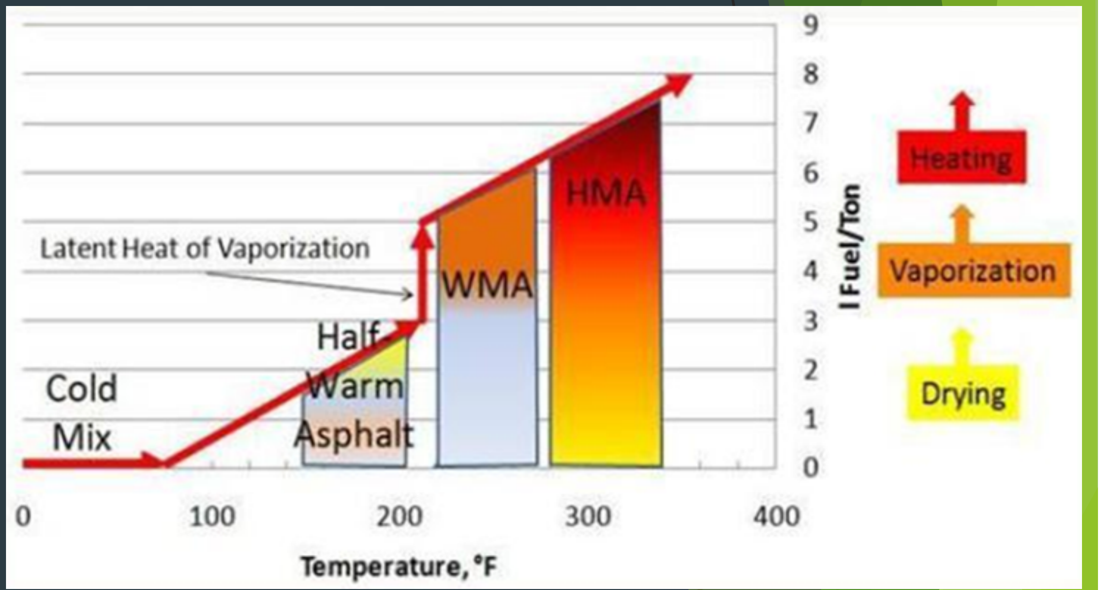
Sustainable Pavement Technologies:

Highlighting Recent Advancements in Warm Mix Asphalt

Ashley Buss, Ph.D.

Warm Mix Asphalt Background

- Temperature reduction of approximately 30 °C compared with traditional HMA production temperatures.
- Benefits
  - Reduction in Emissions
  - Reduced fuel and energy use
  - Paving benefits
  - Reduced compaction effort
  - Longer haul distances
  - Cooler temperature paving



Road to WMA Implementation

Motivation:

- Cost Savings
- Legislation
    - Kyoto Protocol
- Increased need for Sustainable Practices

Road to WMA Implementation

Motivation

Development:

- Additives
  - Chemical
  - Waxes
  - Synthetic Zeolites
- Foaming Processes

Development: Warm Mix Asphalt Types

- Four primary categories
  - Chemical Additives
  - Foamed Asphalt- Mix Additive
  - Wax Additives
  - Foamed Asphalt- Plant Modification

Double Barrel Green System®

Road to WMA Implementation

Motivation

Development 

Research and Beginning Implementation:

- Binder Studies
- Mixture Studies
- QC/QA Concerns
- Moisture Susceptibility
- Demonstration Projects

Early WMA Studies

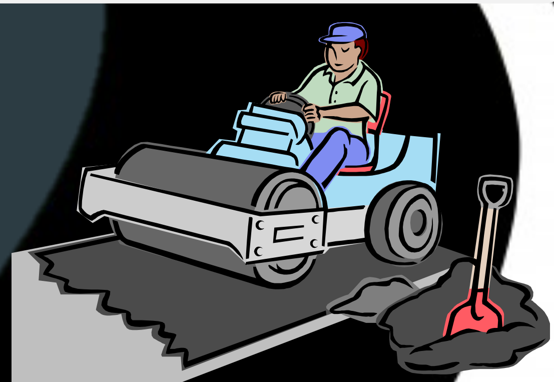
- NCAT demonstrated improved compactibility through reduced air voids
  - Lower compaction temperatures show higher rutting depth in APA
- Moisture damage is a concern for WMA with anti-stripping agents improving results
- Pavement performance in many cases shows similar performance between HMA and WMA

Road to WMA Implementation

Motivation

Development

Research and Beginning Implementation



Construction:

- Economics
- QC/QA Evaluations
- Improved Compaction
- Reduced Temperatures and Emissions

Road to WMA Implementation

Motivation

Development 

Research and Implementation

Construction

Pavement Performance Evaluation:

- Comparable to HMA
- QC/QA concerns addressed
- Long-term monitoring

Warm Mix Asphalt Research and Development

- Important questions about implementing WMA existed
- Development of comprehensive WMA study for implementing asphalt mixes at the state level
- Concerns to be addressed include
  - Use of WMA with Recycled Asphalt Materials
  - Impacts of WMA on moisture sensitivity QC/QA
  - Iowa has recently changed the moisture susceptibility test from AASHTO T-283 to the Hamburg Wheel Tracking Test

Recycled Asphalt Pavement and Recycled Asphalt Shingles

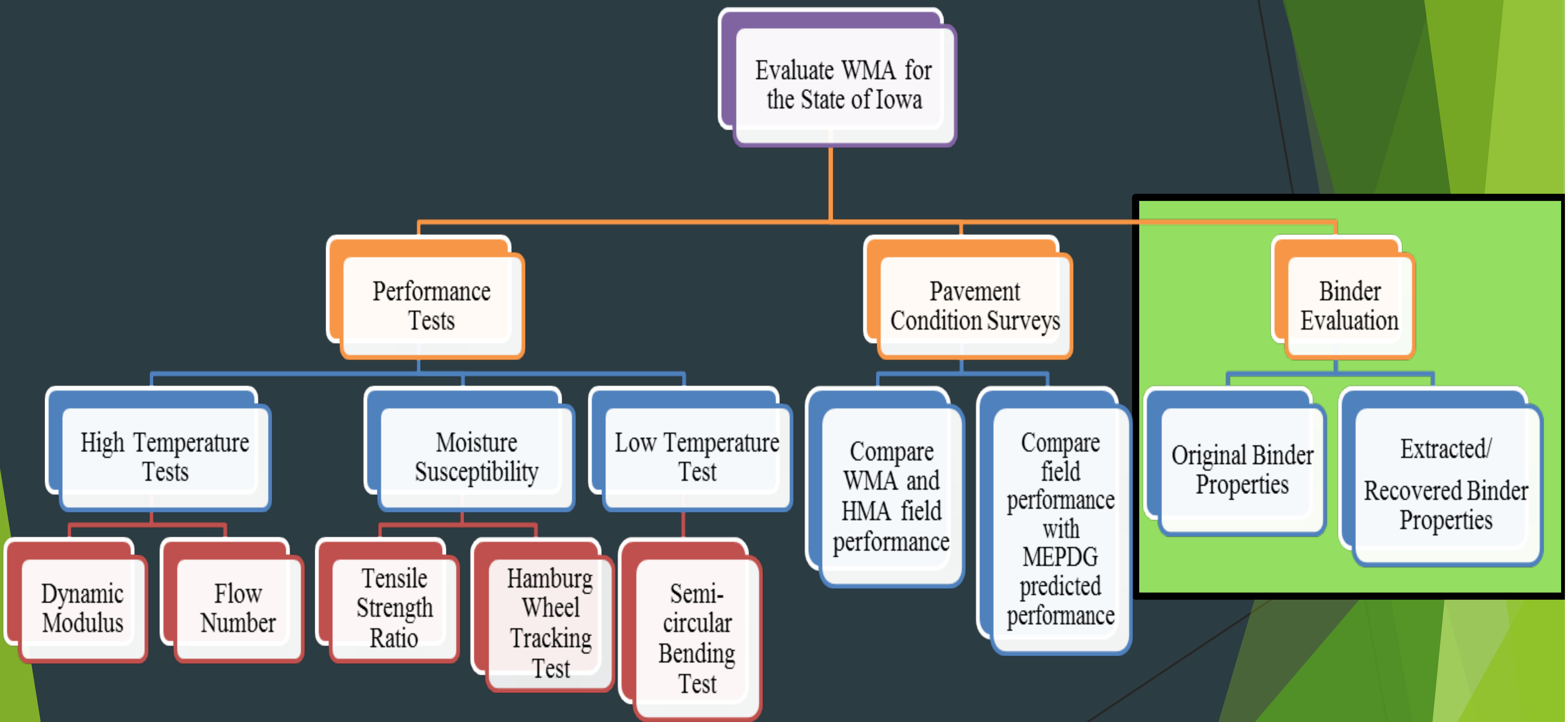
Recycled Asphalt Pavement and Recycled Asphalt Shingles

