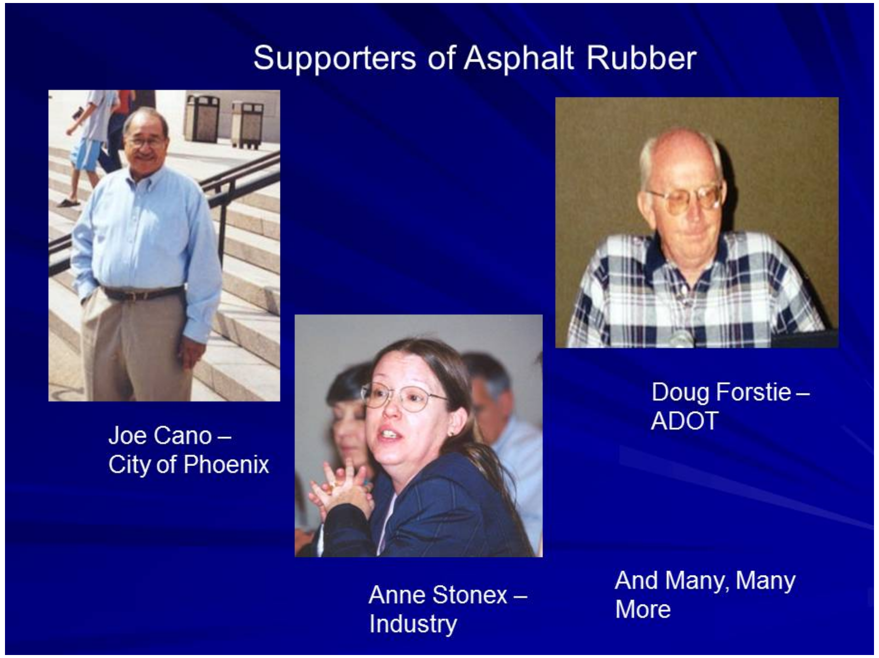
Gene Morris –
ADOT Research
Engineer

William "Bill" Price
ADOT State Engineer

Donna Carlson
RPA – Past Director

Charles H. McDonald

Fred Glendenning,
Director of Public
Works for the City
of Phoenix



George Way
ADOT - RAF

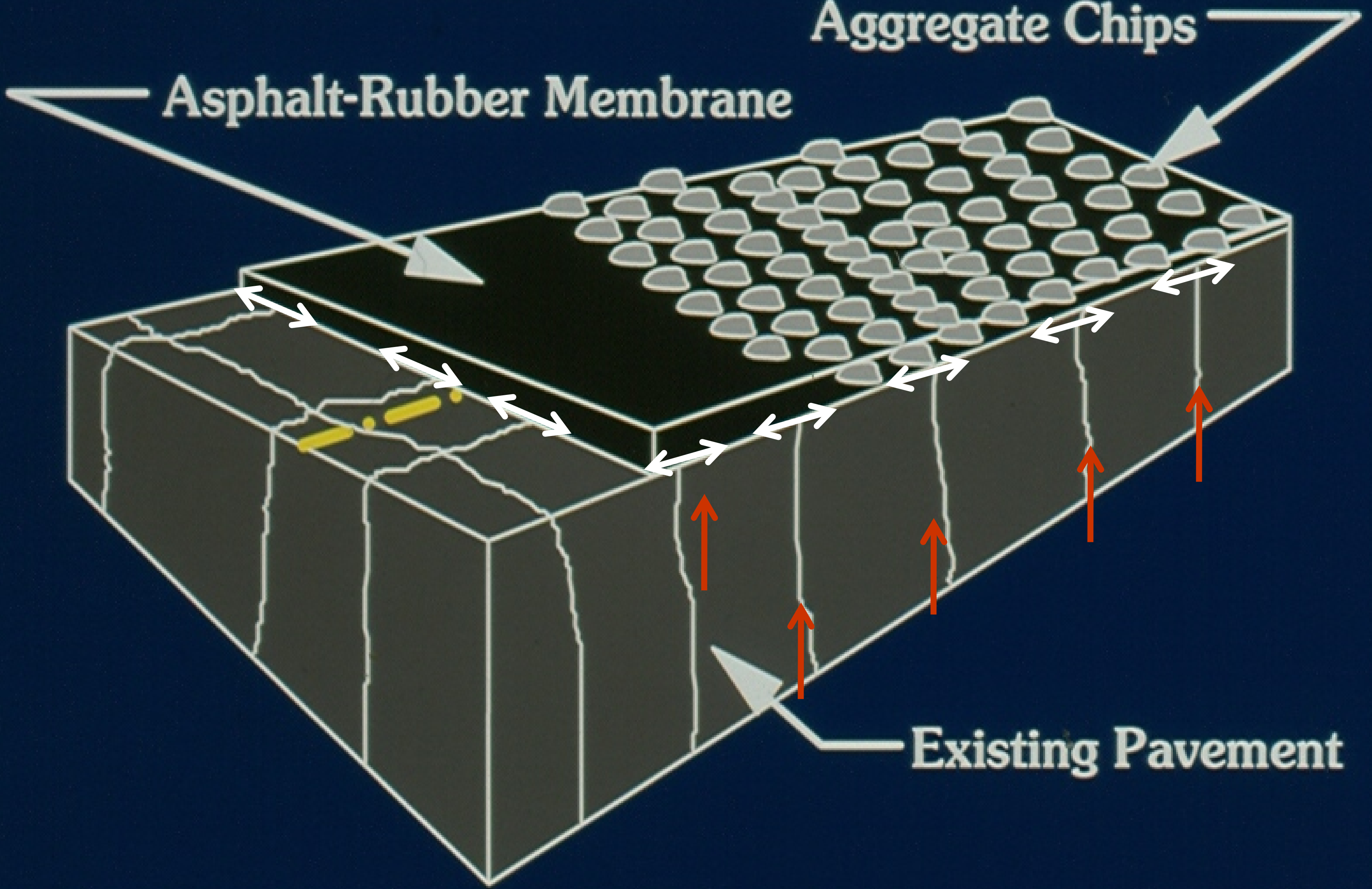
Doug Carlson
RPA – Past Director

Mark Belshe
RPA – Present Director

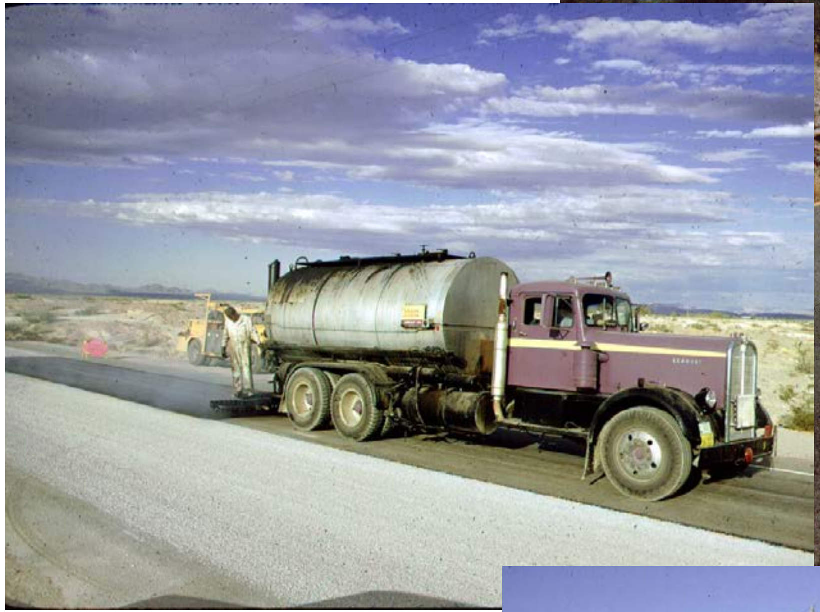
ASU NATIONAL CENTER of EXCELLENCE for SMART INNOVATIONS
ARIZONA STATE UNIVERSITY

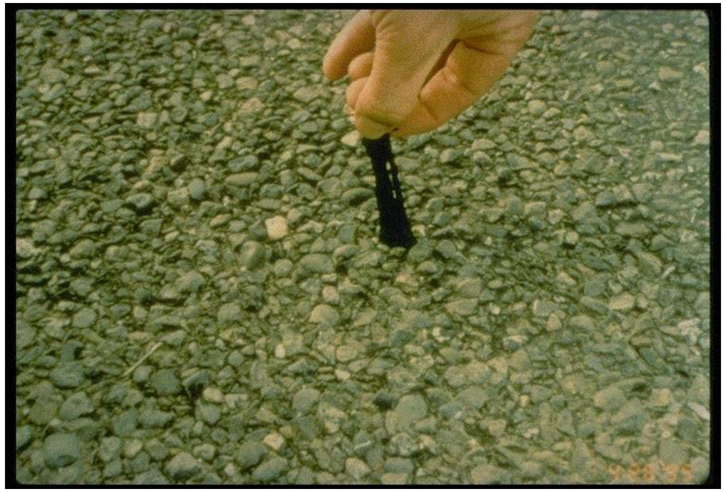
1ST INTERNATIONAL CONFERENCE ON Stone Matrix Asphalt

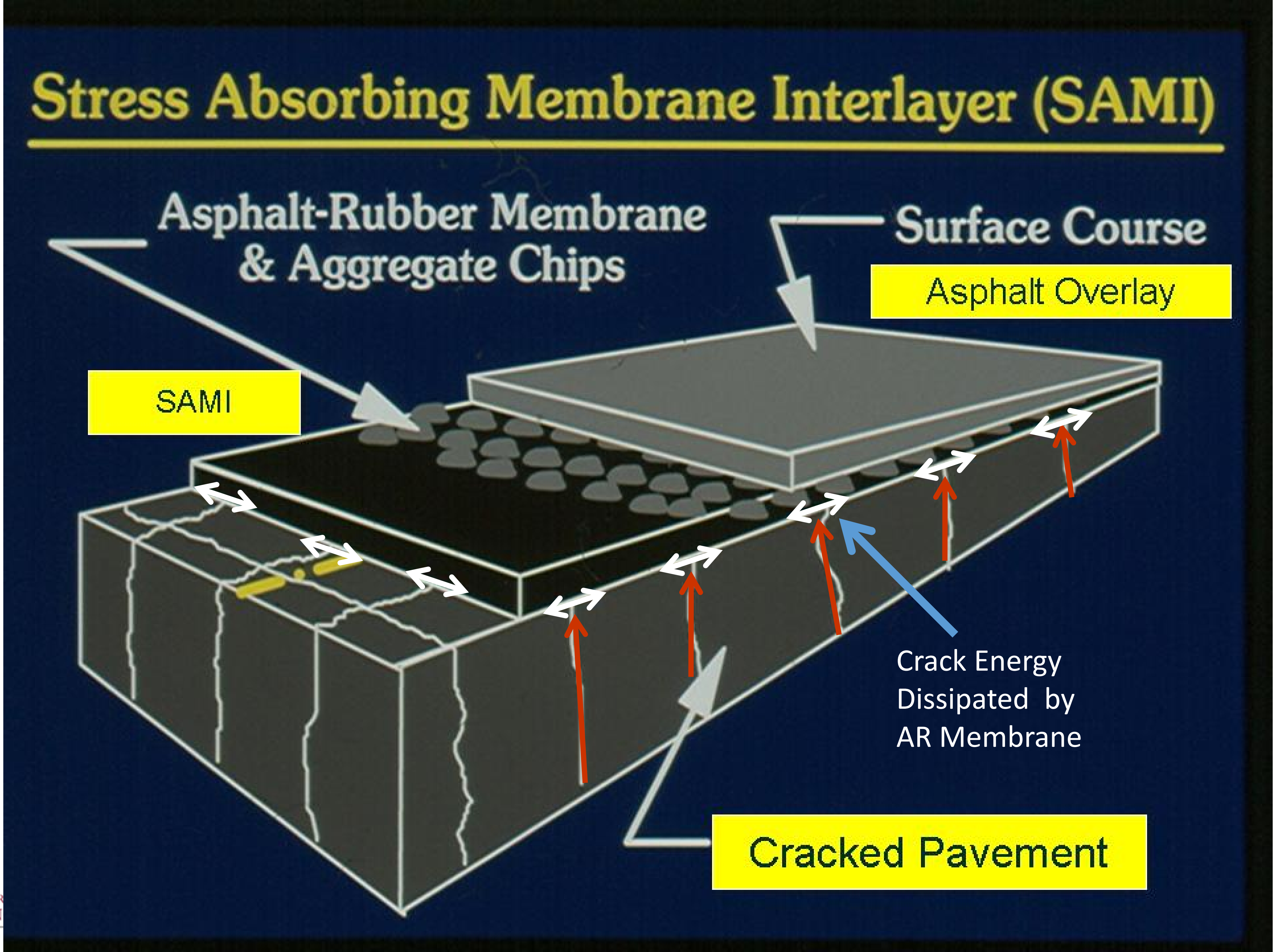
Stress Absorbing Membrane (SAM)



Early Application Placed 1975 Through Mid 1980's







ASU NATIONAL CENTER for SMART INN
ARIZONA STATE UN

Family of products

Rubberized Asphalt Family

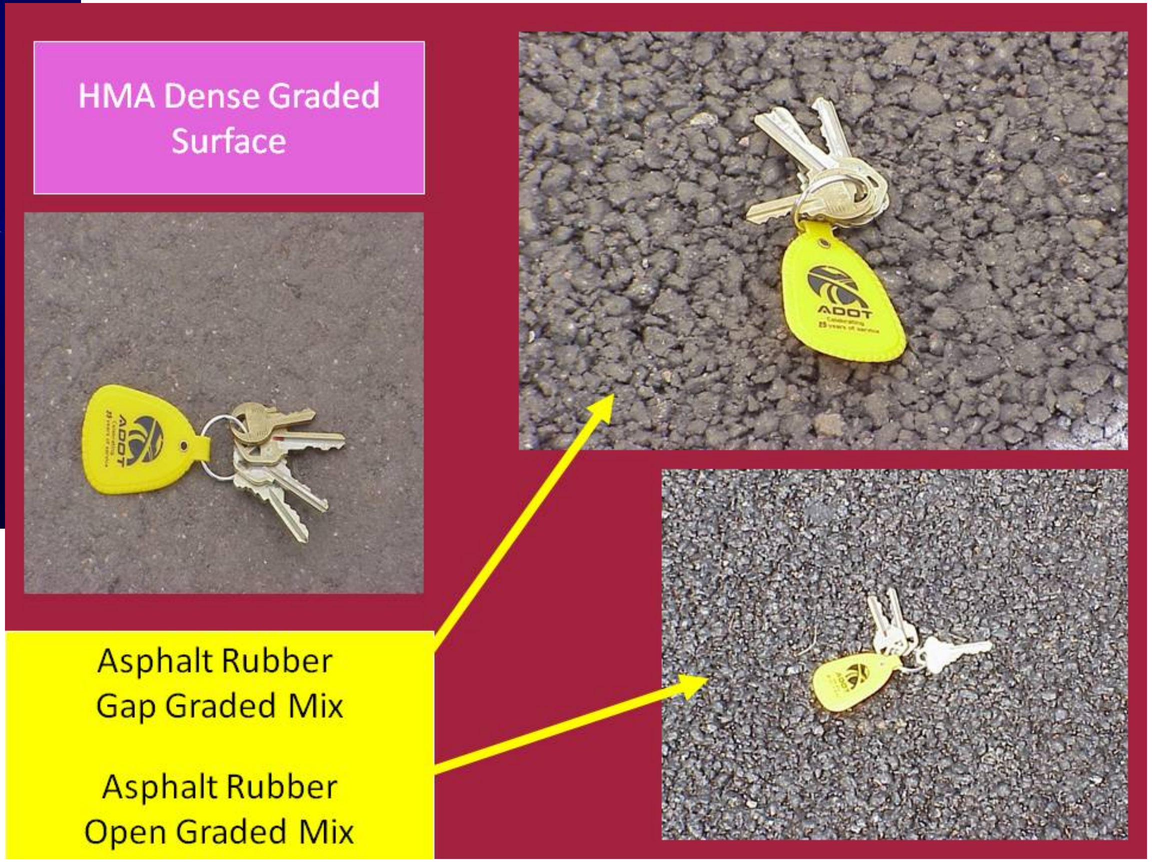
Asphalt-Rubber – 15 % or more RTR

Rubberized Asphalt Binder – Less than 15% RTR, 30 mesh or smaller particles

Rubberized Asphalt Terminal Blend – RTR plus polymer, high solubility

Rubberized Asphalt Binder Hybrid - Combination of RTR and polymer in the asphalt

Rubberized Asphalt Activated - Combination of RTR and charged particles in the asphalt



Where Rubber in Asphalt is specified and used in some form of pavement appliction

States in Green Where Tire Rubber is Used in Asphalt Routinely (DOT, Transportation Authority, County or City)

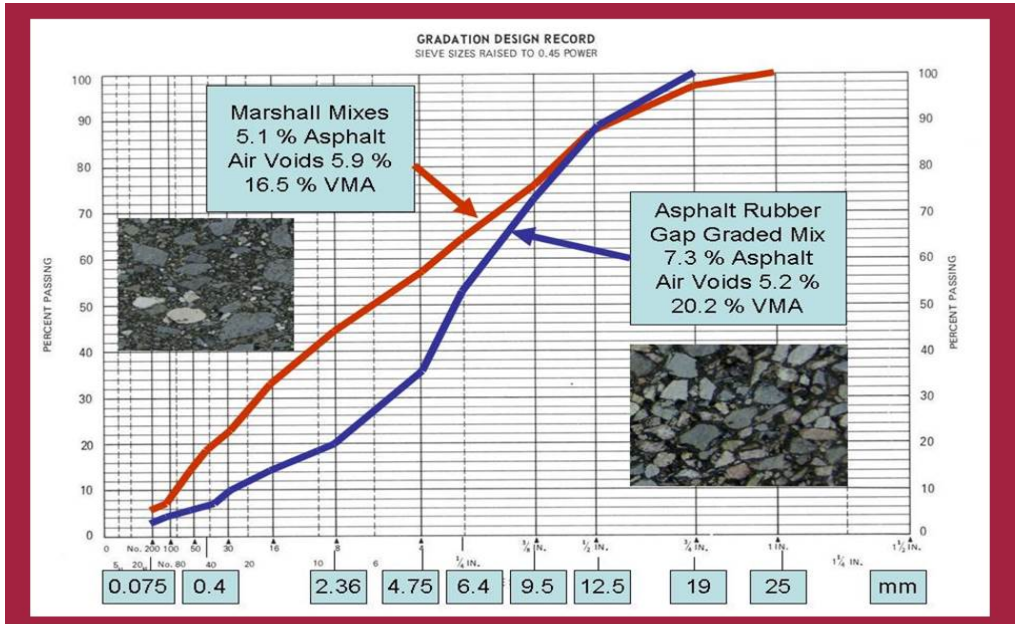
SAMI + SMA

Jakarta, Indonesia
Rubberized SAMI + SMA

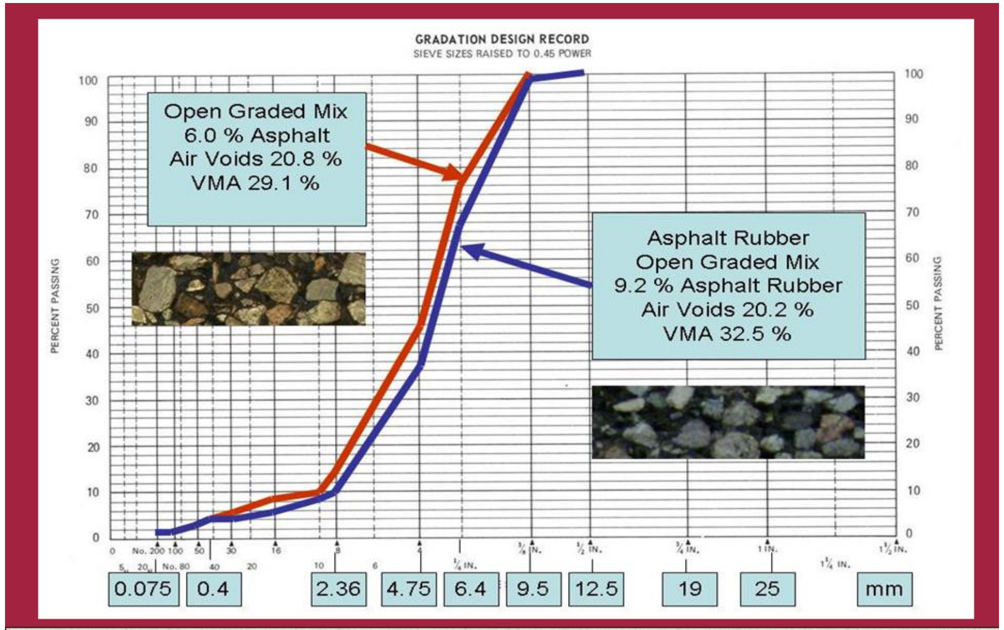
Brazil RJ122 After Paving with A-R
Open Graded & A-R Gap Graded Mixes

Benefits of Asphalt Rubber / SMA Mixtures

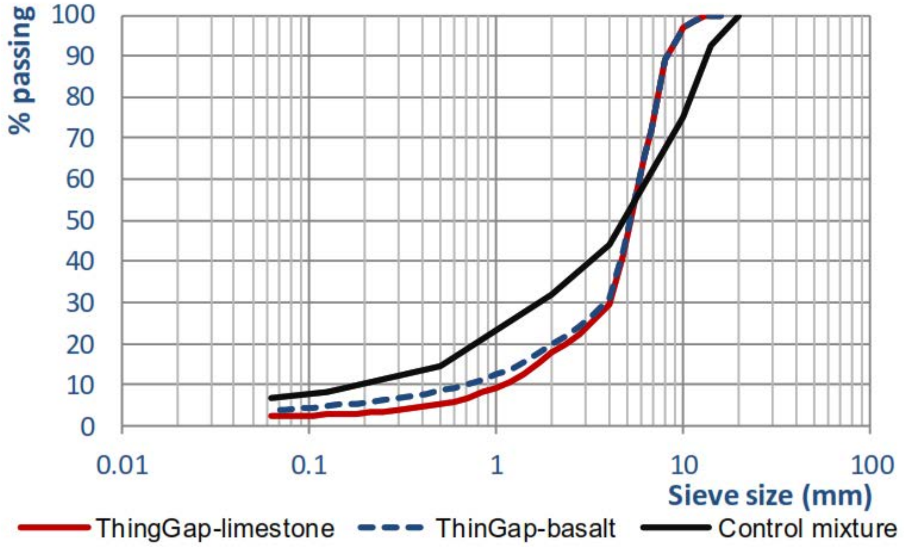
- Less Reflective Cracking
- Less Maintenance/More Durable
- Less Raveling
- Good Rut Resistance
- Good Skid Resistance
- Smooth Ride
- Good in hot & cold climates
- Less Splash & Spray Better Drainage
- Less Noise
- Cost Effective

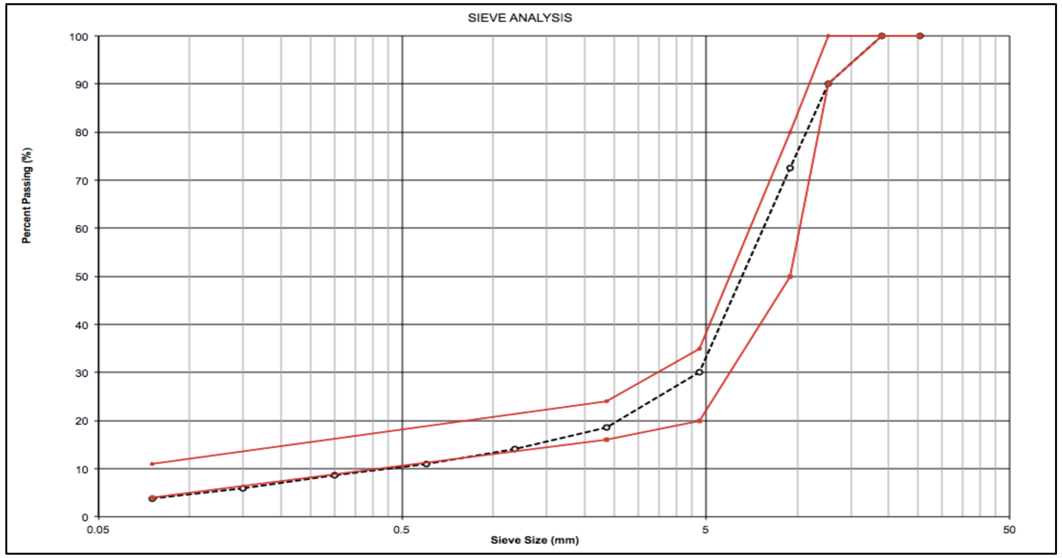


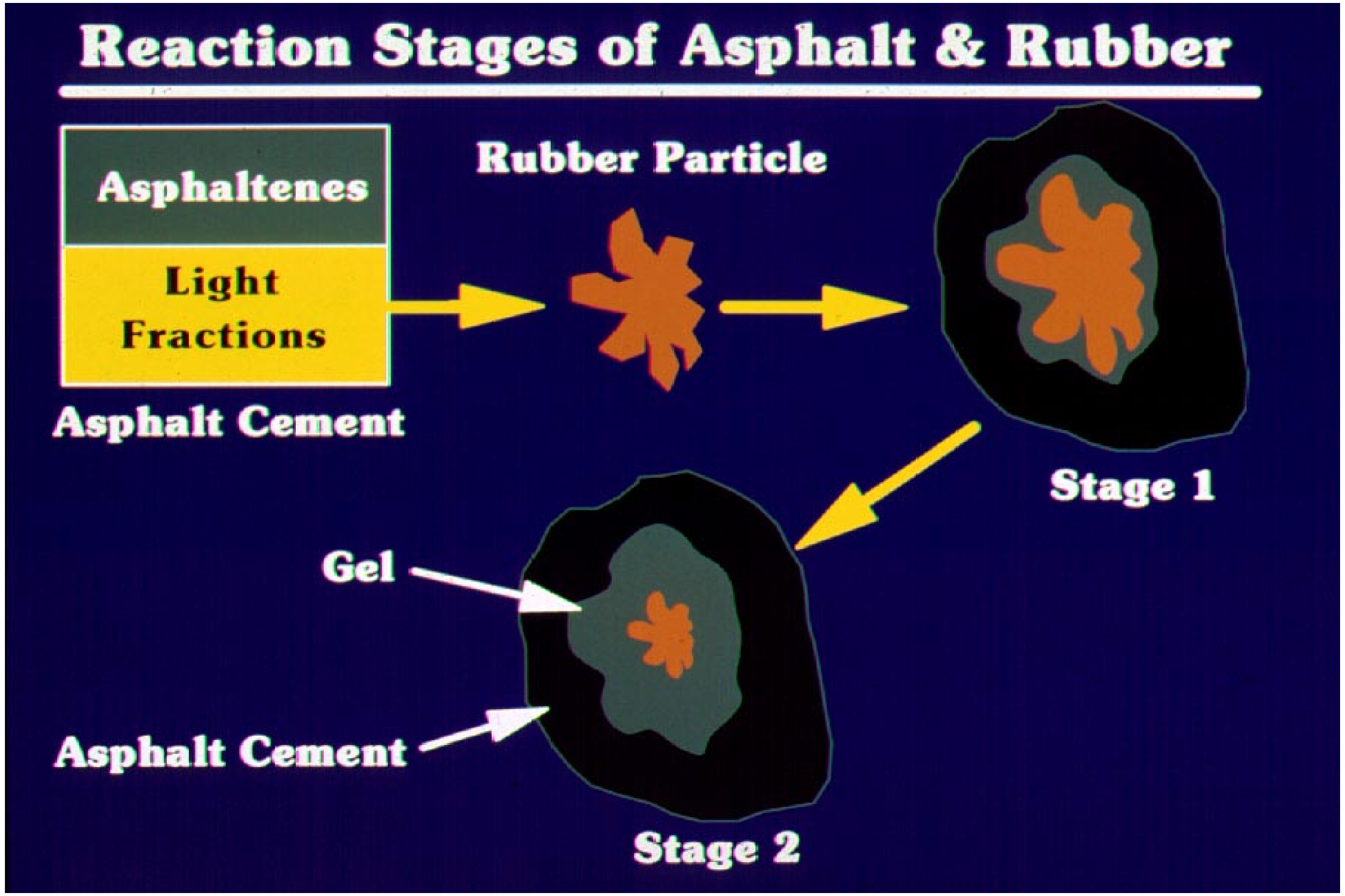
1980's Marshall Mix Gradation for HMA
And Gap Graded Asphalt Rubber Mixes