Photos courtesy of Debra Haugen

Warm Mix Asphalt Projects

Code	Year	Road Name	Project Number	WMA Technology	Mix Type	Binder Grade	RAP	RAS
FM2	2009	U.S. Route 218	NHSX-218-9(129)--3H-34	Evotherm	HMA 10M	64-28	17%	--
FM3	2009	Iowa Hwy 143	STP-143-1(4)--2C-18	Sasobit	HMA 3M	64-22	20%	--
FM4	2009	U.S. Route 65	STP-065-3(57)--2C-91	Foaming	HMA 3M	64-22	20%	--
FM5	2010	County Hwy E67	STP-S-C064(110)-5E-64	Evotherm	HMA 300K	64-22	20%	--
FM6	2010	Iowa Hwy 13	MP-013-2(704)59--76-22	Evotherm	HMA 1M	64-22	5%	--
IA-0	2010	U.S. Route 61	HSIPX-061-4(107)--3L-70	Evotherm	HMA 1M	58-28	20%	--
IA-5	2010	U.S. Route 61	HSIPX-061-4(107)--3L-70	Evotherm	HMA 1M	58-28	13% RAP	5%
IA-7	2010	U.S. Route 61	HSIPX-061-4(107)--3L-70	Evotherm	HMA 1M	58-28	6% RAP	7%