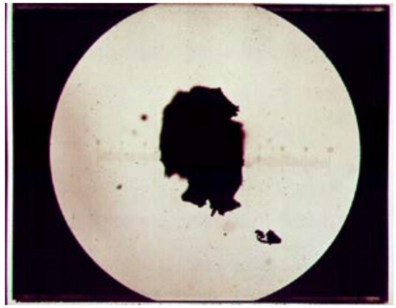
1980's Open Graded Mix Gradations



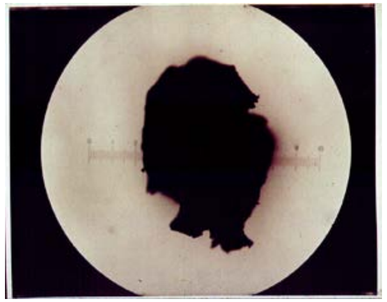




Before



After

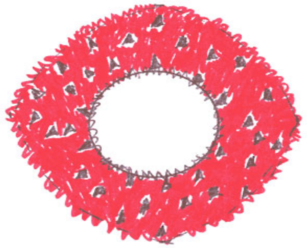


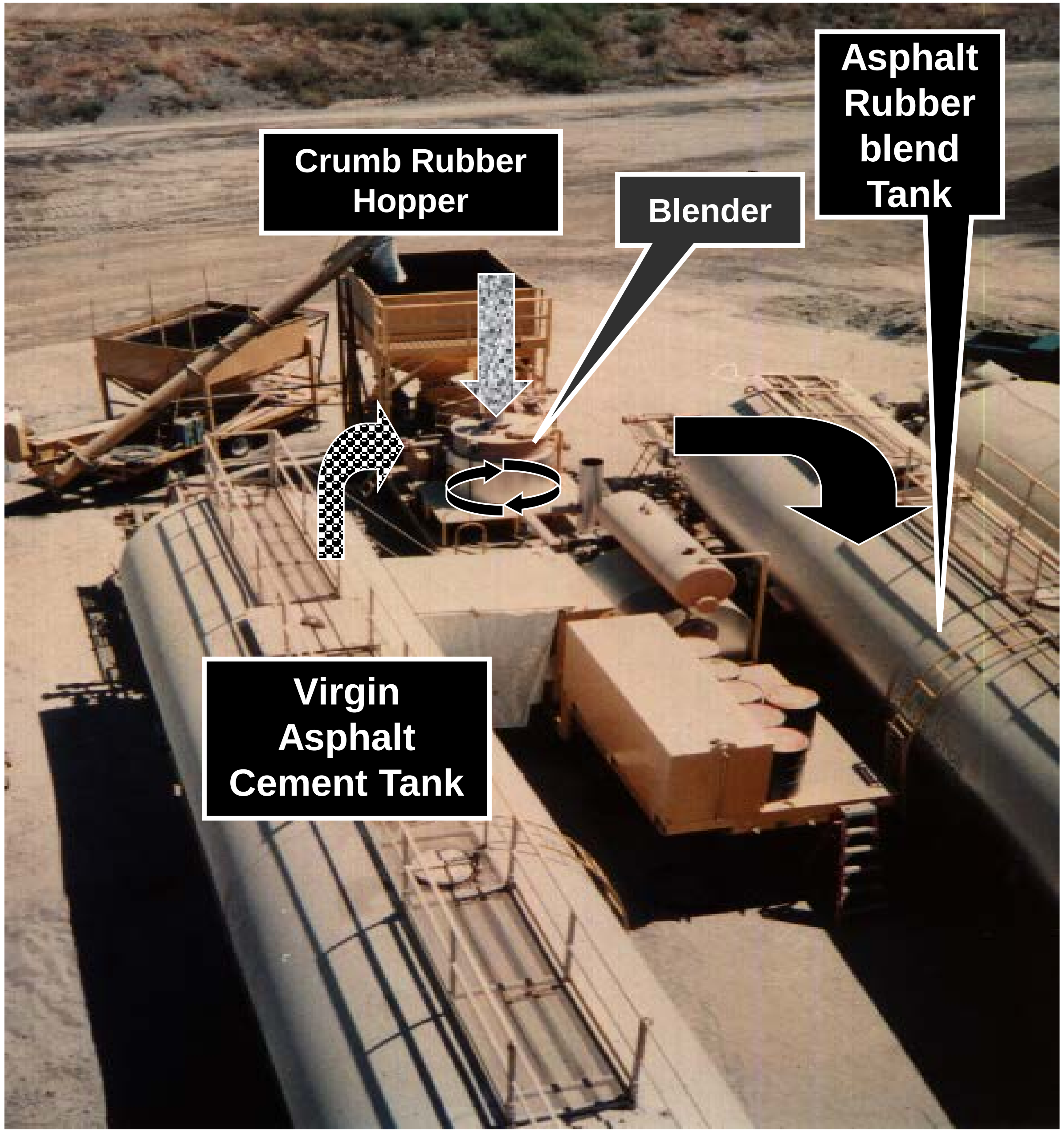
Film Thickness

Dense Graded
HMA
9 Micron

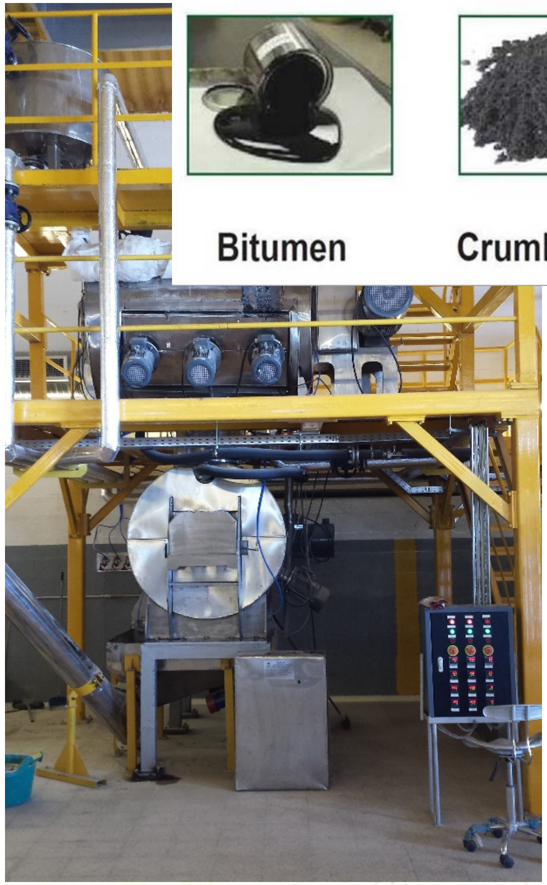
Gap Graded
Asphalt Rubber
18 Micron

Open Graded
Asphalt Rubber
36 Micron




Crumb Rubber Hopper
Blender
Asphalt Rubber blend Tank
Virgin Asphalt Cement Tank


Bitumen
Crumb Rubber
FILLERS

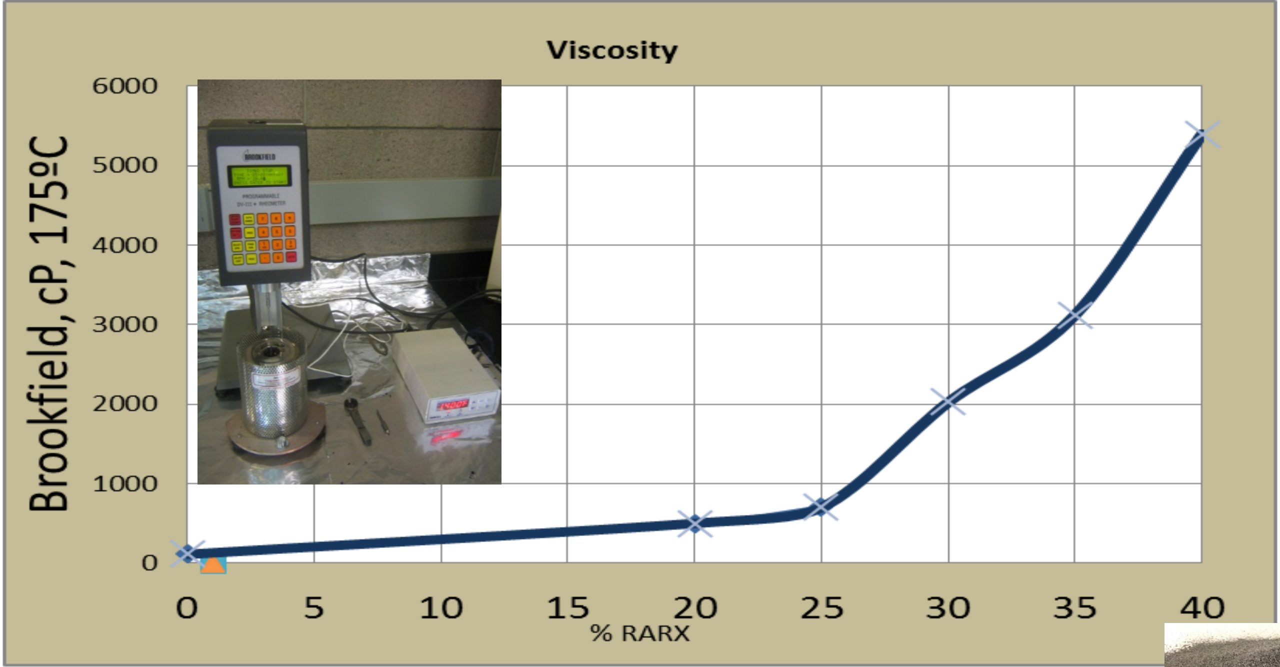


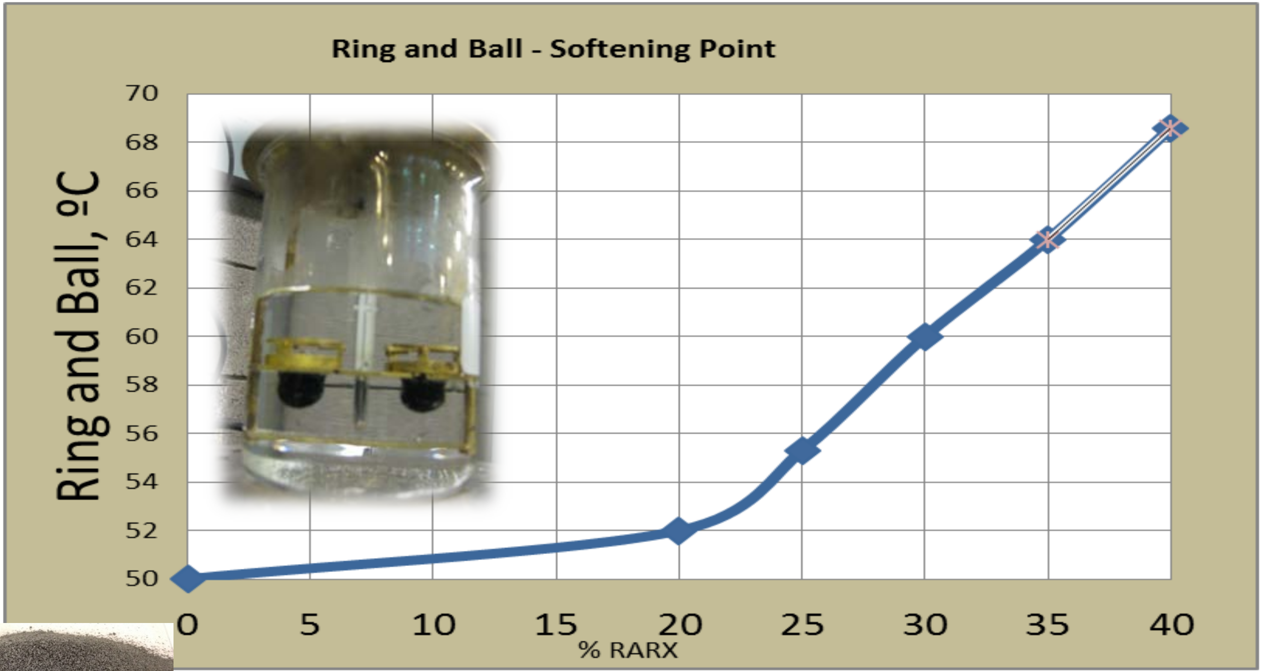
Crumb Rubber - Binder

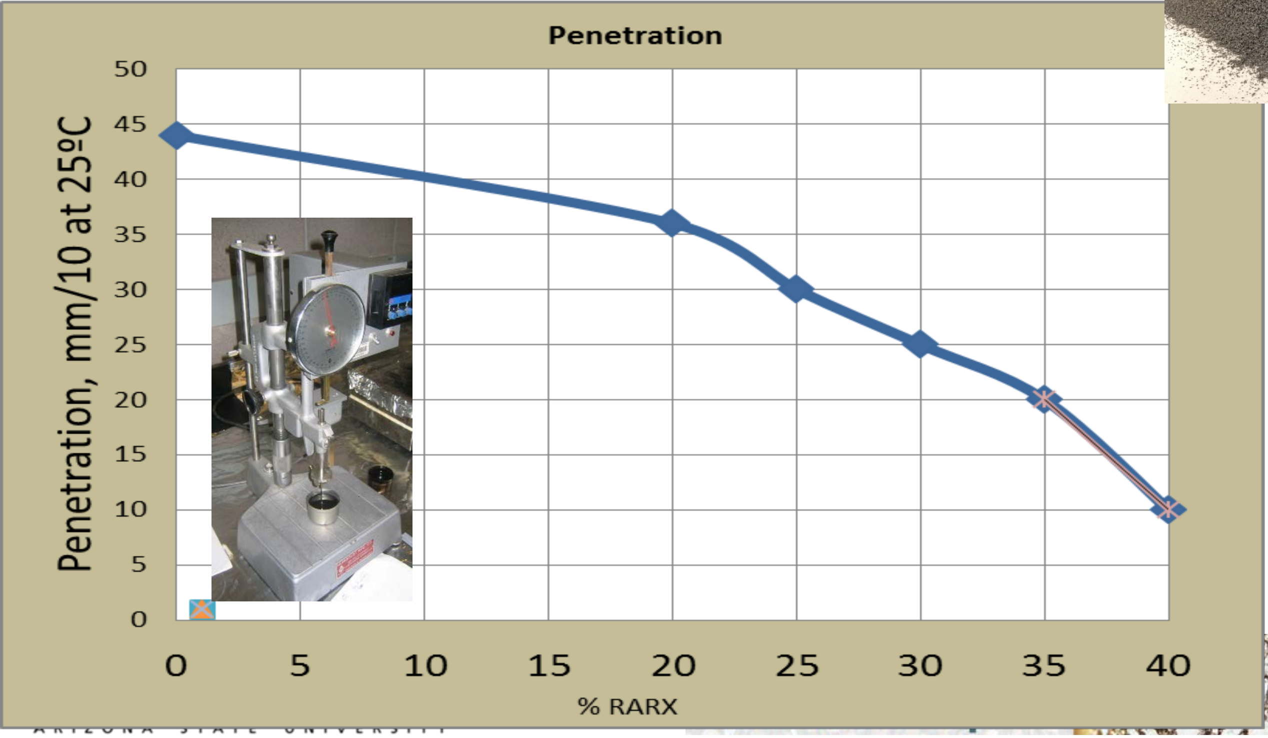
- ❑ prepared by adding 20% CRM (by weight of total binder) to PG 64-22 Binder

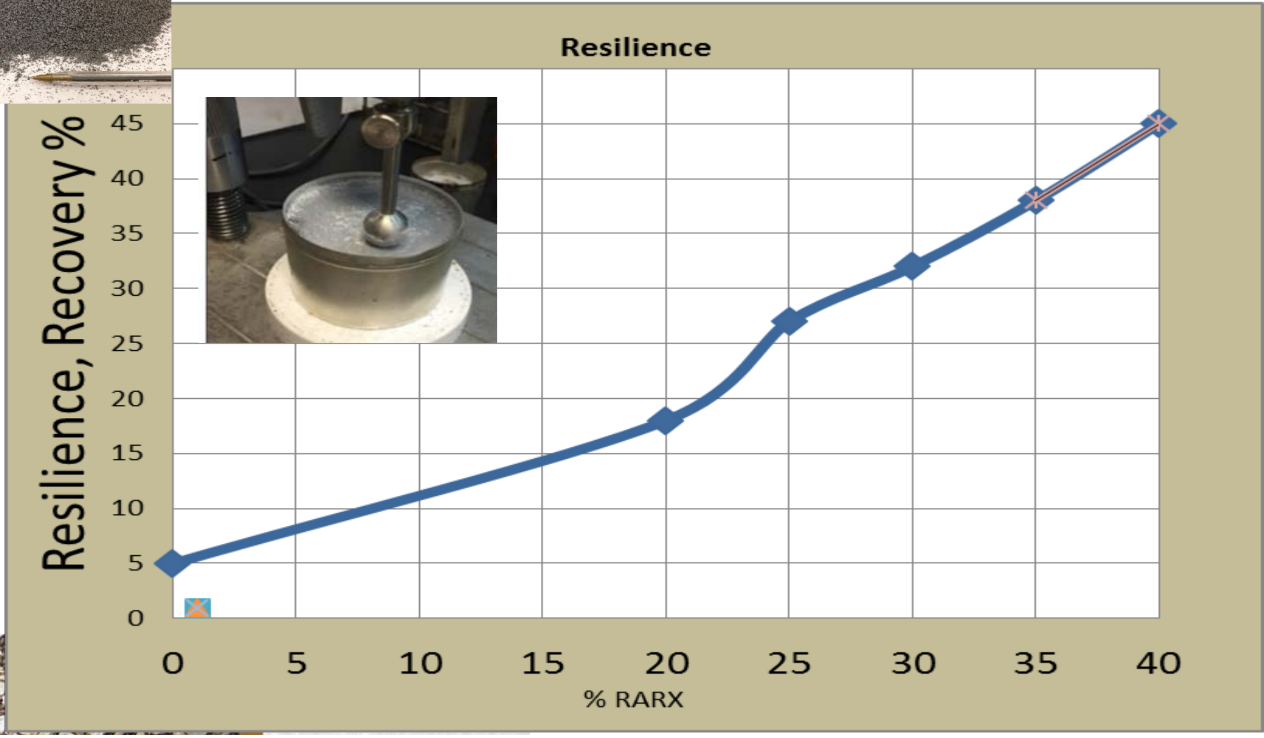
- ❑ Heated the binder to 177°C and then mixed for 50 mins using a blender for swelling.

Blender and closeup view of CRMB binder preparation

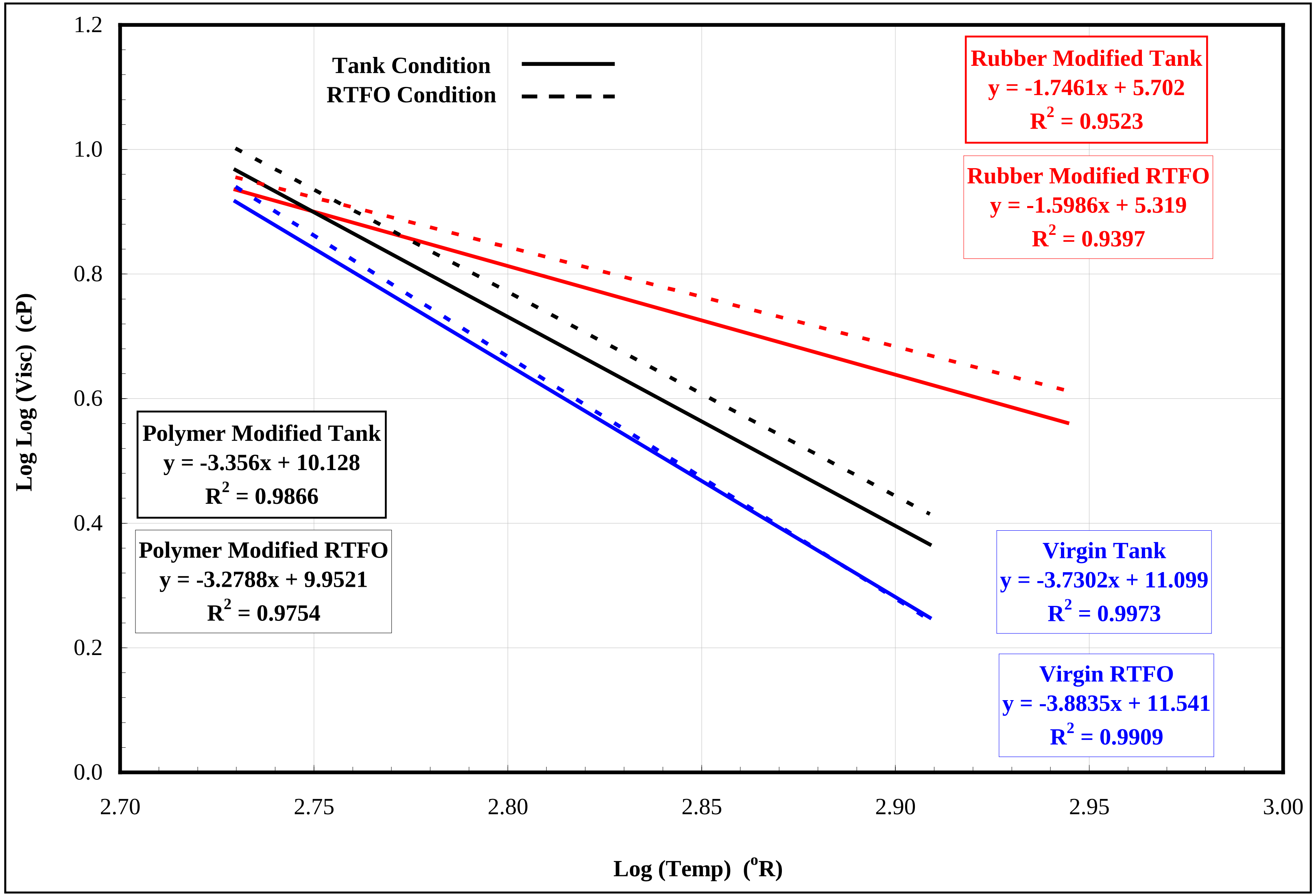

Viscosity
Brookfield, cP, 175ºC
6000
5000
4000
3000
2000
1000
0
0 5 10 15 20 25 30 35 40
% RARX

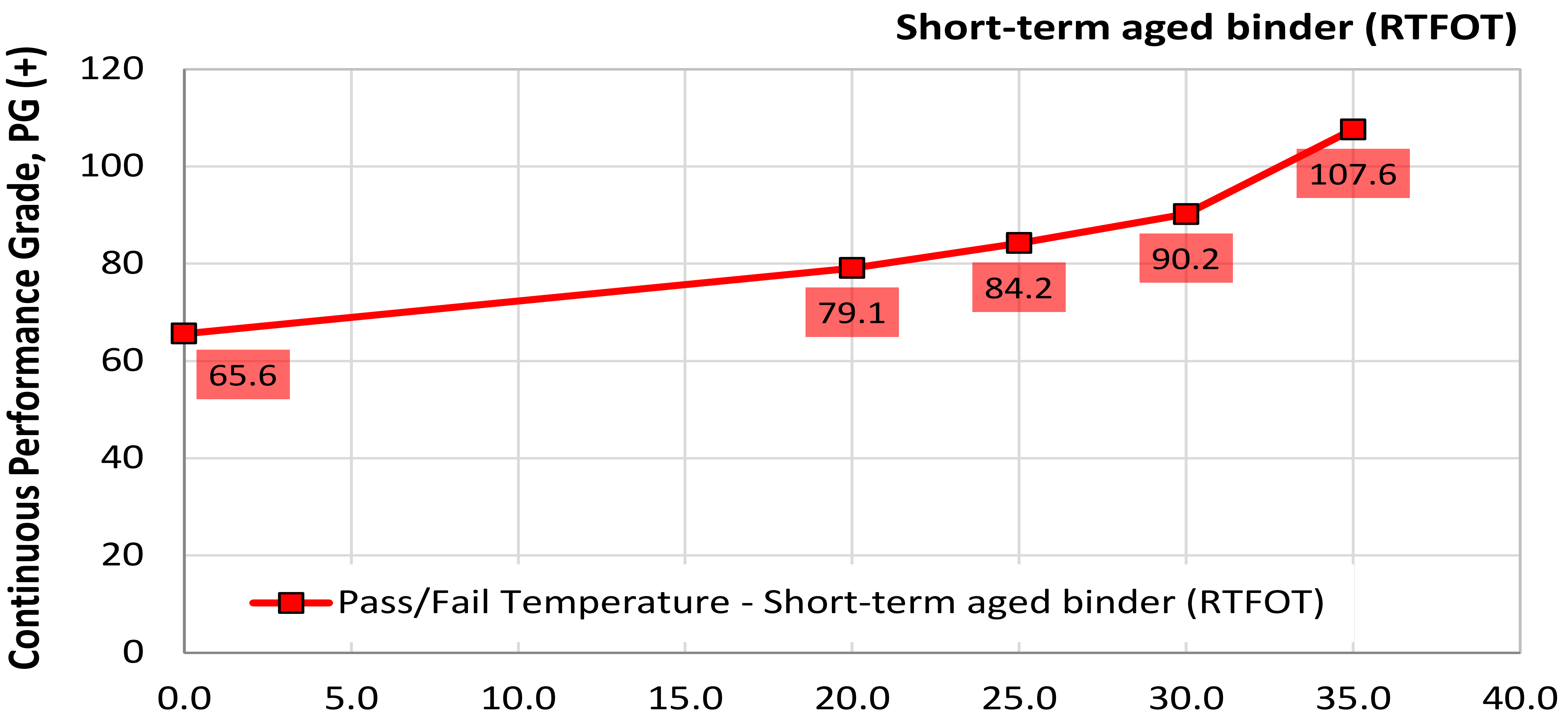

Ring and Ball - Softening Point
Ring and Ball, ºC
70
68
66
64
62
60
58
56
54
52
50
0 5 10 15 20 25 30 35 40
% RARX

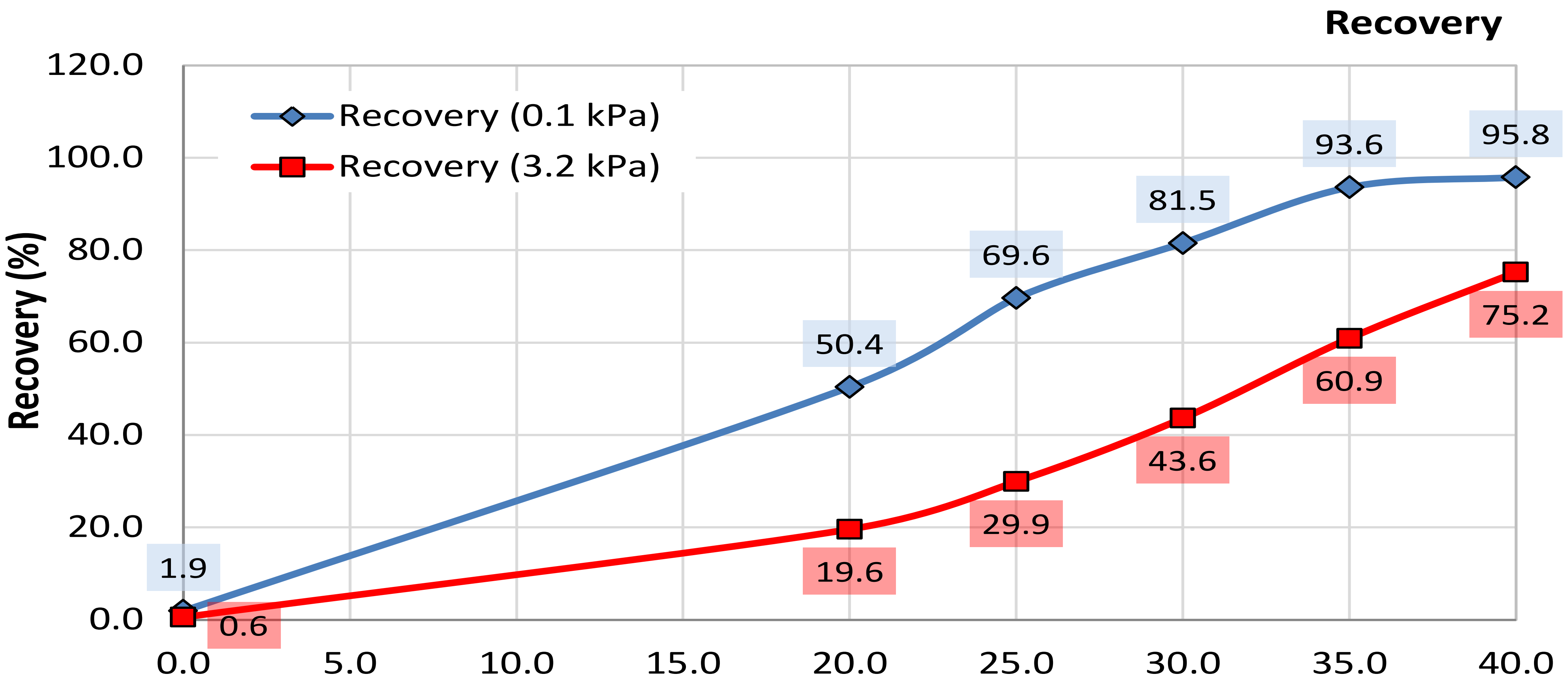

Penetration
Penetration, mm/10 at 25ºC
50
45
40
35
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40
% RARX


Resilience
Resilience, Recovery %
45
40
35
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40
% RARX

Crumb Rubber Binder Characteristics




Short-term aged binder (RTFOT)
Continuous Performance Grade, PG (+)
120
100
80
60
40
20
0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
% Additive, RAR
65.6
79.1
84.2
90.2
107.6
Pass/Fail Temperature - Short-term aged binder (RTFOT)


Recovery
Recovery (0.1 kPa)
Recovery (3.2 kPa)
Recovery (%)
% Additive, RAR
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
1.9
50.4
69.6
81.5
93.6
95.8
0.6
19.6
29.9
43.6
60.9
75.2

MEPDG (PavementME) Input

- Find the PG grading that best match the A_i and VTS_i values for asphalt rubber binders.

Binder Type	**A_i**	**VTS_i**
PG 58-22 AR	8.543	-2.781
PG 64-40	*8.524*	*-2.798*
PG 64 -16 AR	8.048	-2.598
PG 70-40	*8.129*	*-2.648*

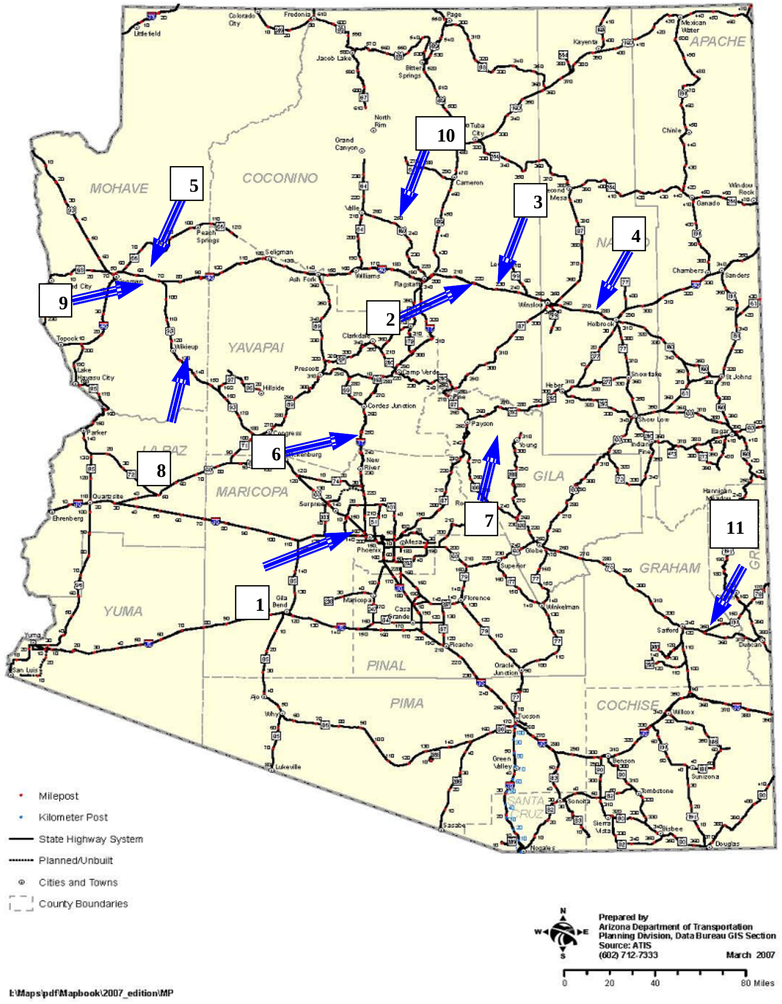
As-Built 12 Pavement Lanes

Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Lane 6	Lane 7
CR-AZ	Control	Air Blown	SBS LG	CR-TB	TP	Fiber
300K	100K	100K	300K	100K	200K	300K

AZ Asphalt Rubber Mixtures

2001-2009

- ADOT /ASU joint research program
- Several AR mixes and binders were tested
- Goal of implementing AR in the MEPDG
- Over 20 projects included AR mixtures



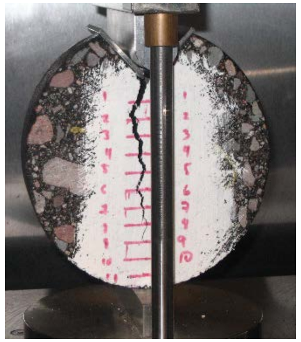
- Arizona Department of Transportation
- Maricopa County, AZ
- Puerto Rico
- Alberta, Canada
- Sweden
- Brazil

Mixtures Properties

Project	Mix	ADOT Spec.	Binder	Target AC(%)	Target Va (%)
I-17	ARAC	413	AR 58-22	7.5	8
	ARAC	413	AR 64-16	8.9	8
Buffalo Range	ARFC	414	AR 58-22	8.8	18
	ARAC	413	AR 58-22	6.8	11
Two Guns	Conv	417	PG 64-22	4.6	7
	ARFC	414	AR 58-22	9.4	18
	ARAC	413	AR 58-22	7.0	9
Jack Rabbit	Conv	417	PG 64-22	4.8	7
	ARFC	414	AR 58-22	9.3	18
	ARAC	413	AR 58-22	7.3	9
Silver Spring	Conv	417	PG 70-22	5.3	7
	ARFC	414	AR 58-22	9.5	18
Badger Springs	Conv	417	PG 70-10	5.2	7
	ARFC	414	AR 58-22	9.0	18
	ARAC	413	AR 58-22	7.8	9
Kohl's Ranch	Conv	417	PG 64-22	5.4	7
	Conv	417	PG 64-22	5.3	7
Burrow Creek	Conv	417	PG 76-16	4.6	7
	ARFC	414	AR 58-22	9.3	18
Antelope Wash	Conv	417	PG 70-10	4.4	7
	ARFC	414	AR 58-22	8.8	18
US 180-Valle Hwy	ARAC	415	AR 58-22	8.4	7
US 70-Duncan	ARAC	415	AR 58-22	9.4	7
Lake Havasu	Conv	417	PG 76-16	4.7	7
	Special	416	PG 76-22 TR+	4.6	7
	ARFC	414	AR 64-16	9.8	18
Palo Parado	Special	416	PG 76-22 TR+	5.3	7
	RAP15%	416	PG 70-10	4.7	7
	ARFC	414	AR 58-22	9.8	18