Comprehensive Research Plan



Superpave Binder Performance Grade

Dynamic Shear Rheometer

Rolling Thin Film Oven

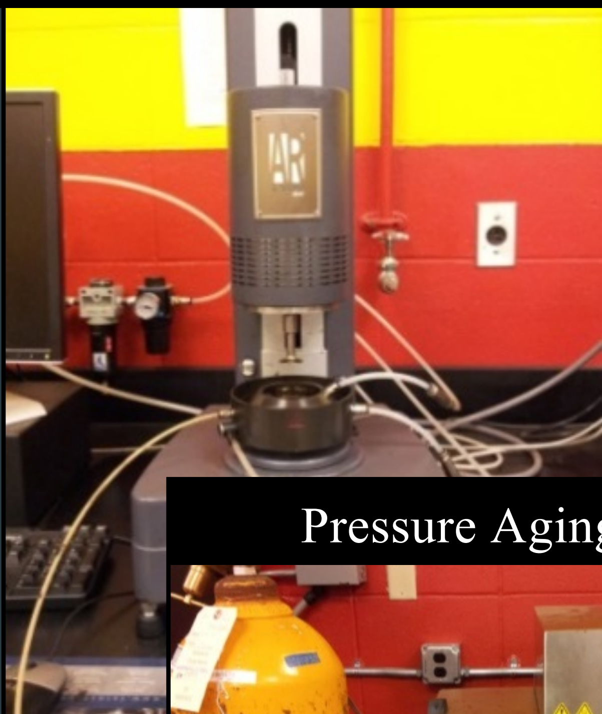
Superpave Binder Performance Grade

Dynamic Shear Rheometer

Rolling Thin Film Oven

Pressure Aging Vessel

Superpave Binder Performance Grade



Dynamic Shear Rheometer

Rolling Thin Film Oven

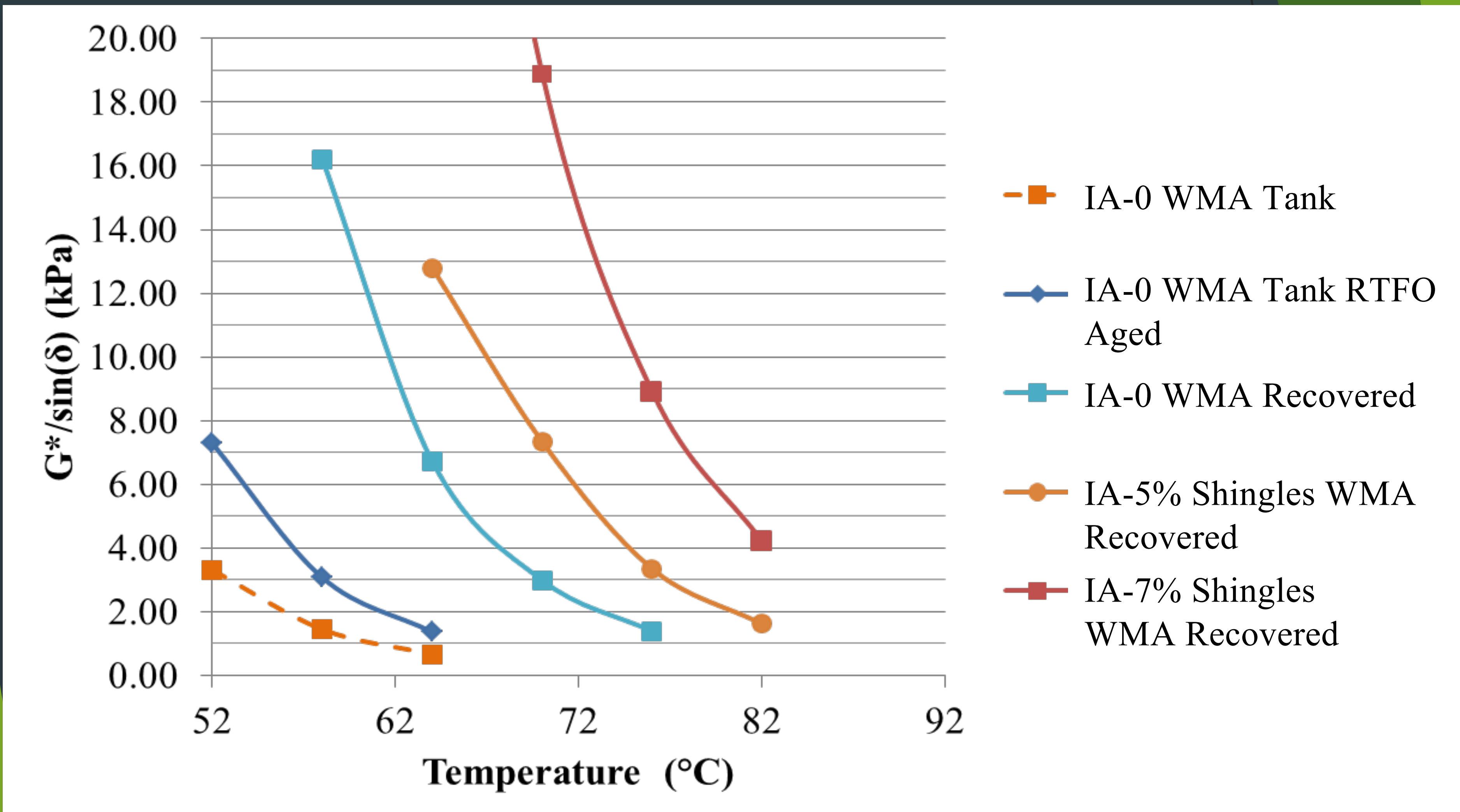
Pressure Aging Vessel

Bending Beam Rheometer

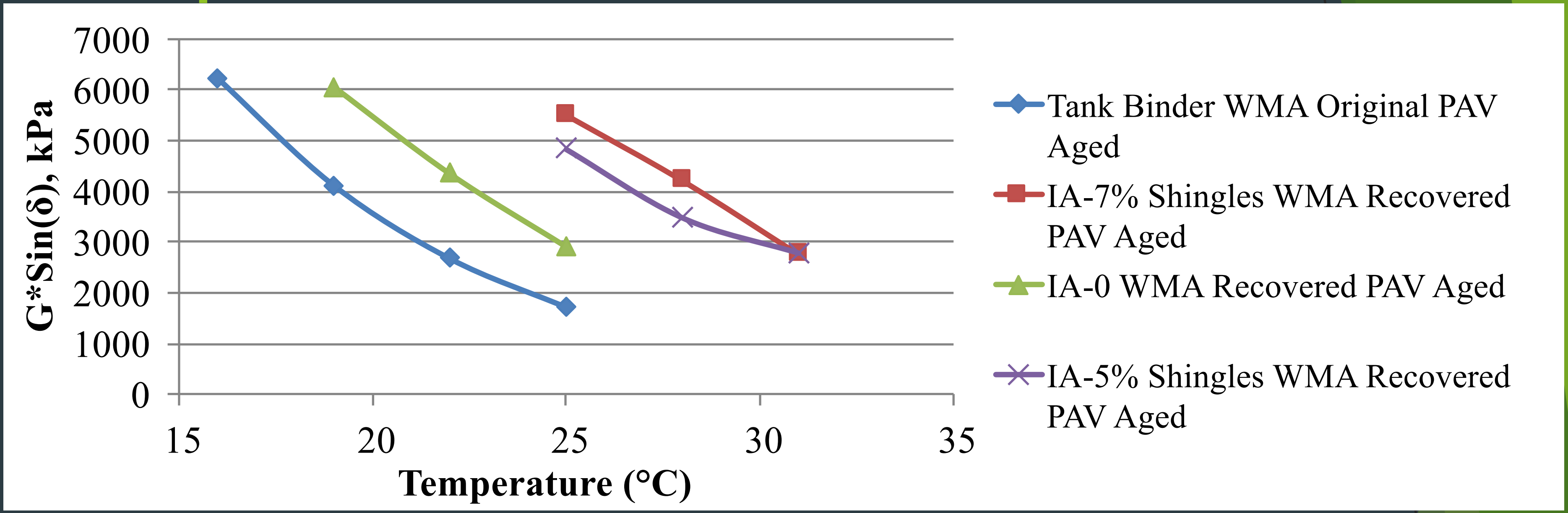
Binder recovery from asphalt cores

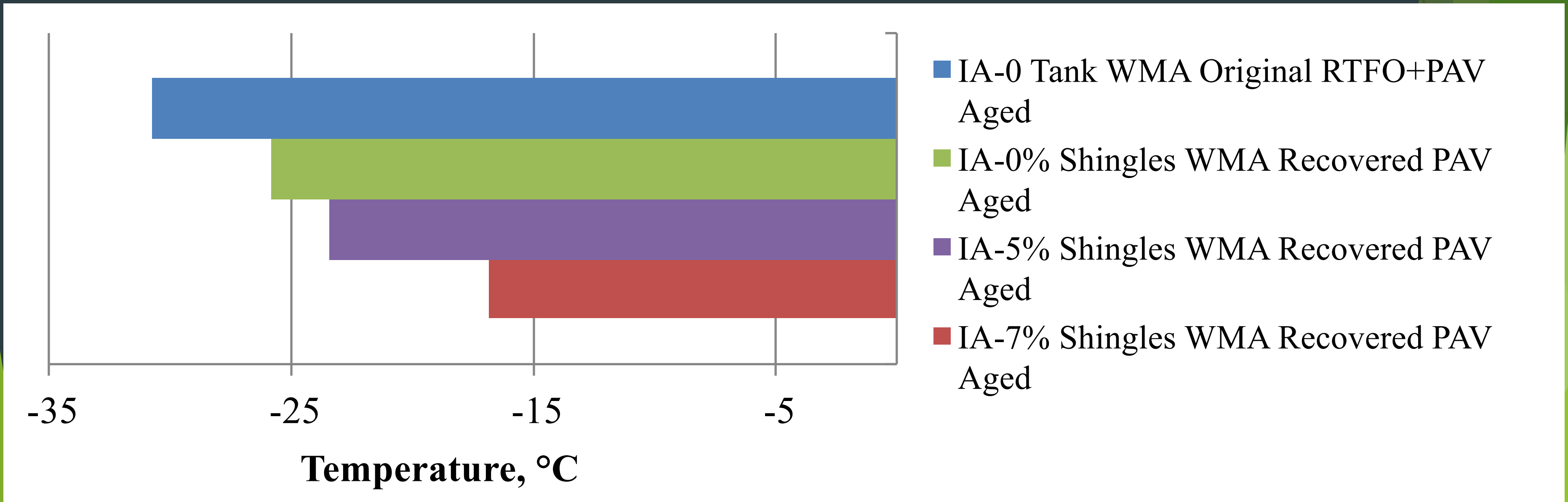
High Temperature Binder Grades

<u>IA-0</u>: 20% RAP/0% RAS, **<u>IA-5</u>**: 18% RAP/5% RAS **<u>IA-7</u>**: 18% RAP/7% RAS