Field → Laboratory Mixes


Dynamic Modulus Test


C* Fracture Test


IDT Test


SCB Test


Hamburg Wheel Tracking Test


Resilient Modulus Test


Beam Fatigue Test

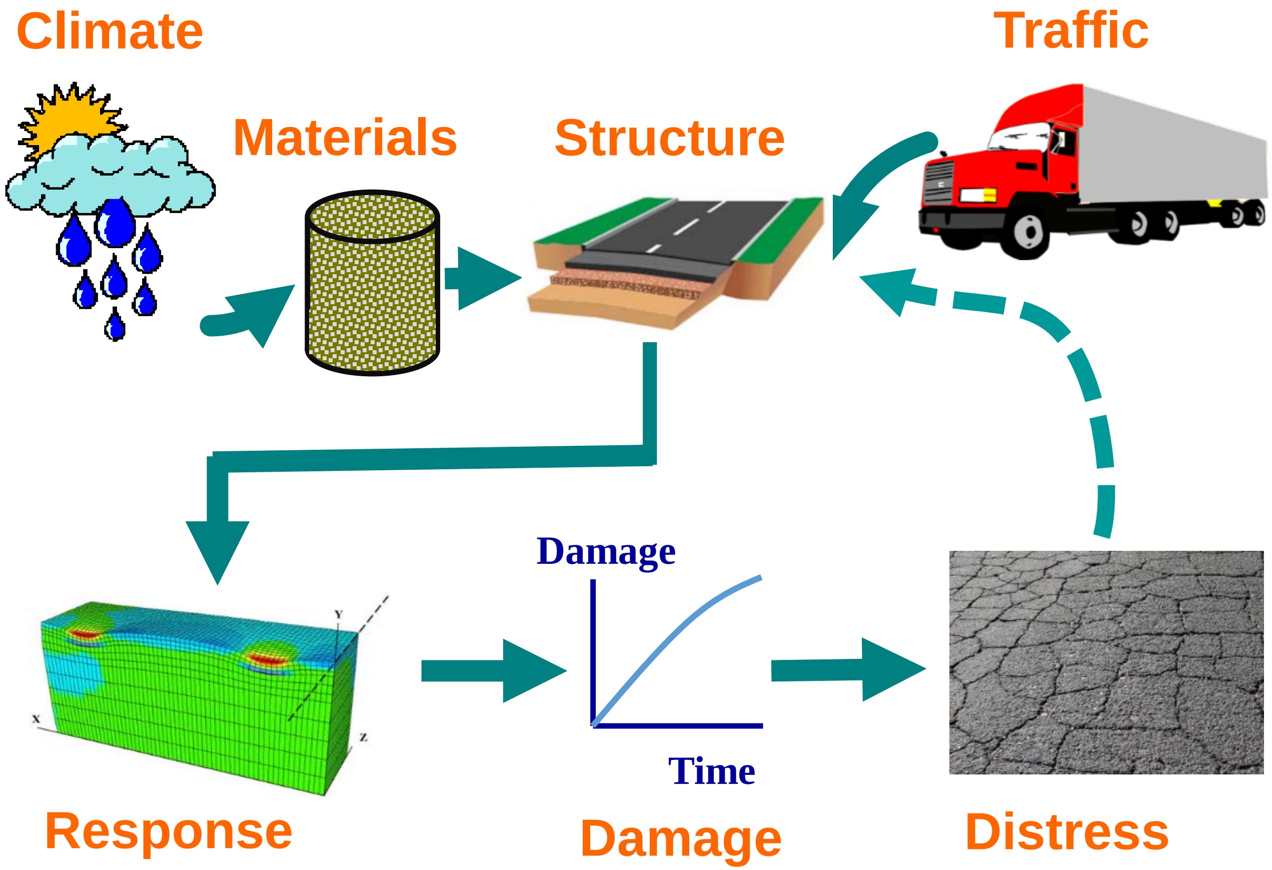

Uniaxial Fatigue Test


Flow Number Test


Asphalt Pavement Analyzer Test

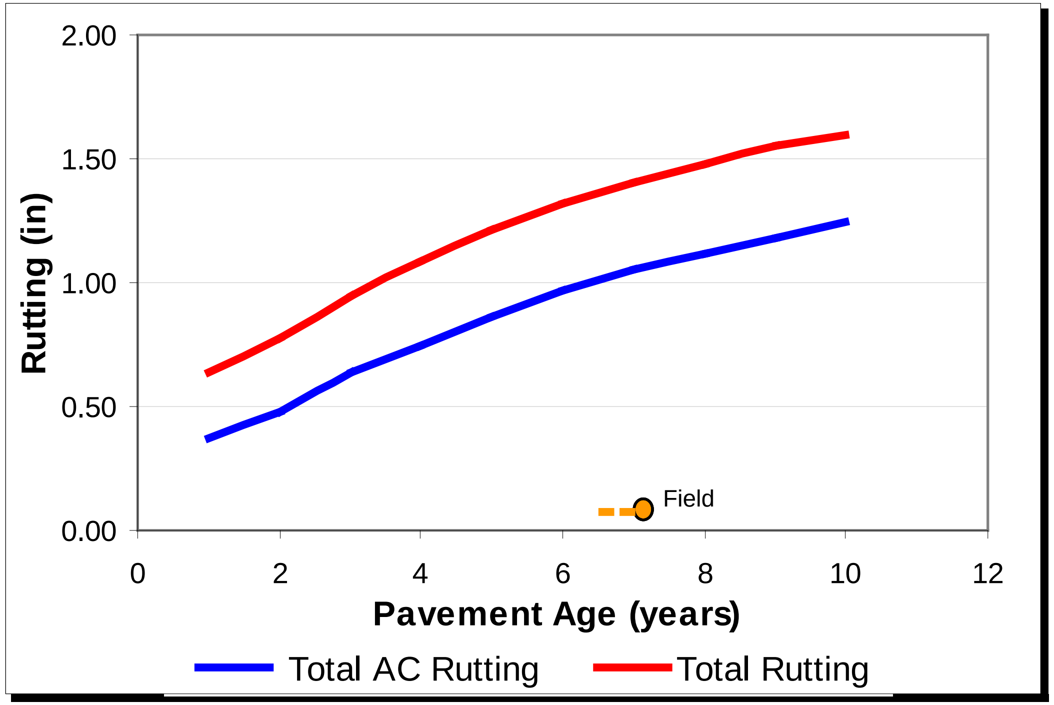
Stiffness	Fatigue / Fracture	Rutting

USE of Data in Pavement Design

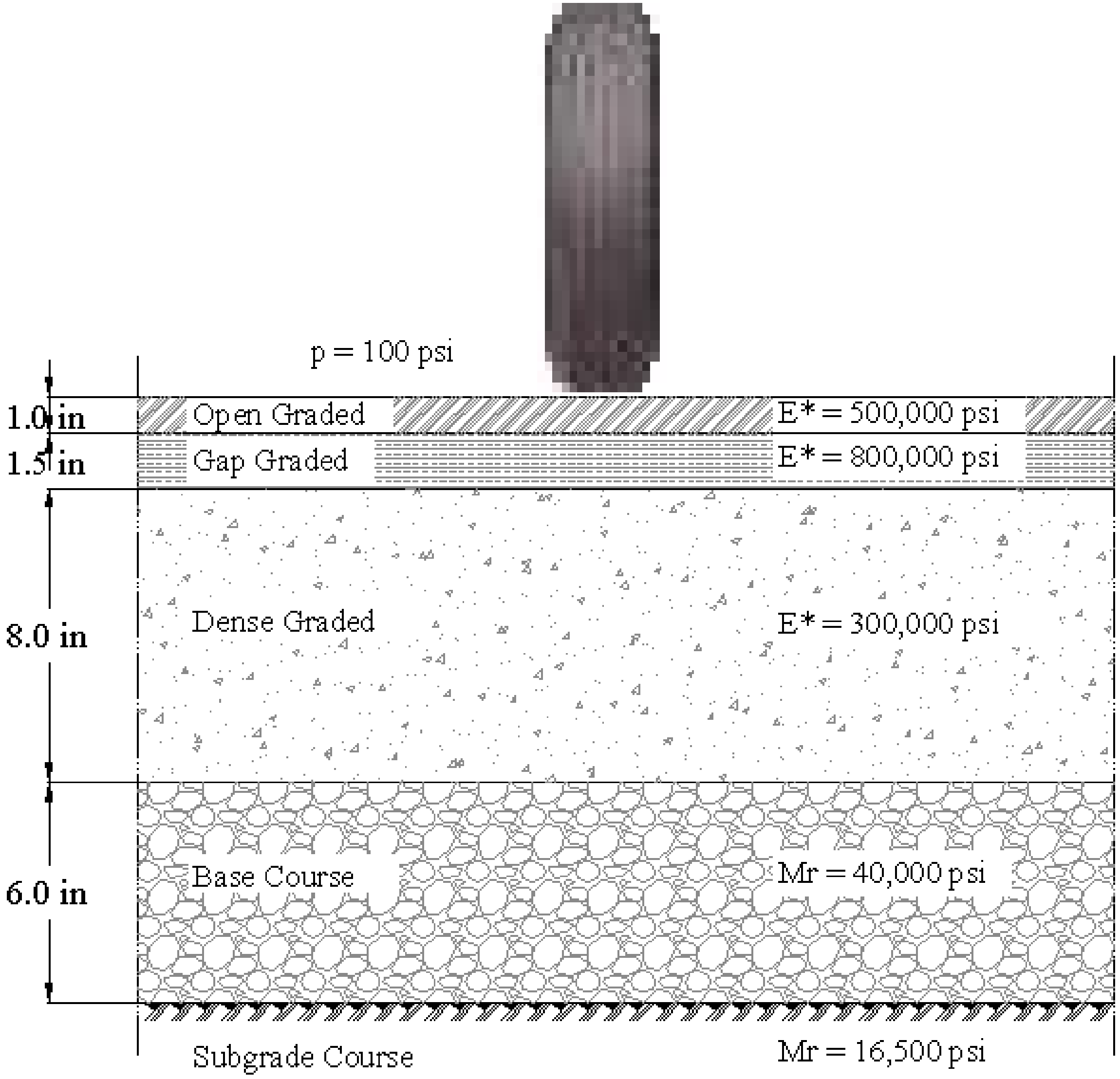


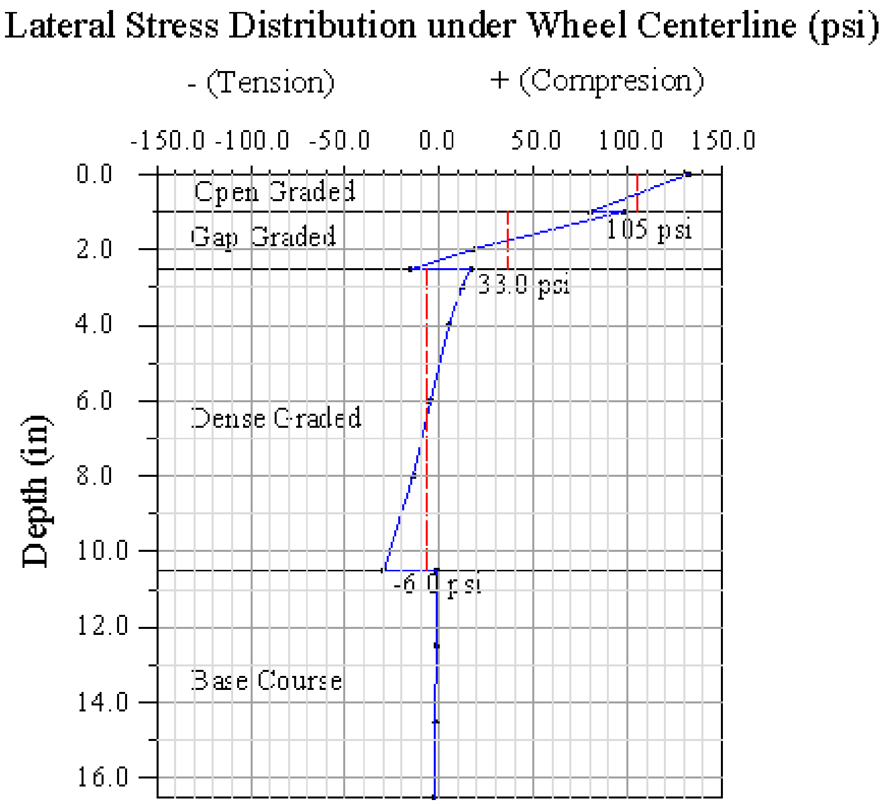
Permanent Deformation - Initial Findings

Buffalo Range Project - Unconfined E* -Default MEPDG Rutting Coefficients						
Year	Rutting (in)					
	ARFC (in)	ARAC (in)	Conventional (in)	Sub total AC (in)	Sub total Base-Subgrade (in)	Total Rutting (in)
1	0.09	0.25	0.03	0.37	0.27	0.64
2	0.11	0.33	0.04	0.48	0.3	0.78
3	0.15	0.44	0.05	0.64	0.32	0.95
4	0.18	0.51	0.06	0.75	0.33	1.08
5	0.21	0.59	0.07	0.86	0.34	1.21
6	0.23	0.67	0.08	0.97	0.35	1.32
7	0.25	0.72	0.08	1.05	0.35	1.4
8	0.27	0.77	0.09	1.12	0.36	1.48
9	0.28	0.81	0.09	1.18	0.36	1.55
10	0.29	0.85	0.1	1.24	0.37	1.6