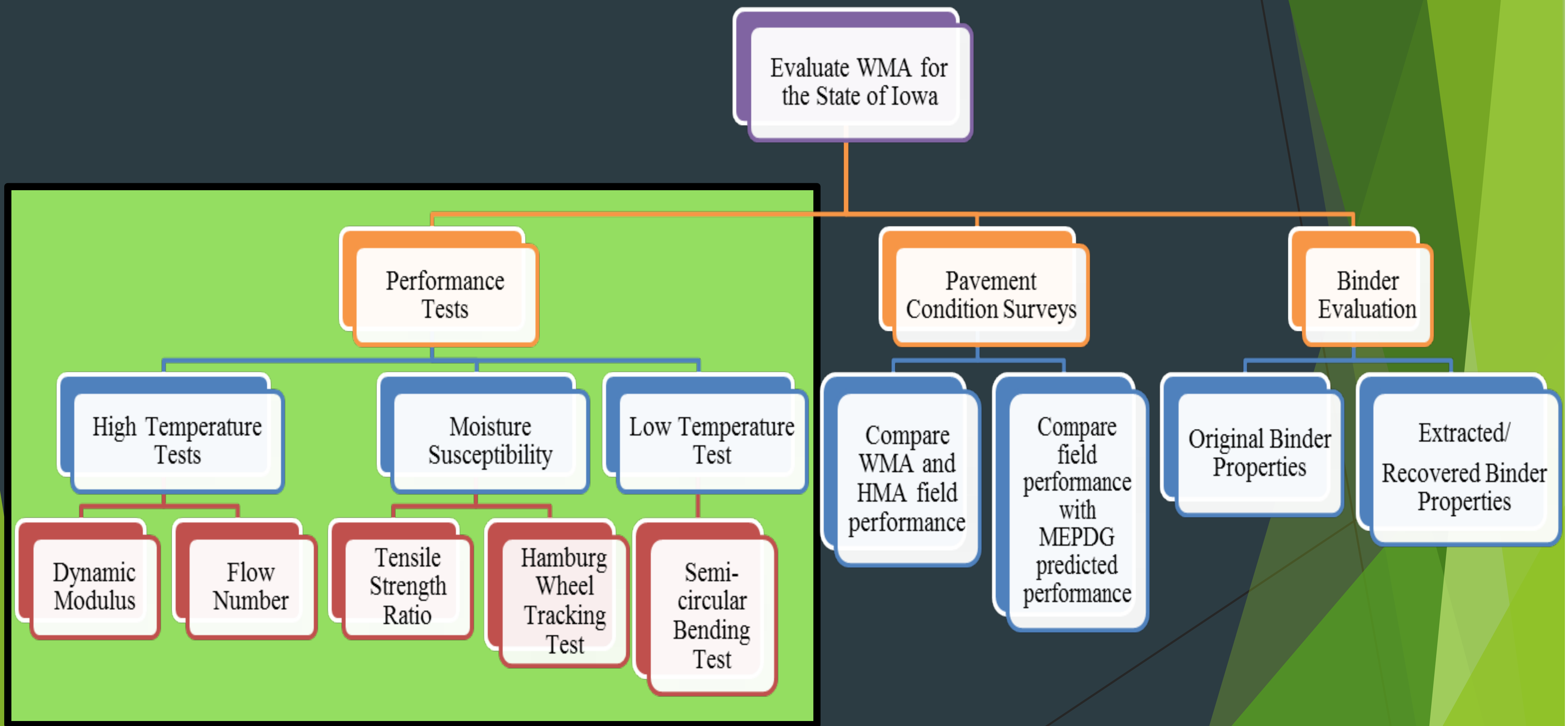


Intermediate and Low Temperature Binder Grades





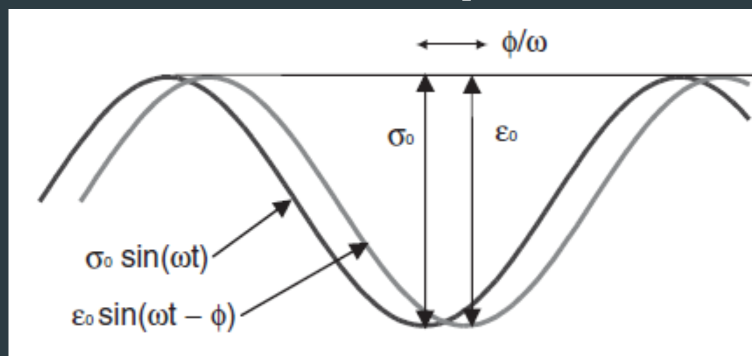
Comprehensive Research Plan



Dynamic Modulus Testing

- Dynamic Modulus Equation

$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

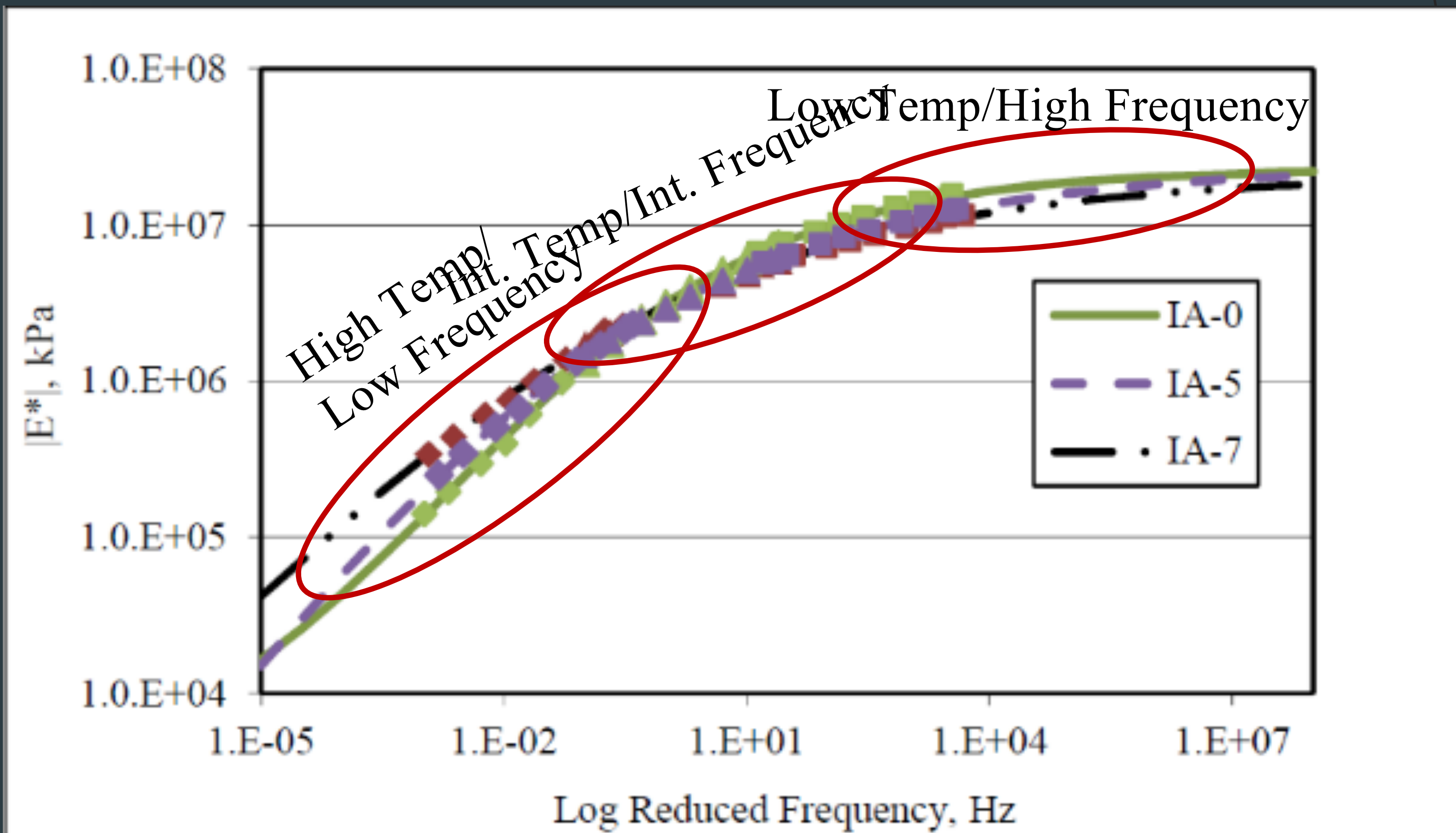


- E* Master Curve Sigmoidal Function

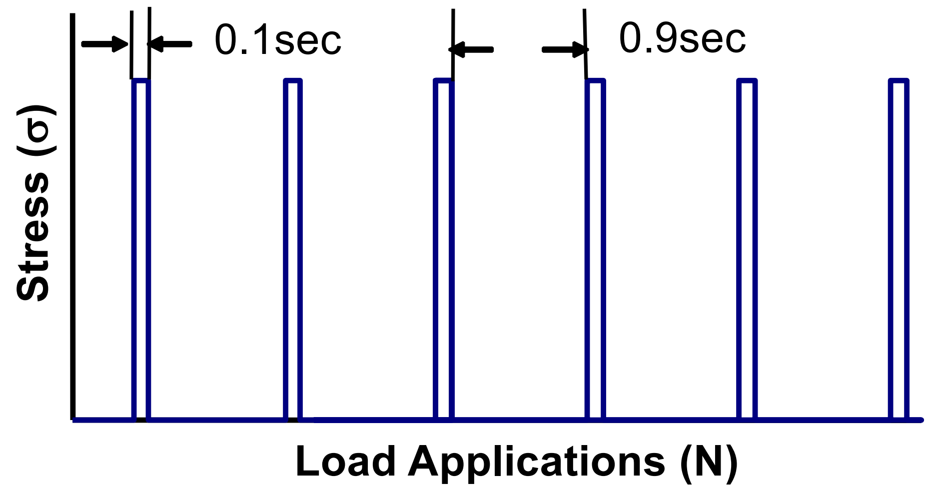
$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma[\log(t) - c(\log(\eta) - \log(\eta_{Tr}))]}}$$

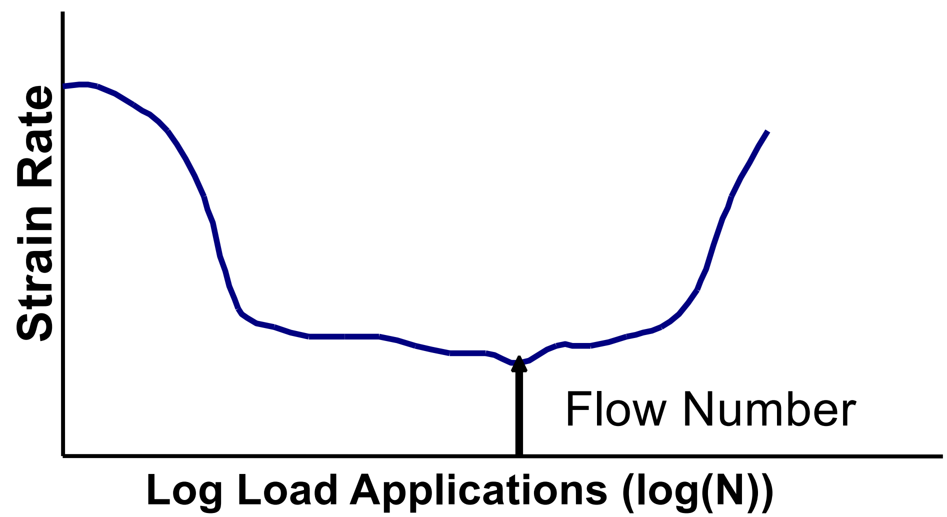
E*	=	Dynamic modulus, psi
t	=	Time of loading, sec
η	=	Viscosity at temperature of interest, CPoise
η_{Tr}	=	Viscosity at reference temperature, CPoise
$\alpha,\beta,\delta,\gamma,c$	=	Mixture specific fitting parameters.

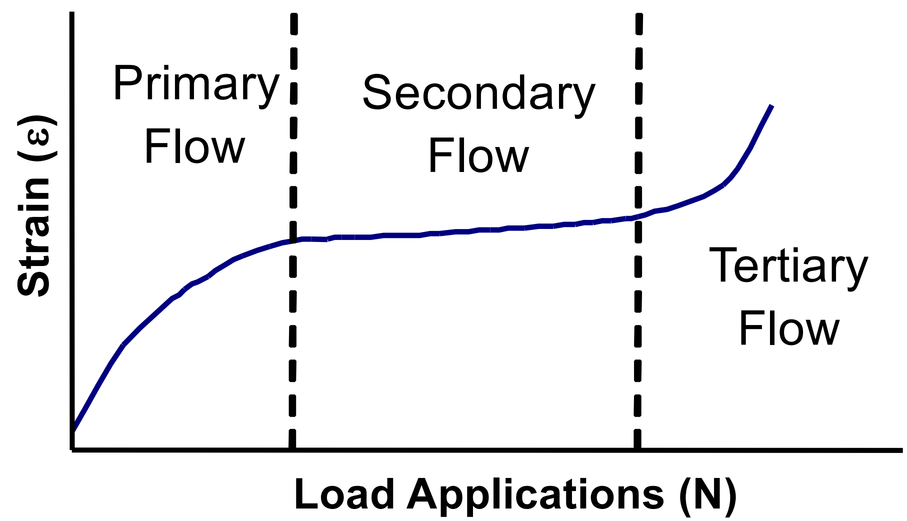
WMA/RAS Dynamic Modulus Results



Flow Number Test for evaluating rutting

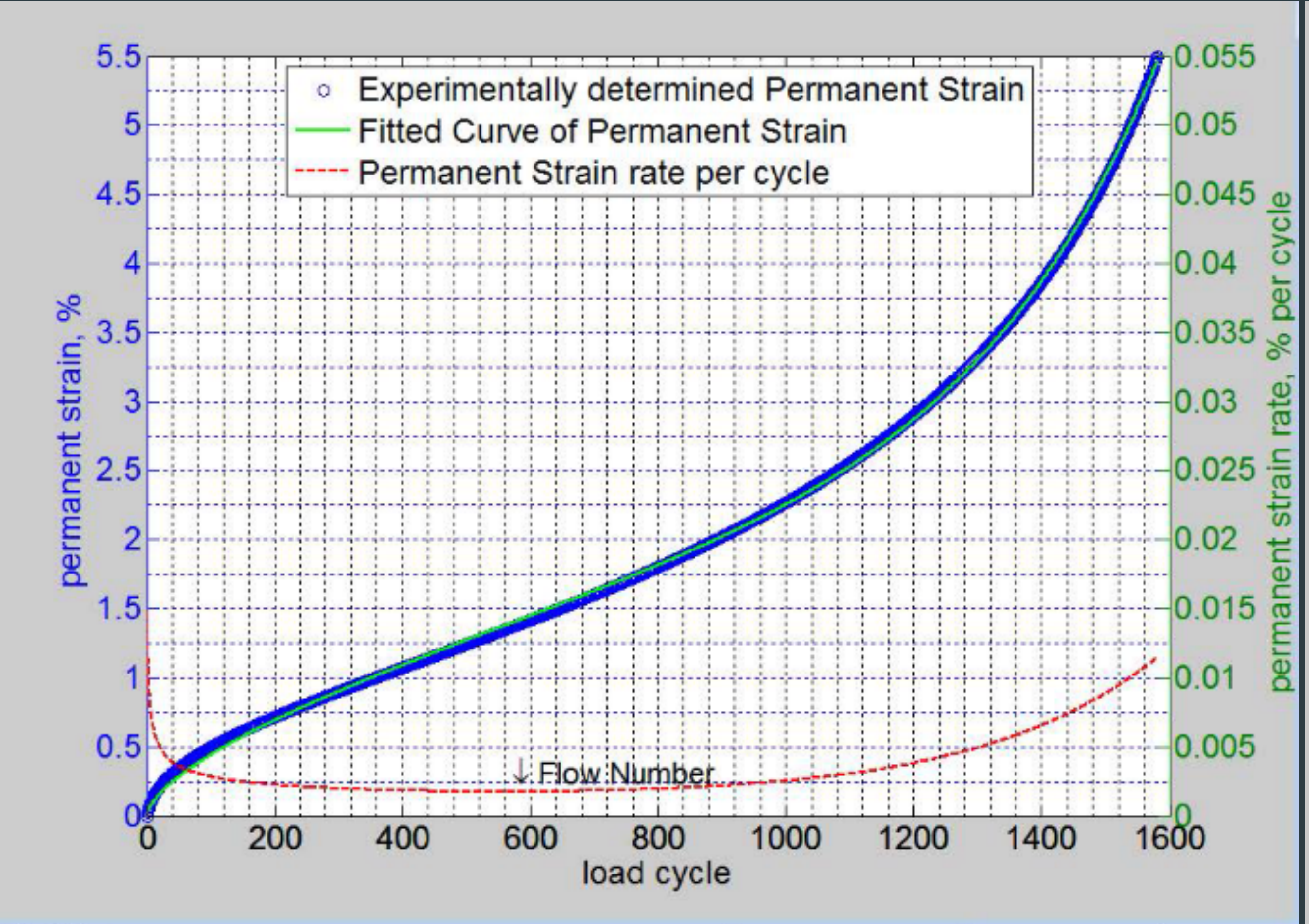




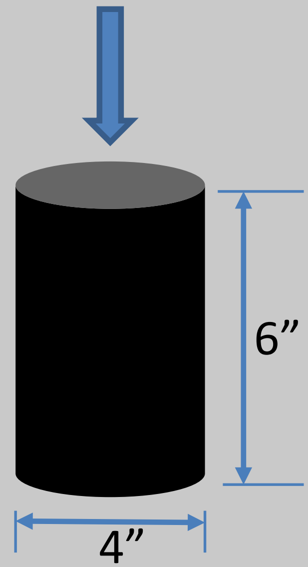