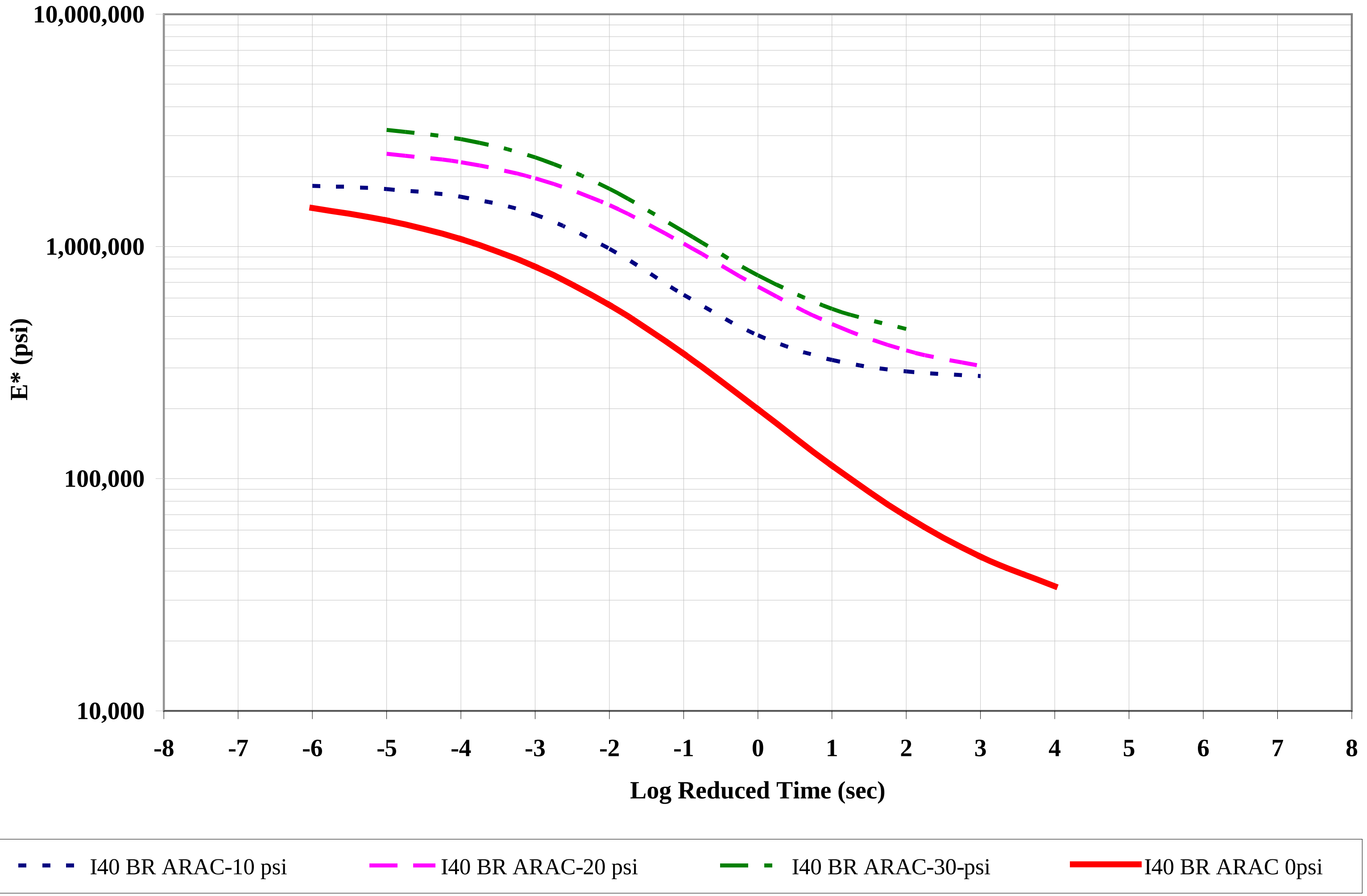


Field Stresses - Lab Confinement Issues

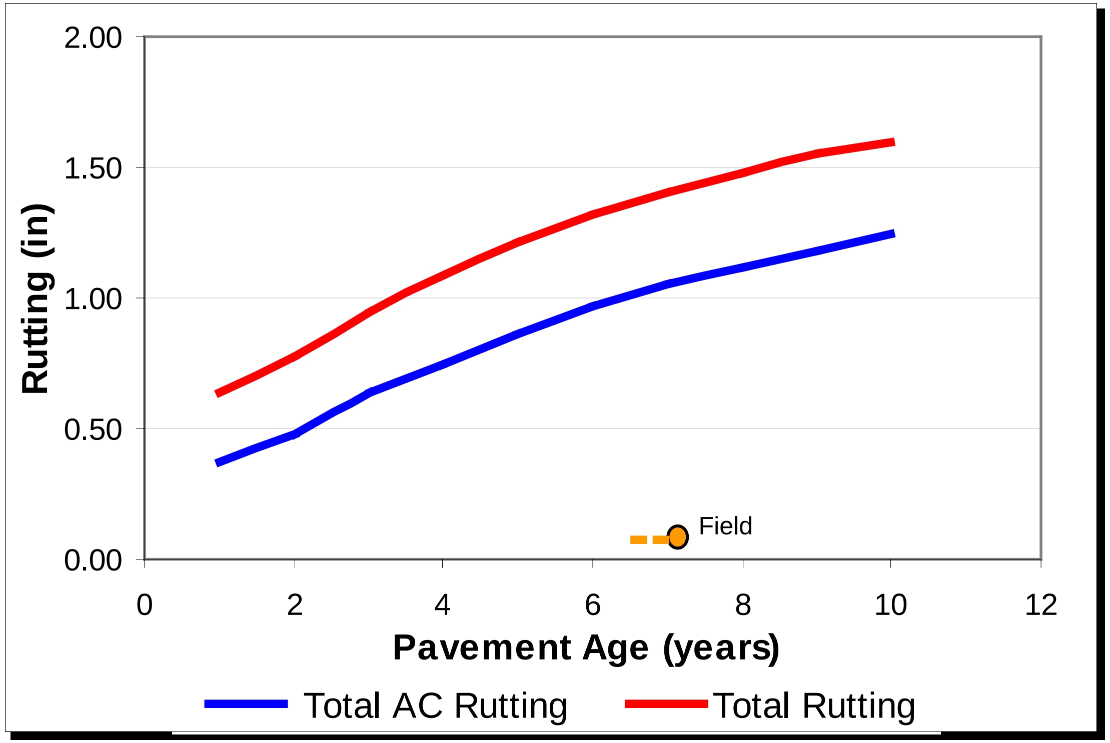




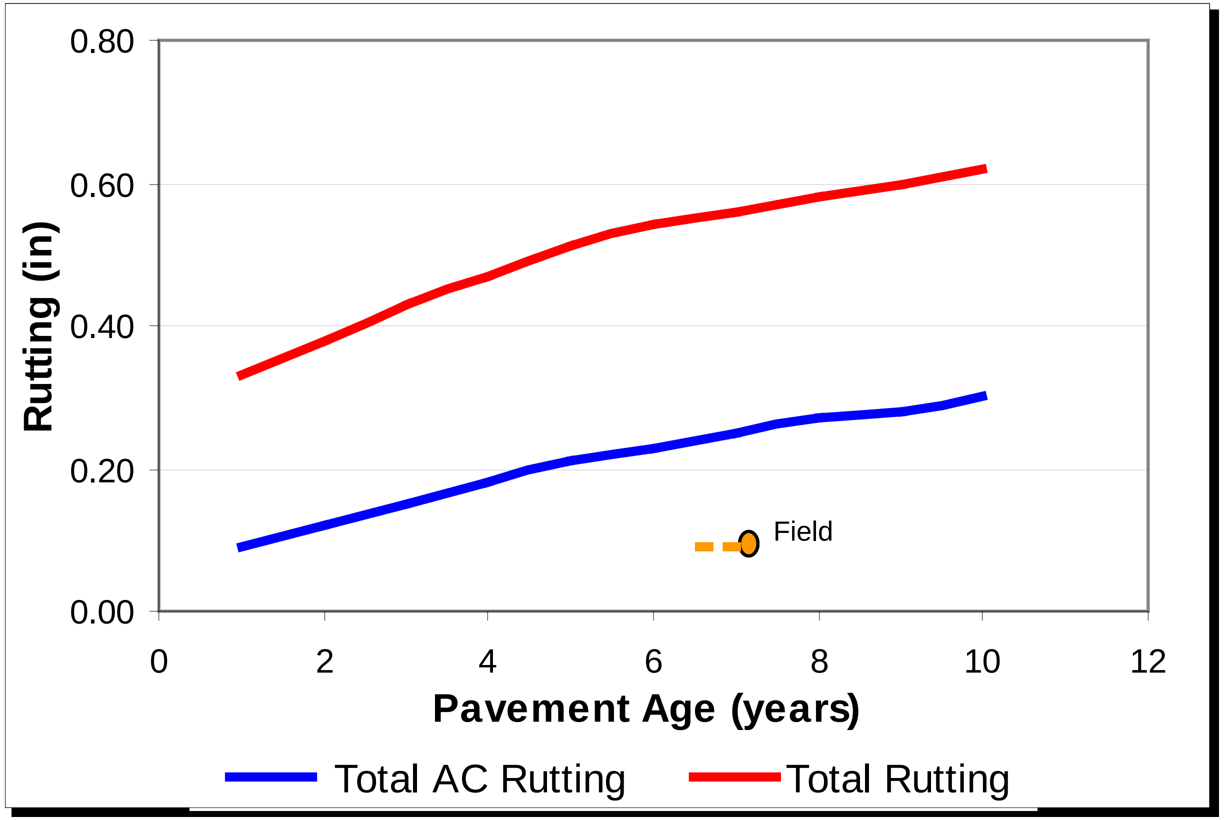
Confined Testing Results



Permanent Deformation Results



Unconfined E* Results

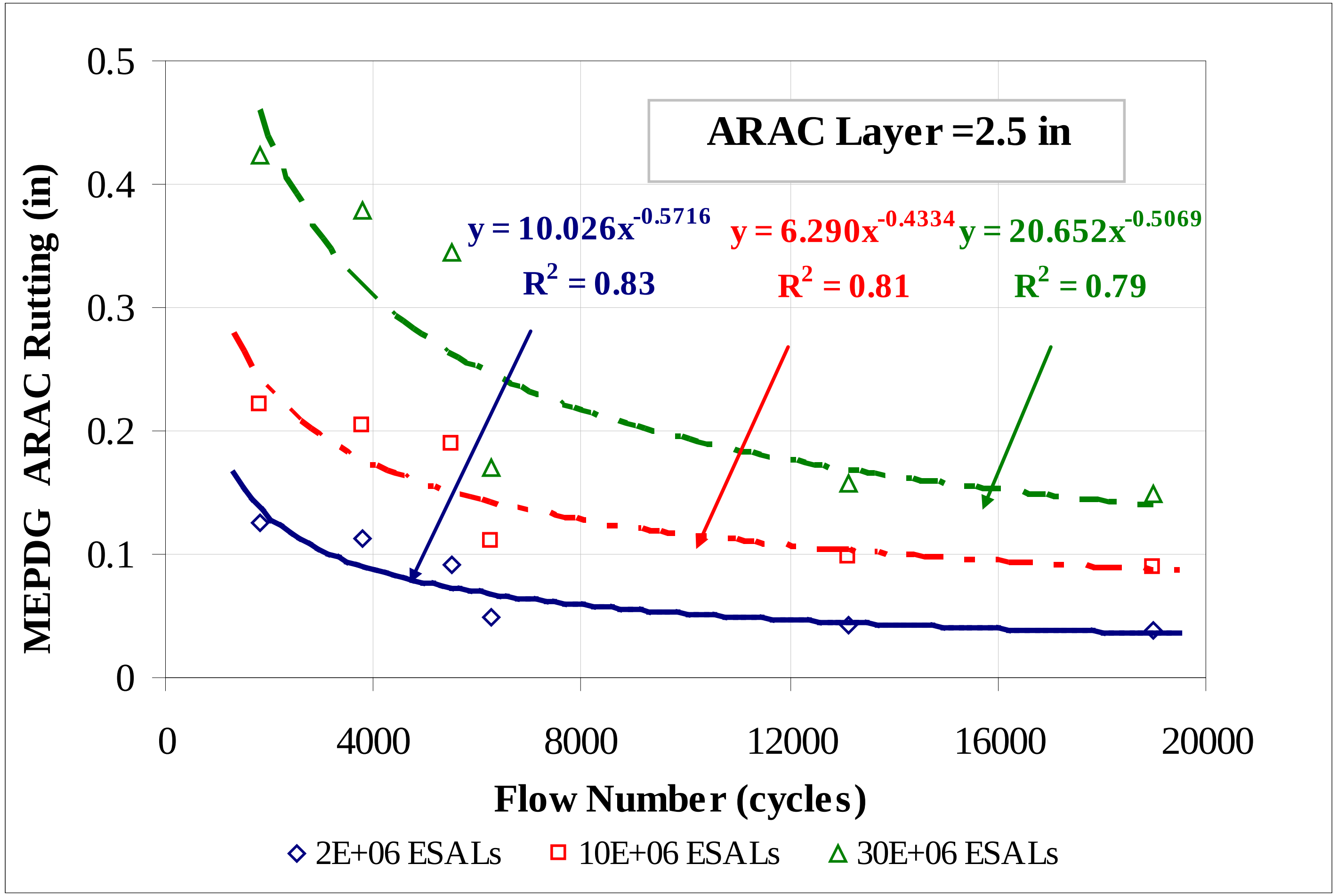


Confined E* Results

Flow Number in terms of Rutting - *Dr. Carolina Rodezno, 2010*

$$R = 0.00462 * FN^{-0.242} * ESALs^{0.483} * h^{-1.021}$$

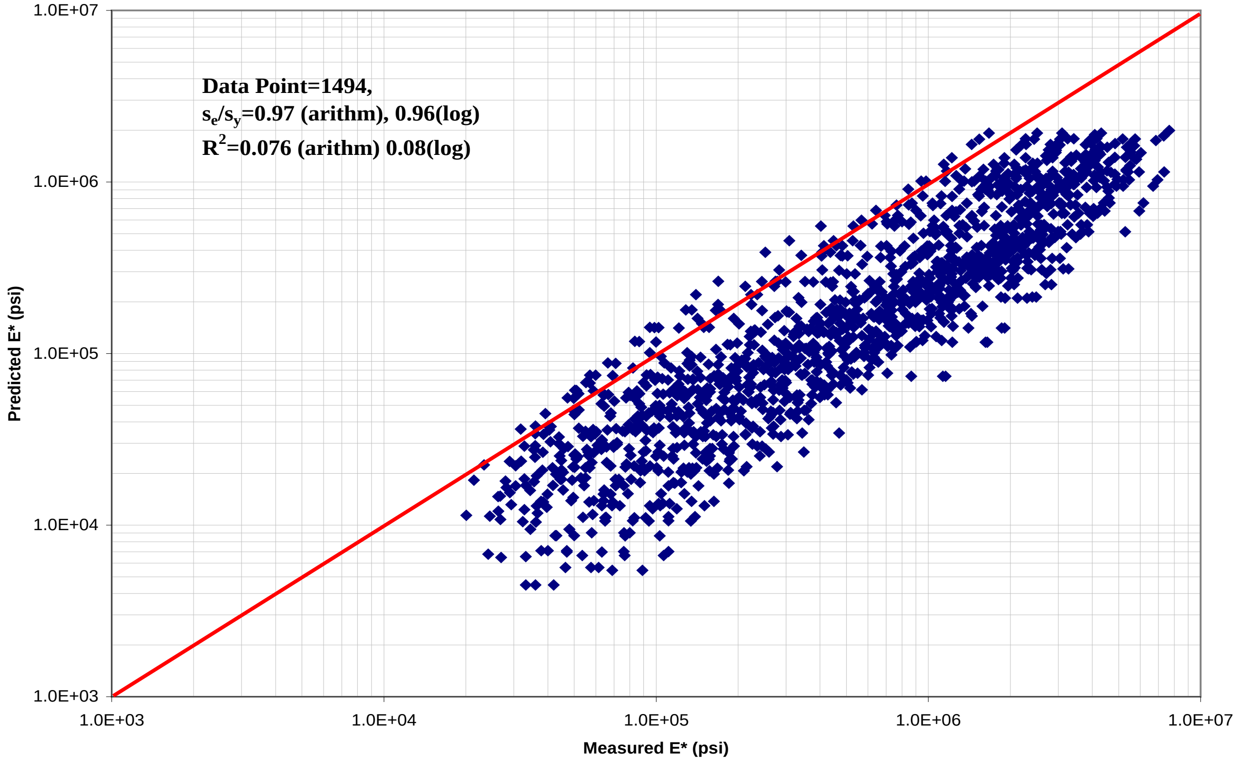
R^2=0.86; S_e/S_y=0.36



PavmentME Level 3 Issues – E* Predictive Equation

$$\log E^* = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4$$
$$- 0.058097V_a - 0.802208\left(\frac{V_{eff}}{V_{eff} + V_a}\right) +$$
$$\frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log(f) - 0.393532\log(\eta))}}$$

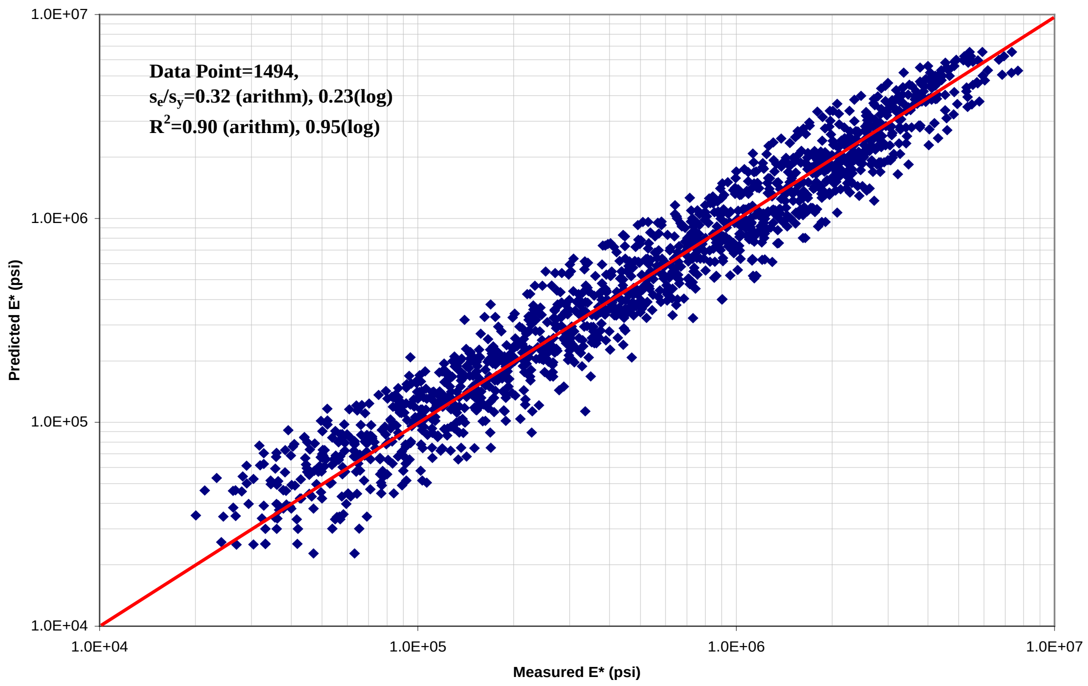
- WE* not calibrated for AR mixes.



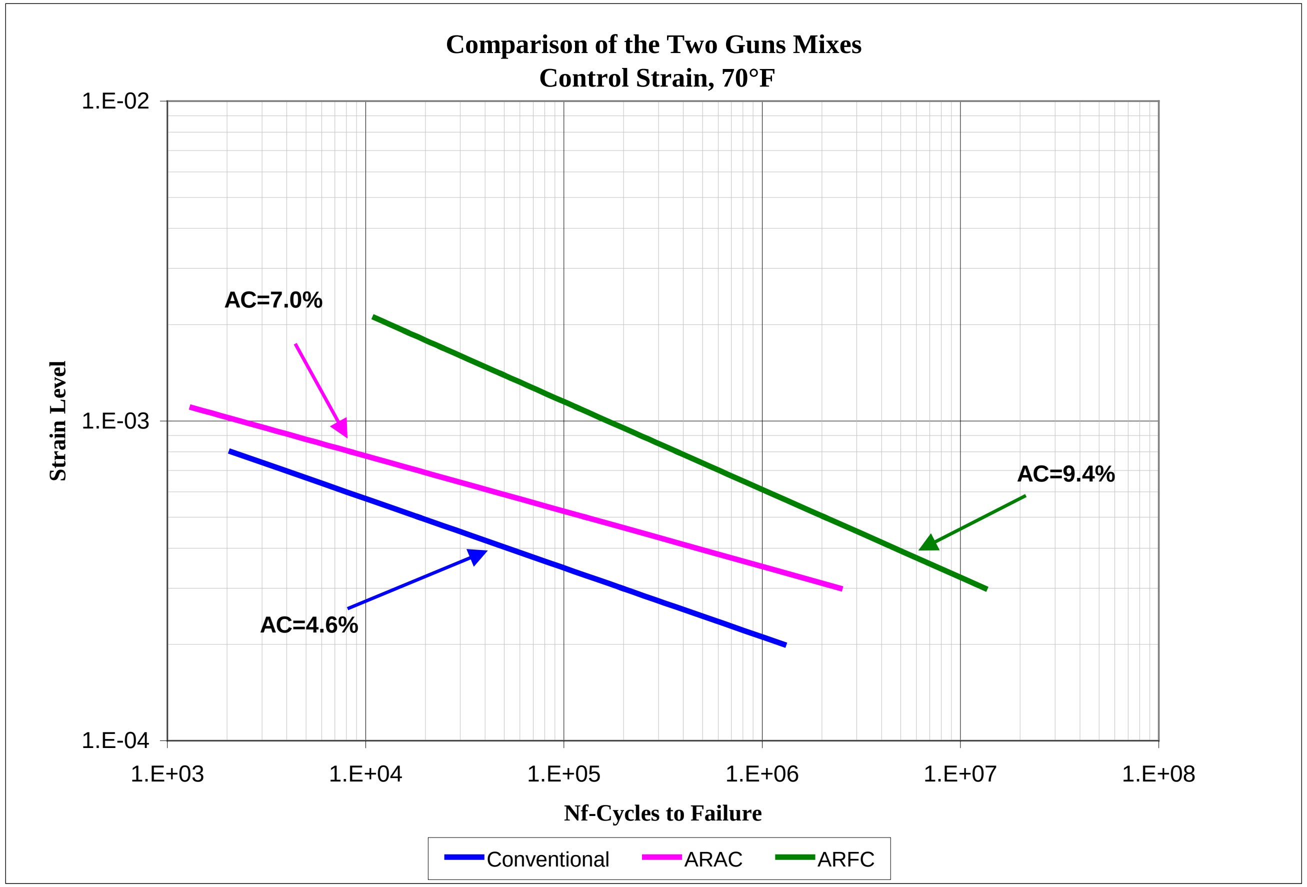
Calibrated WE* Equation for AR Mixes

Dynamic Modulus E*

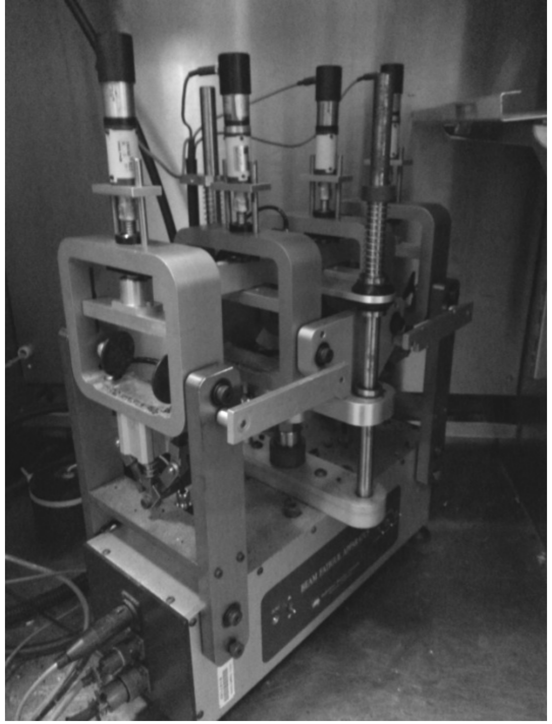
		CURRENT EQUATION	NEW PARAMETERS
COEFFICIENT	INTERCEPT 1	3.750063	0.346064
	P_{200}	0.029320	0.720506
	P_{200}^2	-0.001767	-0.2661
	P_4	-0.002841	0.068005
	VA	-0.058097	-0.042026
	VB_{EFF}	-0.802208	-0.067019
	INTERCEPT 2	3.871977	4.87167
	P_4	-0.002100	0.04564
	P_{38}	0.003958	0.036857
	P_{38}^2	0.000017	-0.001059
	P_{34}	0.005470	0.00547
	K_F	-0.603313	-0.175293
	K_V	0.313351	-0.480331
	B_F	-0.3953	-0.741099
LOG	S_E/S_Y	0.96	0.23
	R^2	0.08	0.95
ARITHMETIC	S_E/S_Y	0.97	0.32
	R^2	0.08	0.90



Fatigue Relationships



$$N_f = k_1\left(\frac{1}{\varepsilon_t}\right)^{k_2}\left(\frac{1}{E}\right)^{k_3}$$



Regression Coefficients k_1, k_2, k_3			
		Min	Max
ARAC	k_1	1.2E-08	7.5E-01
	k_2	4.2	8.2
	k_3	1.3	2.6
ARFC	k_1	3.0E-05	8.0E+03
	k_2	3	6.7
	k_3	1.5	2.7
Design Guide	k_1	7.6E-03	
	k_2	3.95	
	k_3	1.28	

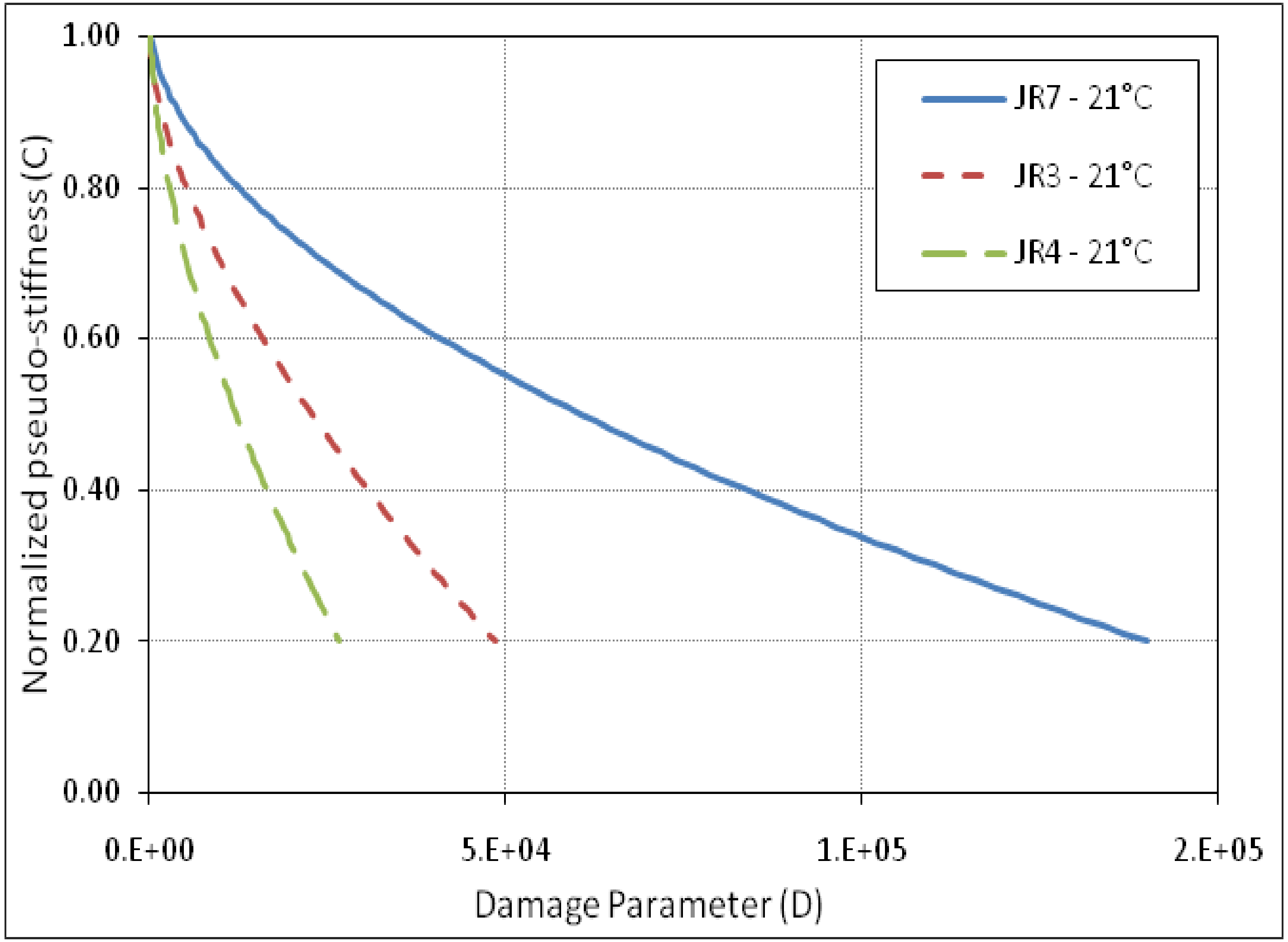
Fatigue Cracking Results

Total Cracking at Surface (%)		
Year	Default Coefficients	ARAC Coefficients
1	0.47	0.44
2	3.31	3.03
3	11.21	9.73
4	17.07	13.14
5	20.71	13.82
6	24	13.88
7	27.42	13.95
8	30.83	14.01
9	34.14	14.08
10	37.3	14.14

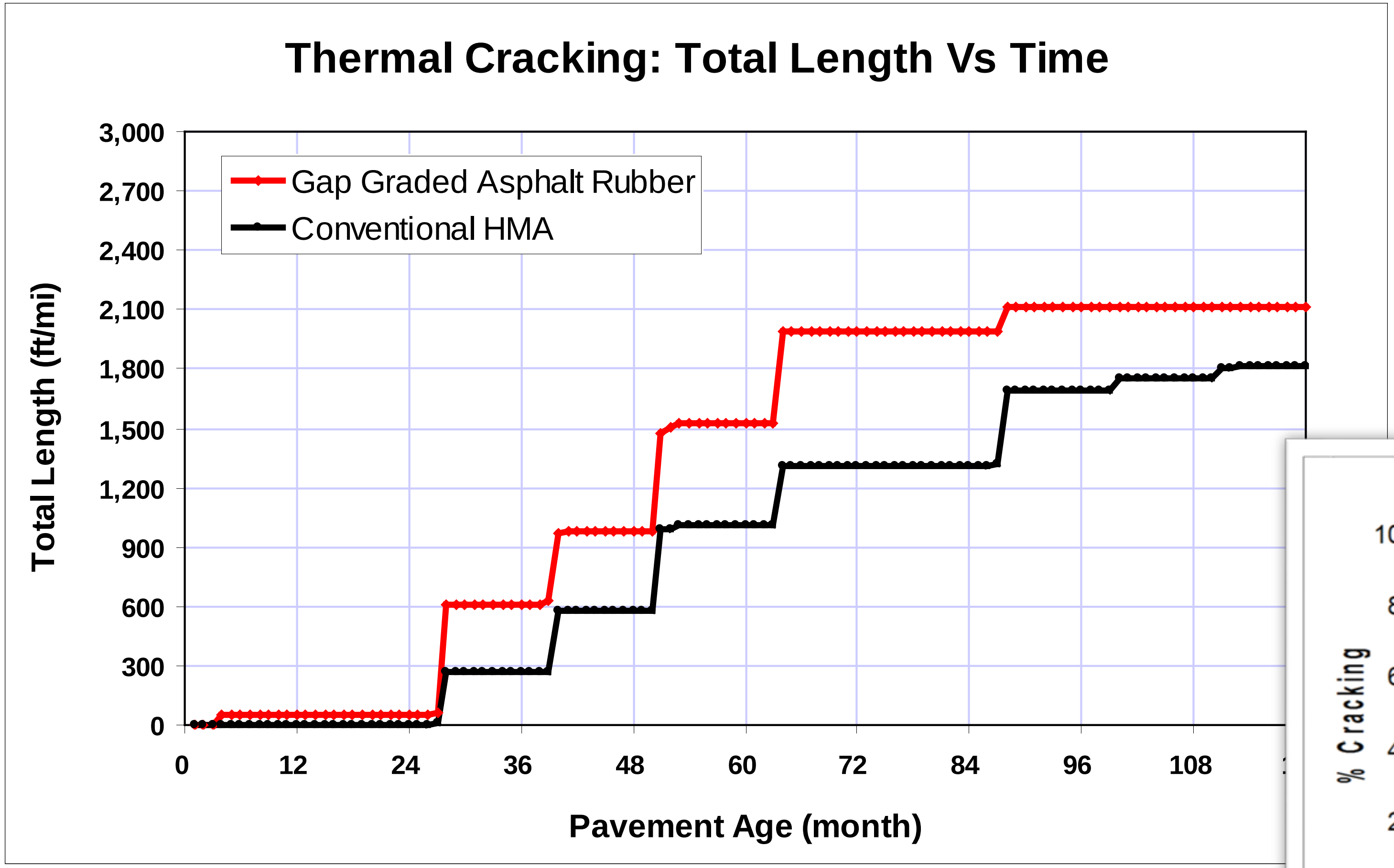
- Based on the field distress survey, the fatigue cracking after 7 years was approximately 7%.
- Use of specific ARAC coefficients and confined E* and seems to help in better predicting of fatigue cracking.