Flow Number = Minimum Strain Rate

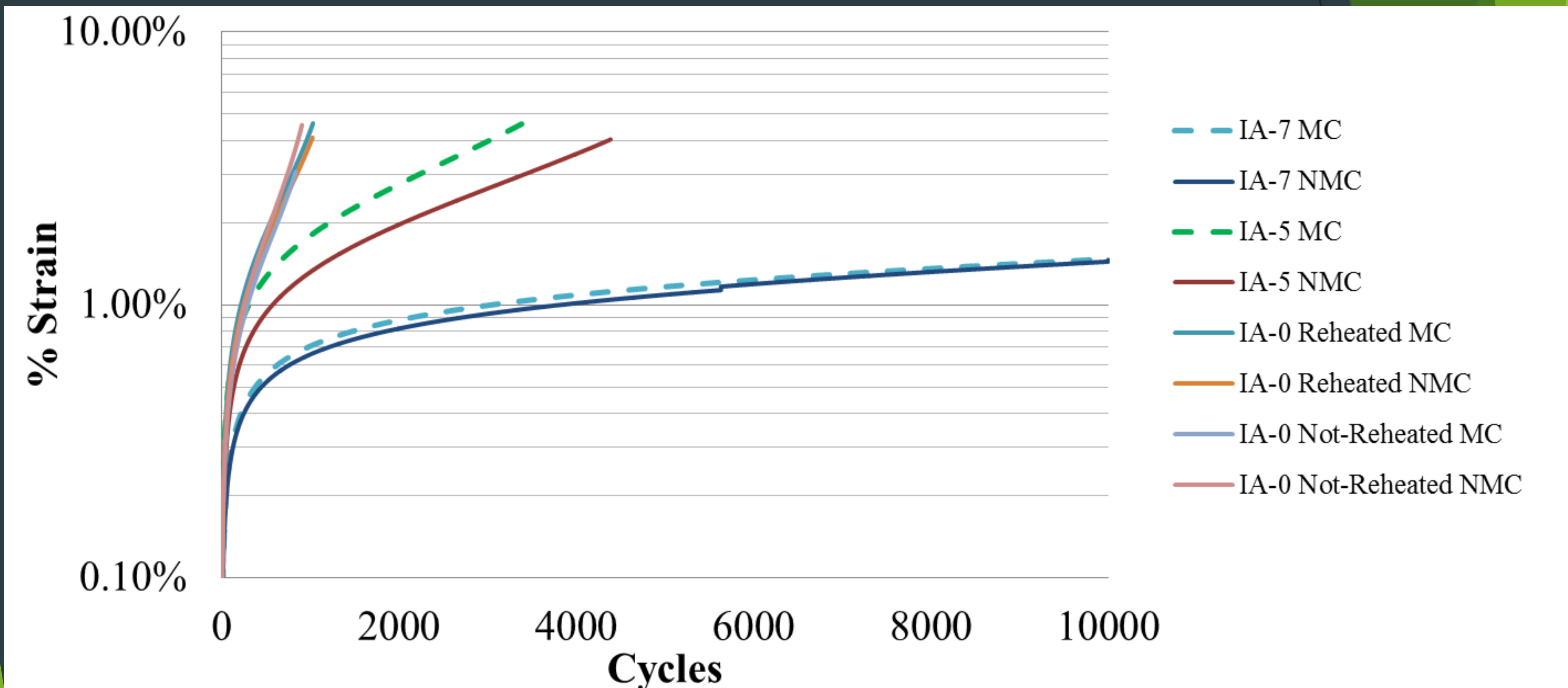
Flow Number Test for evaluating rutting



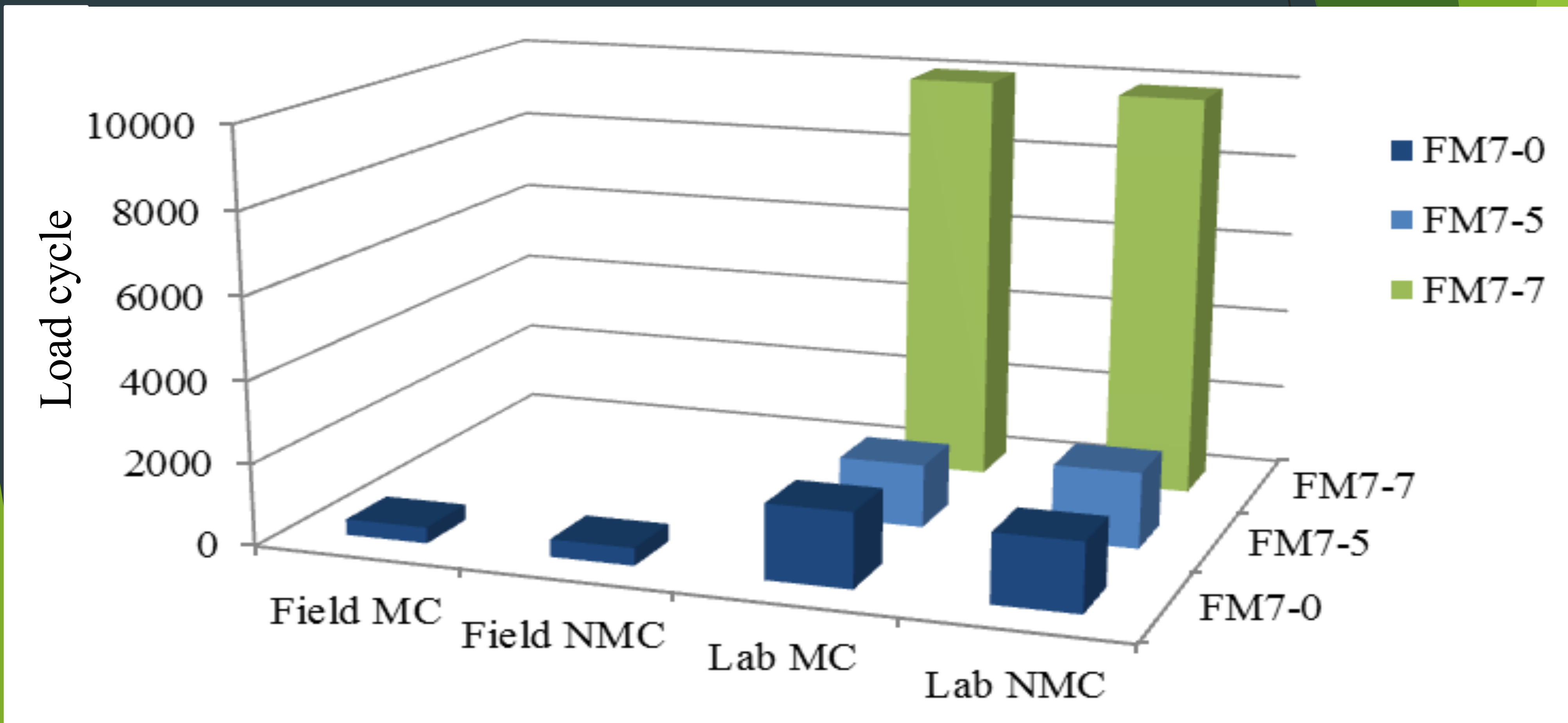
37 °C Test Temperature
1 Hz Loading
0.1 second 600 kPa load
0.9 second rest