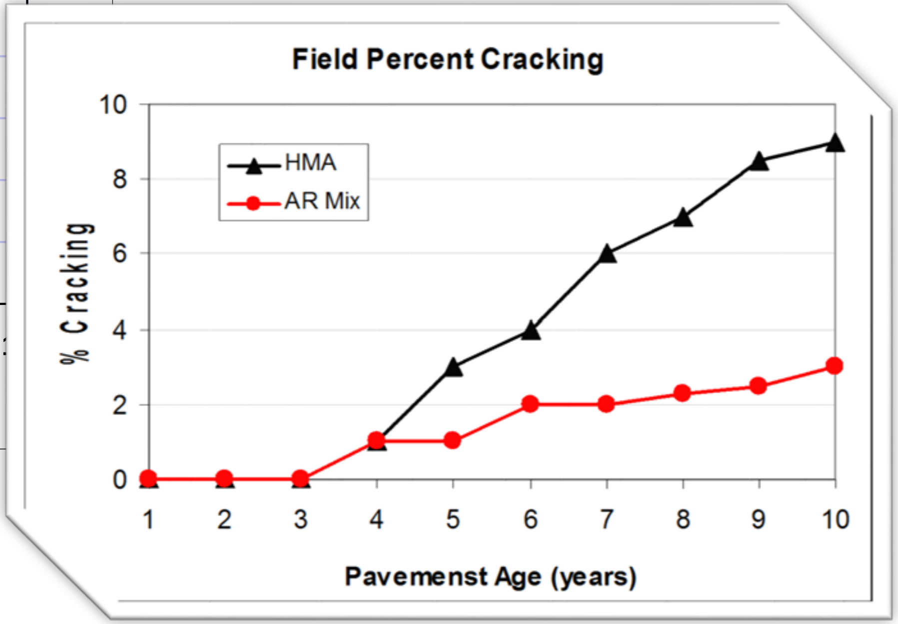
Continuum Damage Theory (CDT)

Dr. Luiz G. R. Mello, University of Brasilia



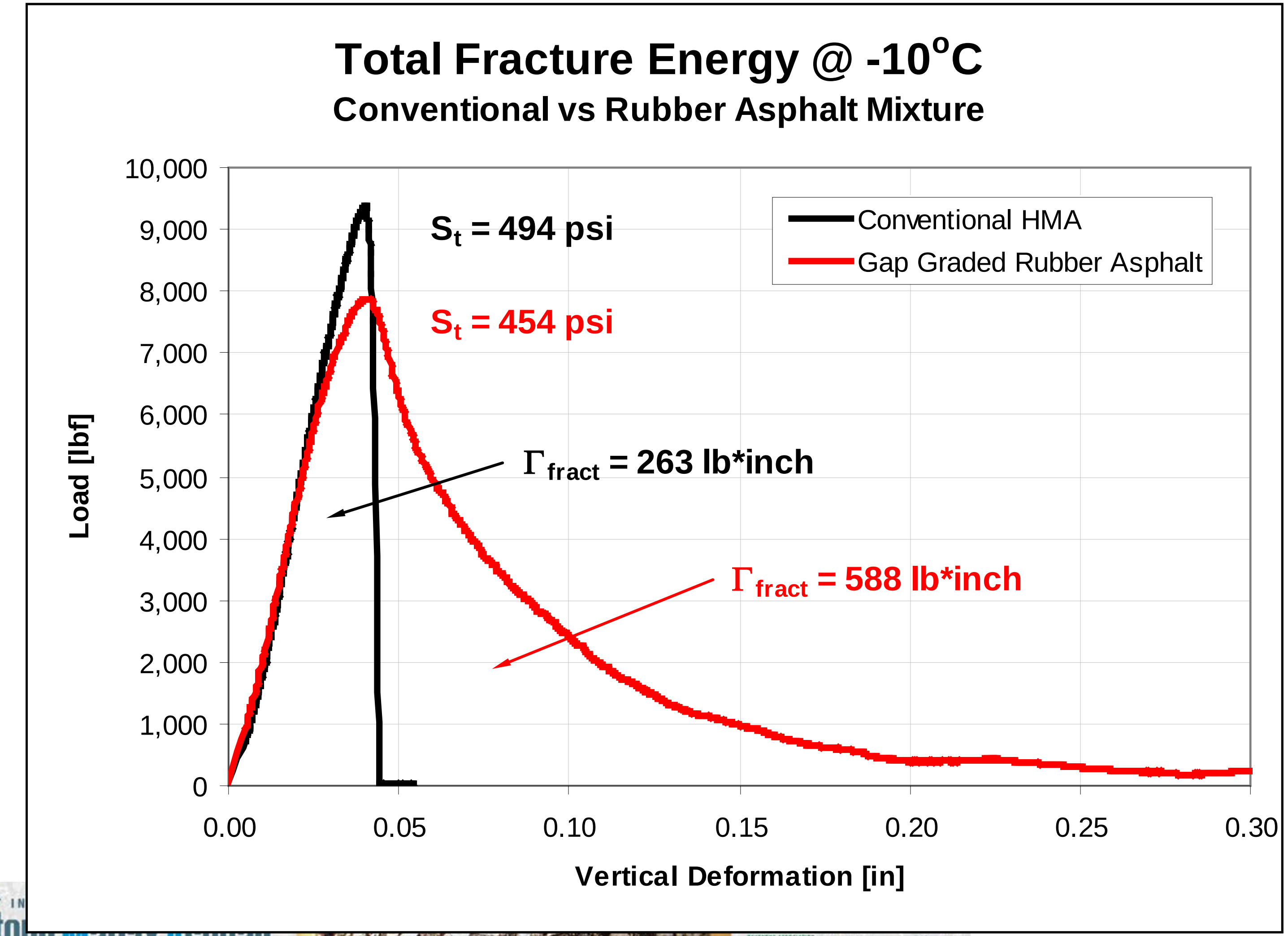
Thermal Cracking Prediction from MEPDG

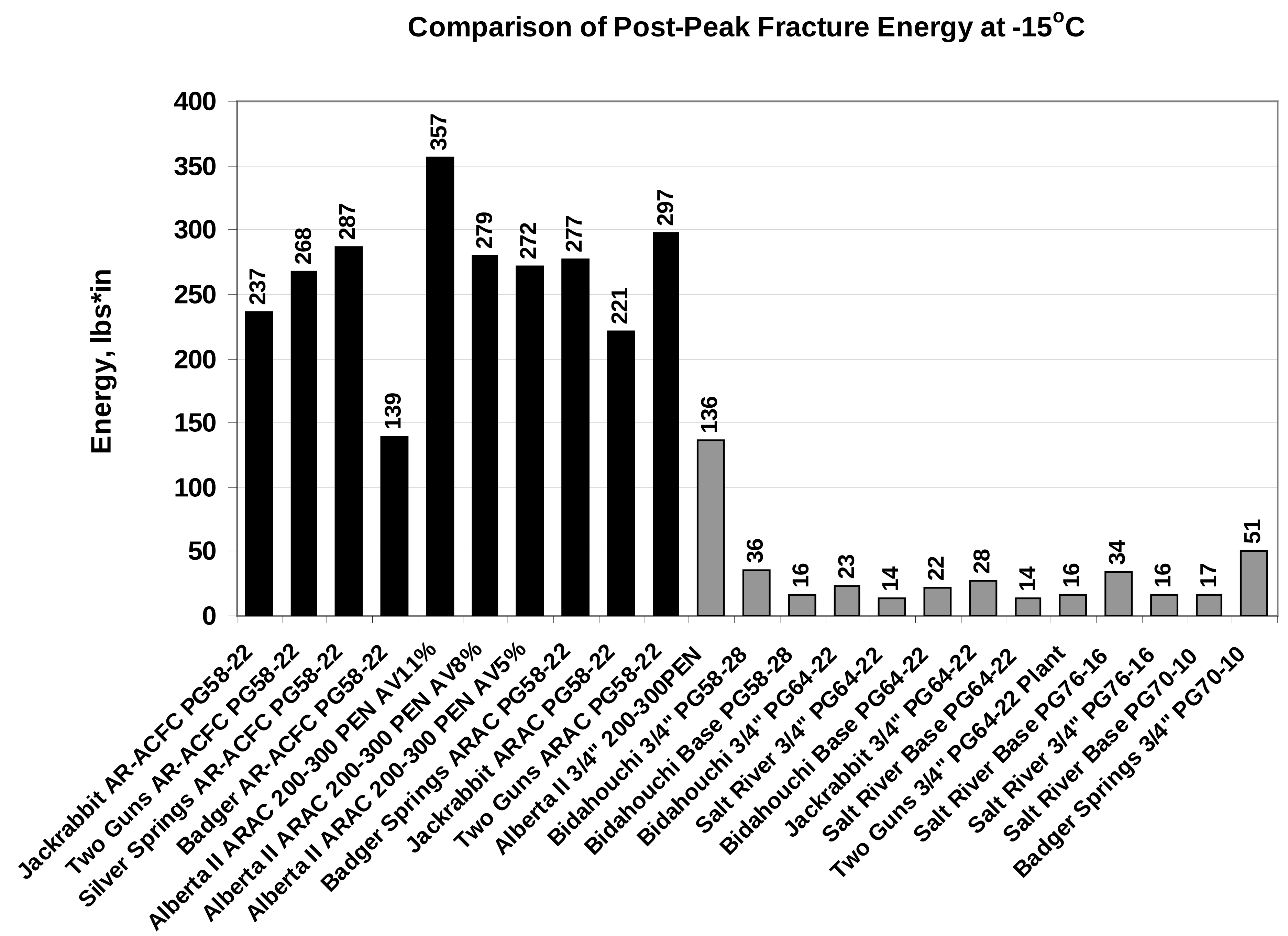




Fracture Energy: Conventional Vs. Asphalt Rubber

$$\log A = 4.389 - 2.52 * \log(E * St * n)$$




Comparison of Post-Peak Fracture Energy at -15°C
Energy, lbs*in
400
350
300
250
200
150
100
50
0
237
268
287
139
357
279
272
277
221
297
136
36
16
23
14
22
28
14
16
34
16
17
51
Jackrabbit AR-ACFC PG58-22
Two Guns AR-ACFC PG58-22
Silver Springs AR-ACFC PG58-22
Badger AR-ACFC PG58-22
Alberta II ARAC 200-300 PEN AV11%
Alberta II ARAC 200-300 PEN AV8%
Alberta II ARAC 200-300 PEN AV5%
Badger Springs ARAC PG58-22
Jackrabbit ARAC PG58-22
Two Guns ARAC PG58-22
Alberta II 3/4" 200-300PEN
Bidahouchi 3/4" PG58-28
Bidahouchi Base PG58-28
Bidahouchi 3/4" PG64-22
Salt River 3/4" PG64-22
Bidahouchi Base PG64-22
Jackrabbit 3/4" PG64-22
Salt River Base PG64-22
Two Guns 3/4" PG64-22 Plant
Salt River Base PG76-16
Salt River 3/4" PG76-16
Salt River Base PG70-10
Badger Springs 3/4" PG70-10

"A" Parameters for Crack Depth Fracture Model

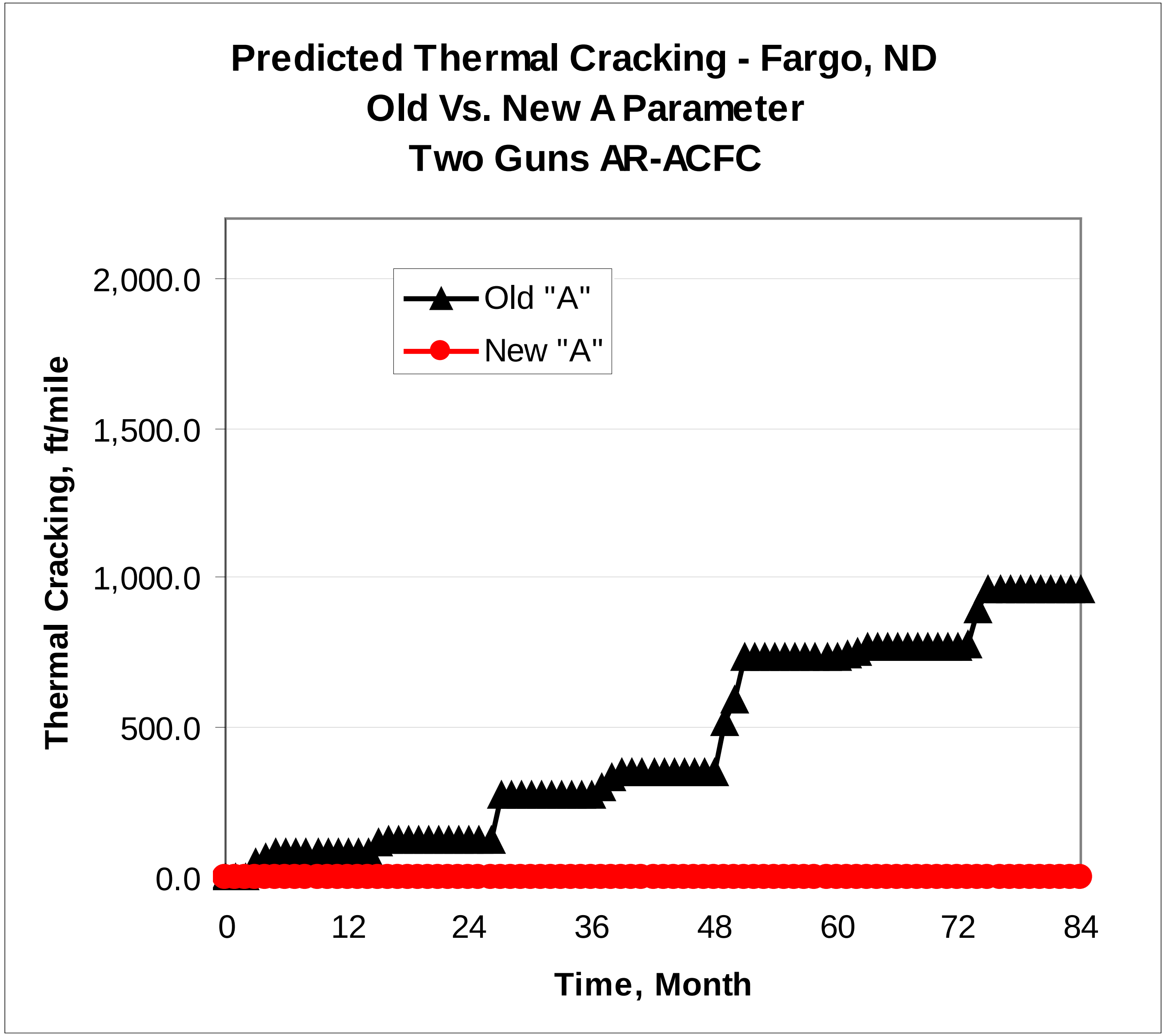
- Paris crack growth law: $$\Delta C = A(\Delta K)^n$$

- "A" developed by Molenaar: $$\log A = 4.389 - 2.52 * \log(E * \sigma_m * n)$$

- "A" developed by Schapery: $$A = \frac{\pi}{6\sigma_m^2 I_1^2}\left[\frac{(1-\nu^2)D_1}{2\Gamma}\right]^{1/m}\left[\int_0^{\Delta t} w(t)^n\,dt\right]$$