Warm Mix Asphalt/RAS: Flow Number Results



Warm Mix Asphalt/RAS: Flow Number Results

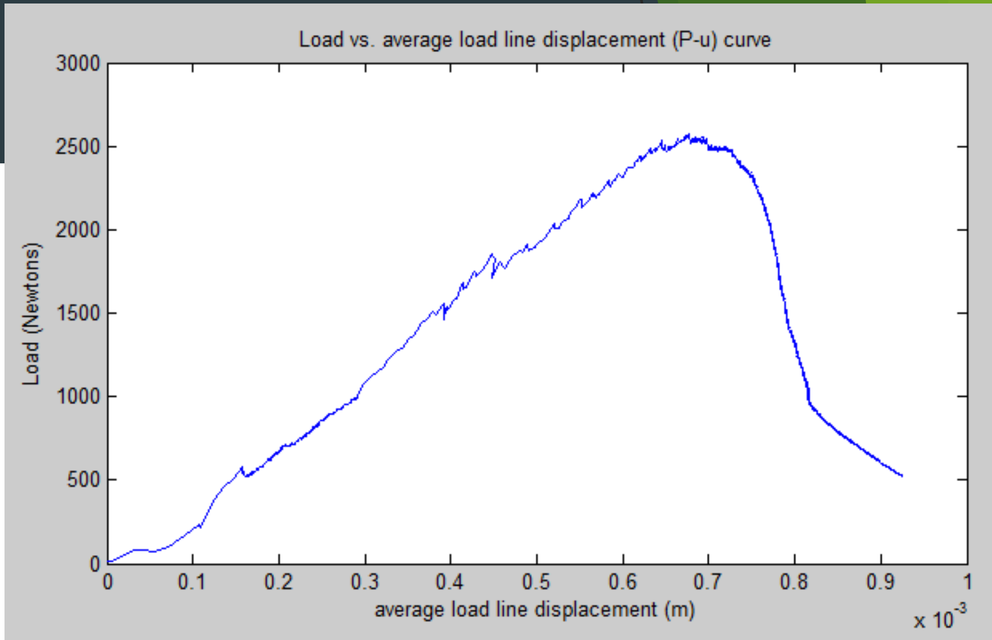


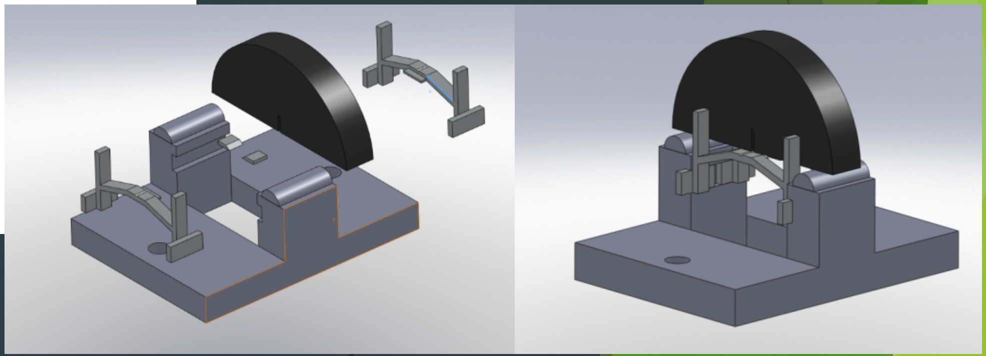
Semi-circular Bend Test Fracture Energy

$$G_f = \frac{W_f}{A_{lig}}$$

where

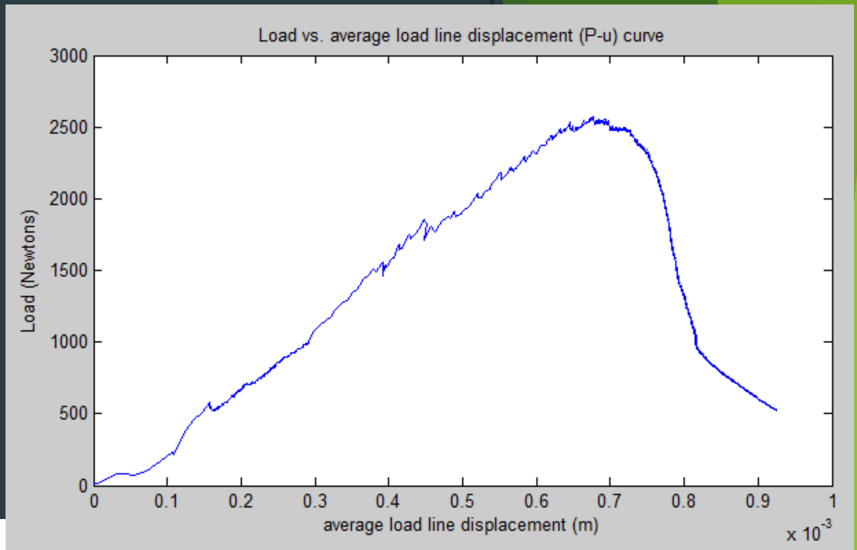
G_f	=	fracture energy (J/m^2);
W_f	=	work of fracture (J), and
W_f	=	$\int P du$
P	=	applied load (N);
u	=	average load line displacement (m);
A_{lig}	=	ligament area (m^2), and
A_{lig}	=	$(r - a) \times t$
r	=	specimen radius (m);
a	=	notch length (m);
t	=	specimen thickness (m).





Semi-circular Bend Test Fracture Energy

- Area under the curve of the stress strain graph and the area extrapolated under the tail of the curve



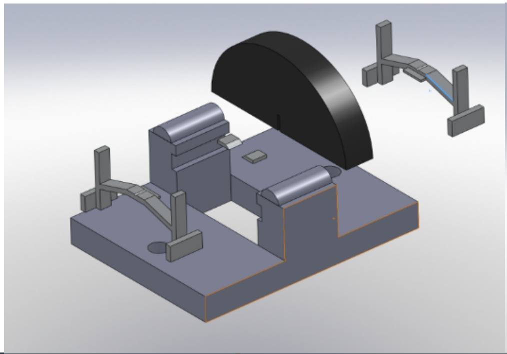
$$W = AREA = \sum_{i=1}^{n}(u_{i+1} - u_i) \cdot (P_i) + \frac{1}{2} \cdot (u_{i+1} - u_i) \cdot (P_{i+1} - P_i)$$

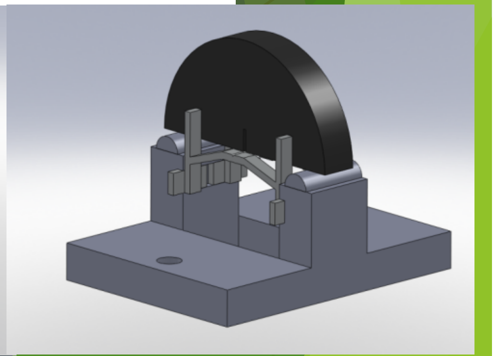
P_i = applied load (N) at the *i* load step application;

P_{i+1} = applied load (N) at the *i* +1 load step application;

u_i = average displacement at the *i* step;

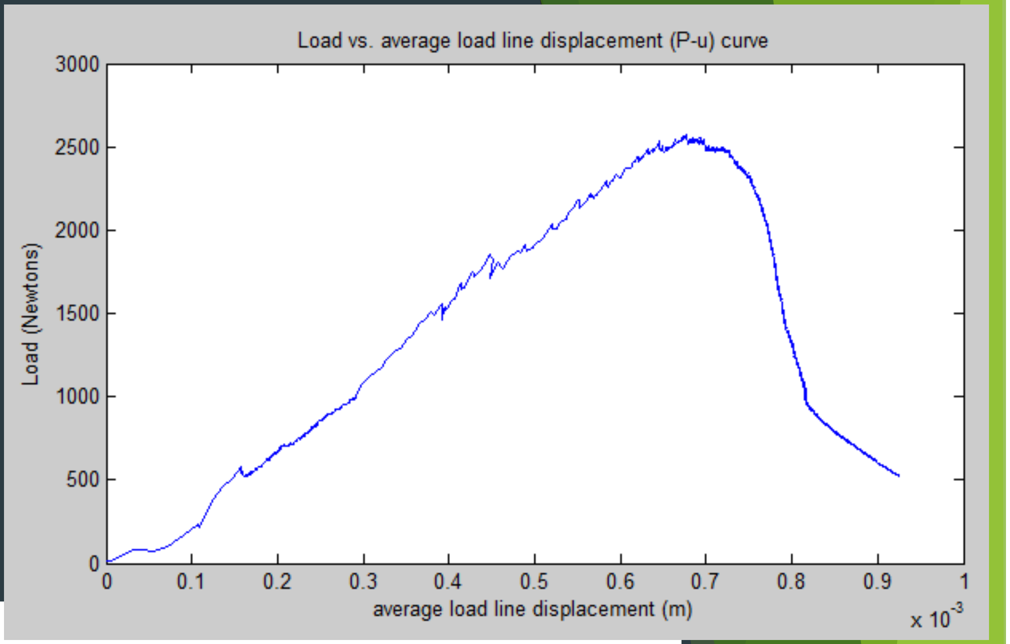
u_{i+1} = average displacement at the *i* +1 step.





Fracture Energy

- Extrapolate the area under the tail
  - Power law with an assumed coefficient equal to -2 for the post peak stress-strain curve with P-values lower than 60% of the peak load



$$P = \frac{c}{u^2}$$

$$W_{tail} = \int_{u_c}^{\infty} P\,d(u) = \int_{u_c}^{\infty} \frac{c}{u^2}\,d(u) = \frac{c}{u_c}$$

$$W_f = W + W_{tail}$$

(Marasteanu and Xue, 2012)

Fracture Toughness

- Fracture toughness (Kic) is obtained as the stress intensity factor at the critical load.
- Derived using linear elastic fracture mechanics.
  - Assumption of linear elastic conditions is reasonable: fracture process zone is small and modulus changes less than 5% for time range of the test

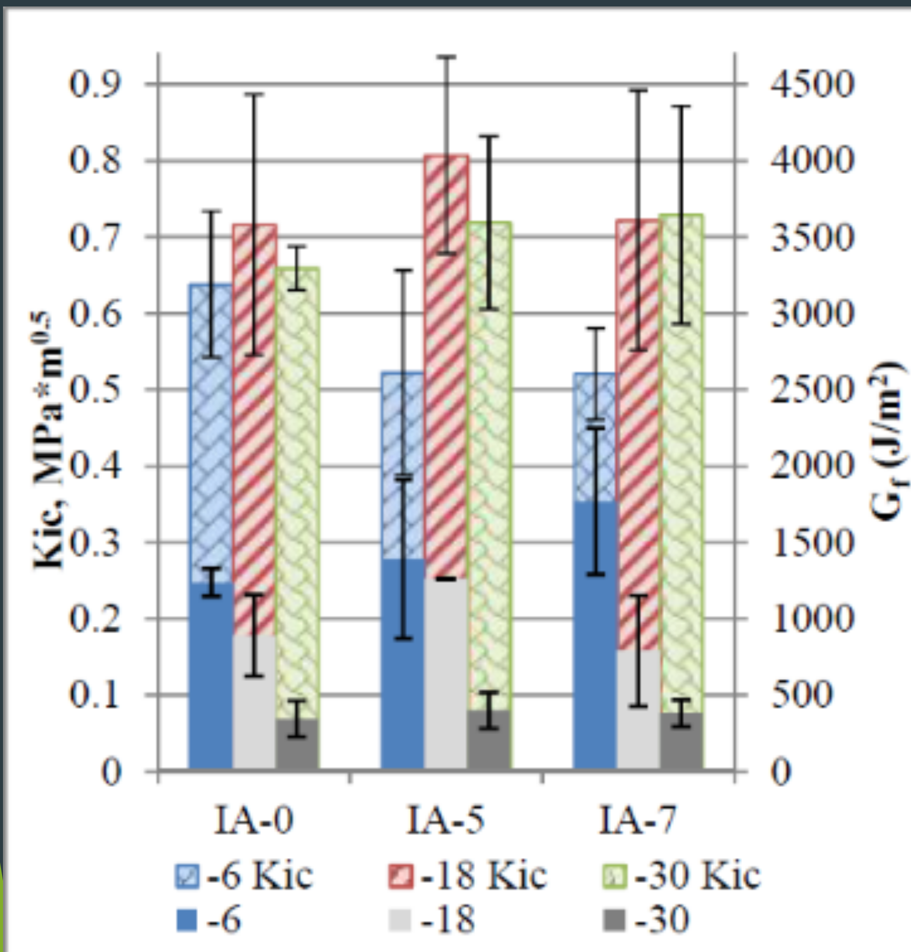
$$\frac{K_I}{\sigma_0\sqrt{\pi a}} = Y_{I(0.8)}$$