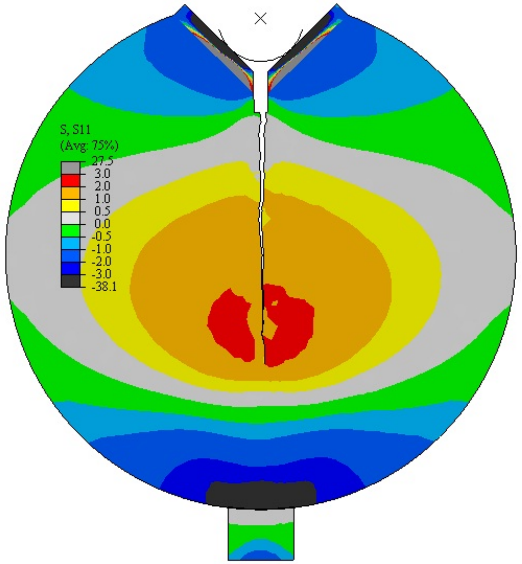
where:

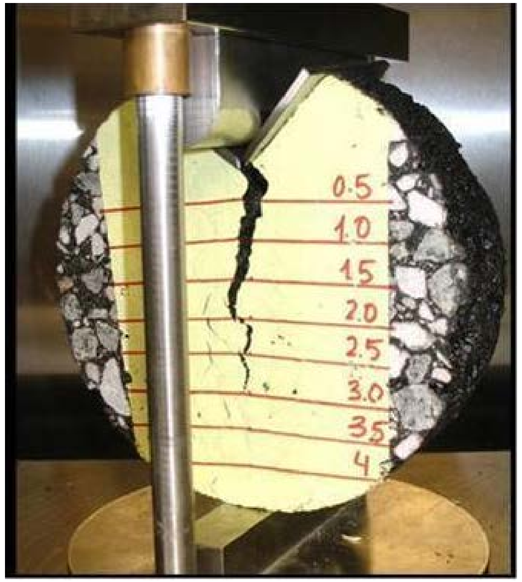
$n = 2[1 + (1/m)]$
σ_m = tensile strength
I_1 = value of the integral of the dimensionless stress-strain curve of the material
ν = Poisson's ratio
D_1 = intercept of the creep compliance curve
m = slope of the creep compliance curve
Γ = fracture energy
$w(t)$ = the normalized waveform of the applied load with time
Δt = period of the loading to complete one cycle of loading

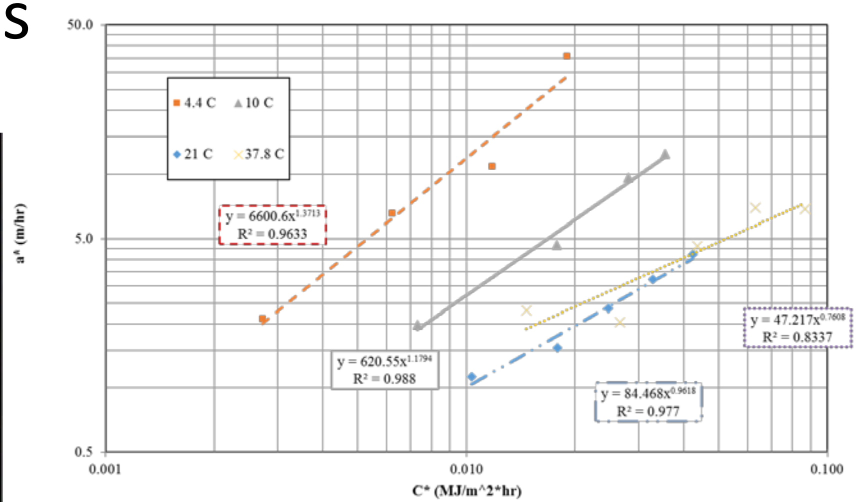

Predicted Thermal Cracking - Fargo, ND
Old Vs. New A Parameter
Two Guns AR-ACFC
Thermal Cracking, ft/mile
2,000.0
1,500.0
1,000.0
500.0
0.0
0
12
24
36
48
60
72
84
Time, Month
Old "A"
New "A"

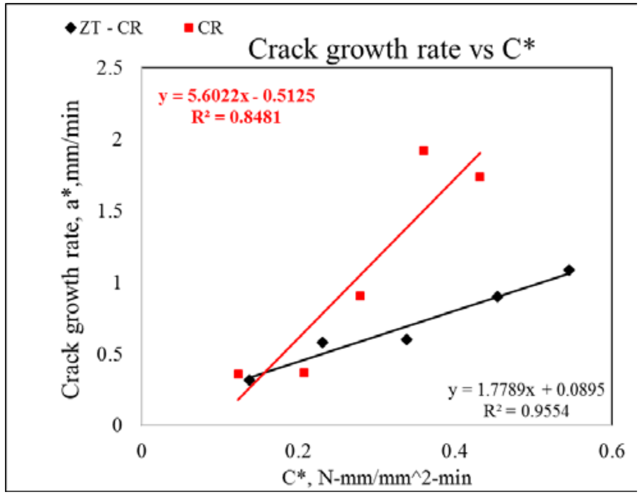
C* Fracture Test *(Jeff Stempihar, PhD 2013)*

Develop test geometry, protocol, temperature and loading rate dependency, FE analysis and predictive models

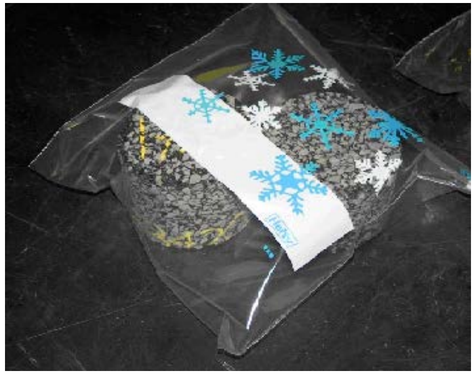


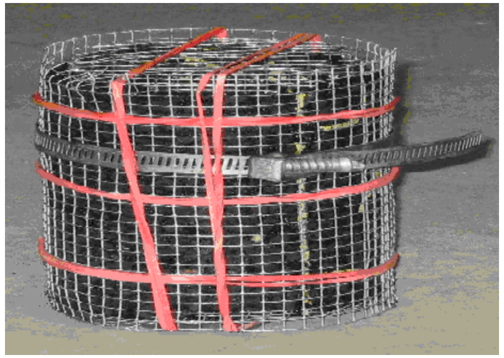


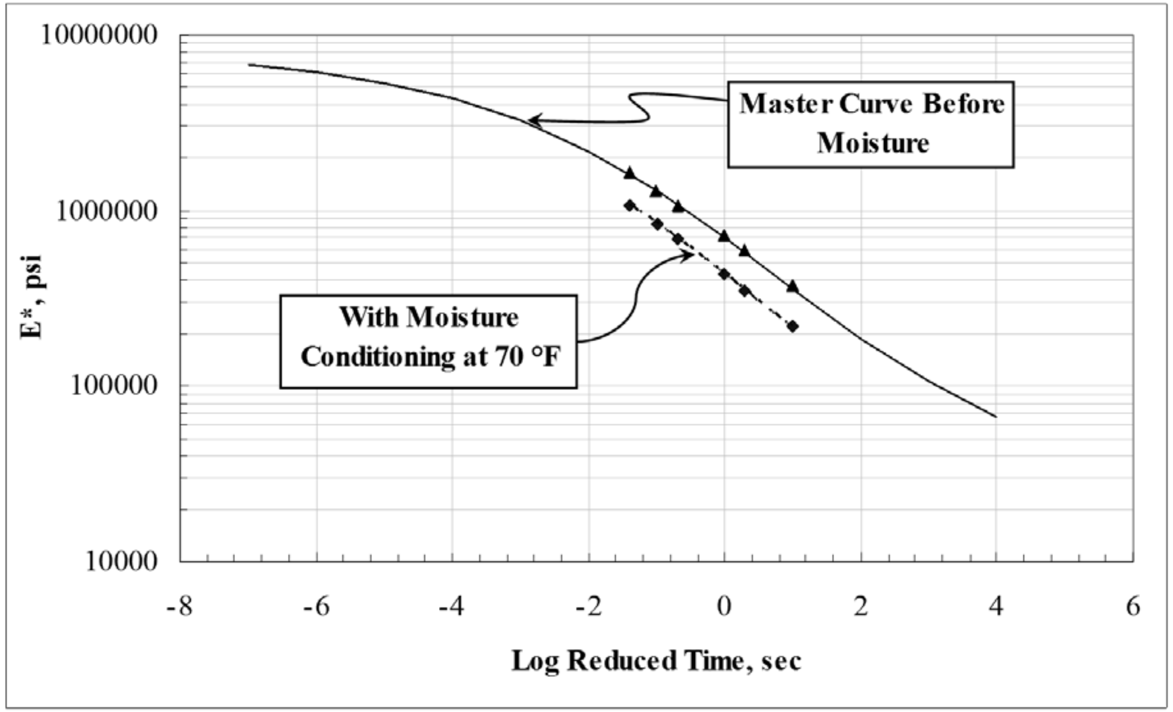




Moisture Susceptibility AASHTO T 283 Test Method





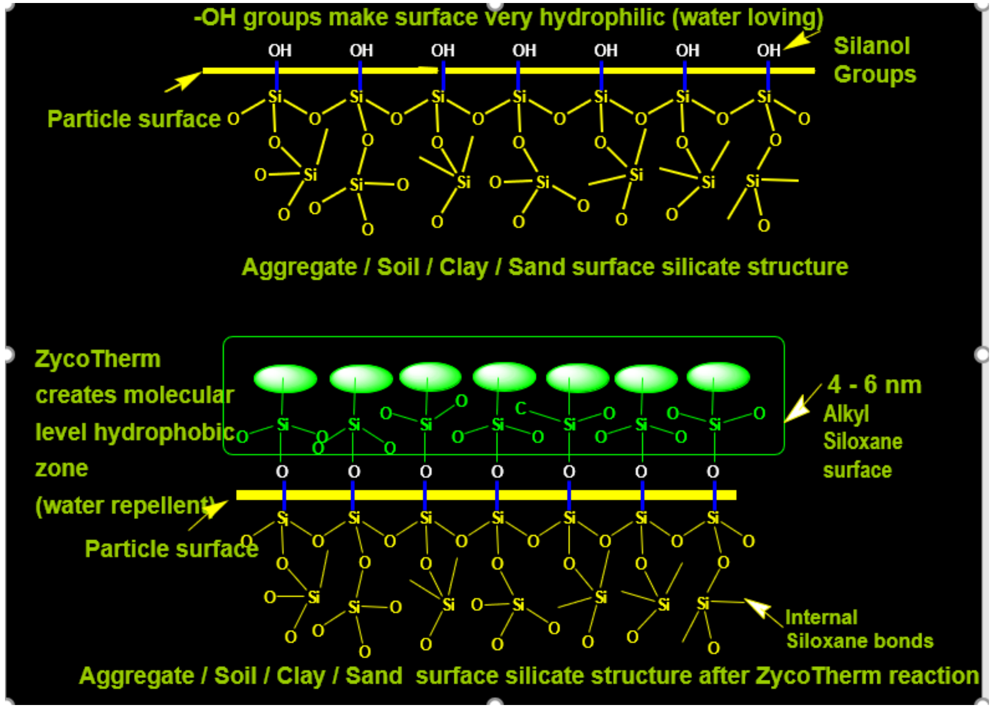


Threshold TSR / ESR

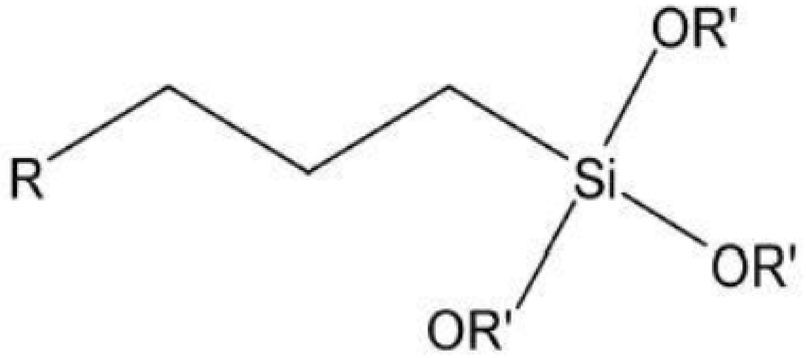
Type of Mix	Pass Criteria
CONV	≥ 70 %
ARAC	≥ 65 %
ARFC	≥ 50 %

Recent Study

Use of Organosilane for better moisture damage resistance and <u>reduction in mixing temperatures</u> of CRMB mixtures.



Nanotechnology Organosilane Compounds for Chemical Bonding in Road Construction. Asphalt Pavement Technology(Ajay Ranka, 2014).



Organosilane alkylalkoxy compound.

- Affecting the aggregate surface at the Nano level.

- Organosilane is the organo functional alkoxysilane

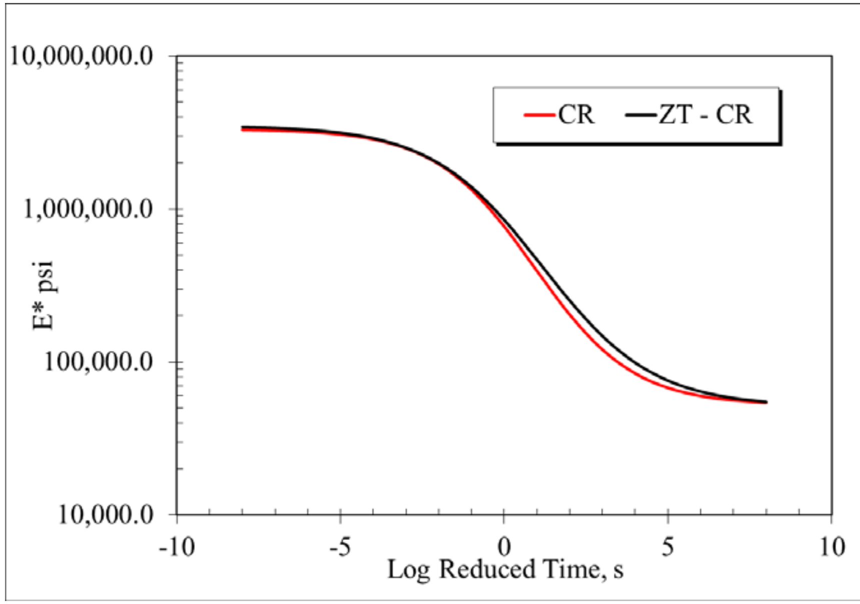
Organosilane - Results

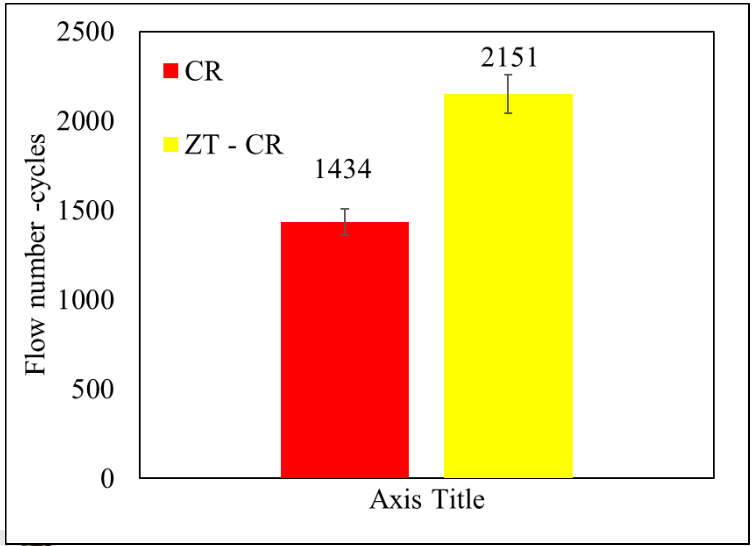
ZT - CR Mix	Conditioned			Dry (Unconditioned)		
Average Air Voids	6.06%			6.03%		
Tensile strength (kPa)	748.7	895.9	465.7	913.2	1028	711.8
Average tensile strength (kPa)	703.5			884.5		
Tensile Strength Ratio (%)	80%					

CR Mix	Conditioned			Dry (Unconditioned)		
Average Air Voids	6.03%			6.06%		
Tensile strength (kPa)	645.7	741.7	629.3	1072	827.7	938.5
Average tensile strength (kPa)	672.2			946.1		
Tensile Strength Ratio (%)	71%					

- Increased moisture resistance due to antistripping property of Organosilane

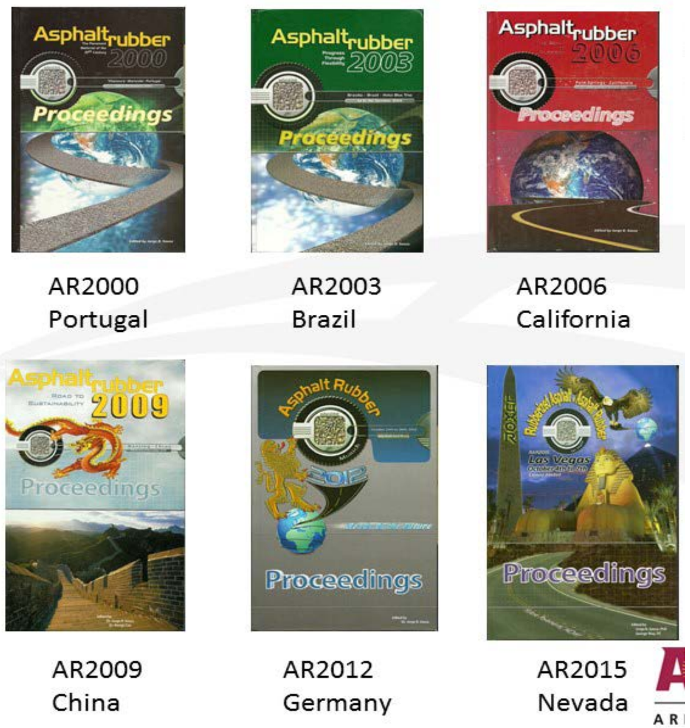
Dosage: 0.15 % by weight of virgin binder used in CRMB preparation





Concluding Remarks

- AR SMA mixtures and projects over the past two decades provided great opportunities to evaluate, validate and fine tune various laboratory tests procedures so they can be used as performance indicators.
- New emerging technologies (Reacted and Activated / Pre-Activated) will facilitate a wider implementation especially when supported with excellent laboratory and field performance.



Thank you!