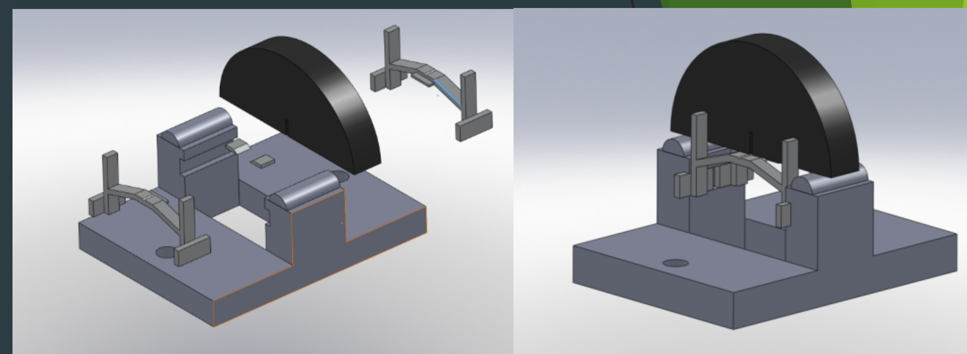
σ_0	=	$\frac{P}{2rt}$
P	=	applied load (MN);
r	=	specimen radius (m);
t	=	specimen thickness (m);
a	=	notch length (m);
Y_I	=	the normalized stress intensity factor (dimensionless).

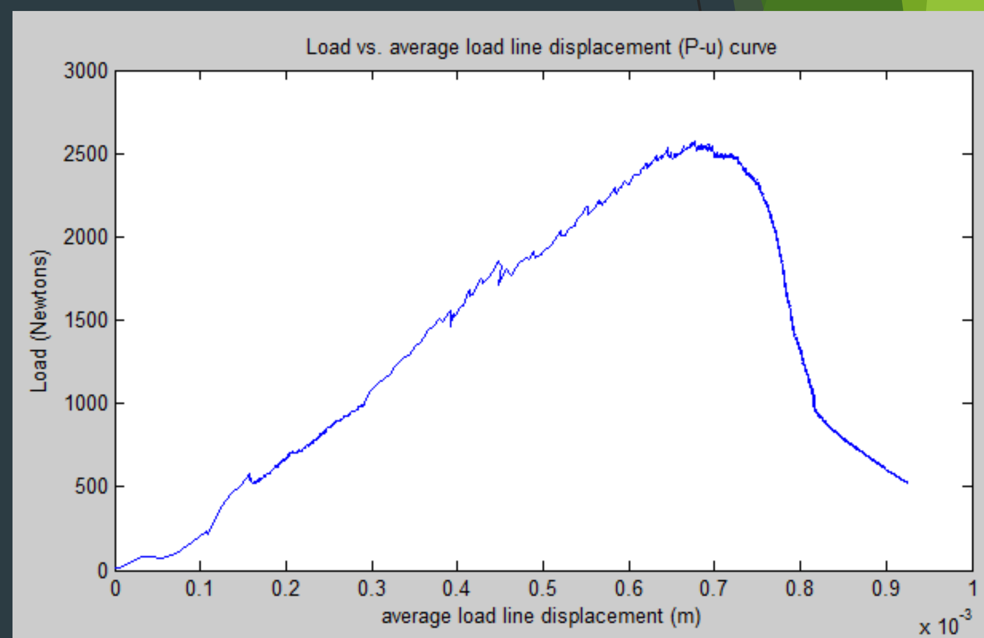
$$Y_{I(0.8)} = 4.782 + 1.219\left(\frac{a}{r}\right) + 0.063exp(7.045\left(\frac{a}{r}\right))$$

(Lim et al., 1994; Li and Marasteanu, 2004; Li and Marasteanu, 2006)

Semi-Circular Bend Test-RAS/WMA Results

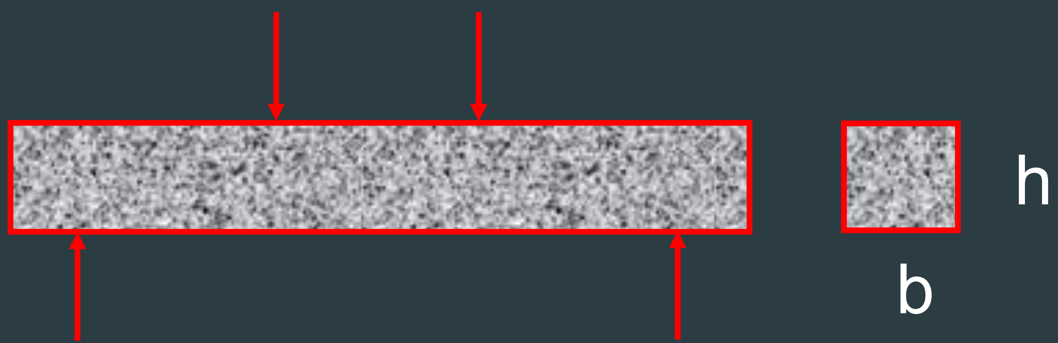






Renderings courtesy of Sheng Tang

Beam Fatigue Test



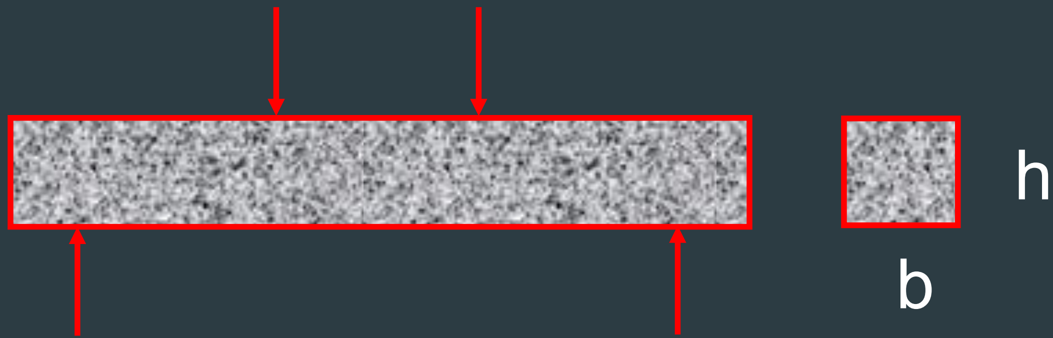
- AASHTO T321, “Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending
  - Tensile Stress, $\sigma = 3aP/bh^2$
  - Tensile Strain, $\varepsilon = 12hd/(3L^2-4a^2)$
  - Flexural Stiffness Mod., $E_s = Pa(3L^2-4a^2)/48Id$

    d is dynamic deflection — a = distance between support and load (in)

    I is moment of inertia — P = total dynamic load (lbs.)

    L is reaction span length

Beam Fatigue Test



- Six Beams for each mix were tested at:
  - 7% Air Voids
  - strain levels of 350, 450, 525, 650, 800, and 1000 micro-strains were applied
  - 18 beams tested

Beam Fatigue Test

- The power law relationship between the applied strain and the fatigue life gives Nf,

$$N_f = K1(1/\varepsilon_o)^{K2}$$

N_f = cycles to failure;

ε_0 = flexural strain;

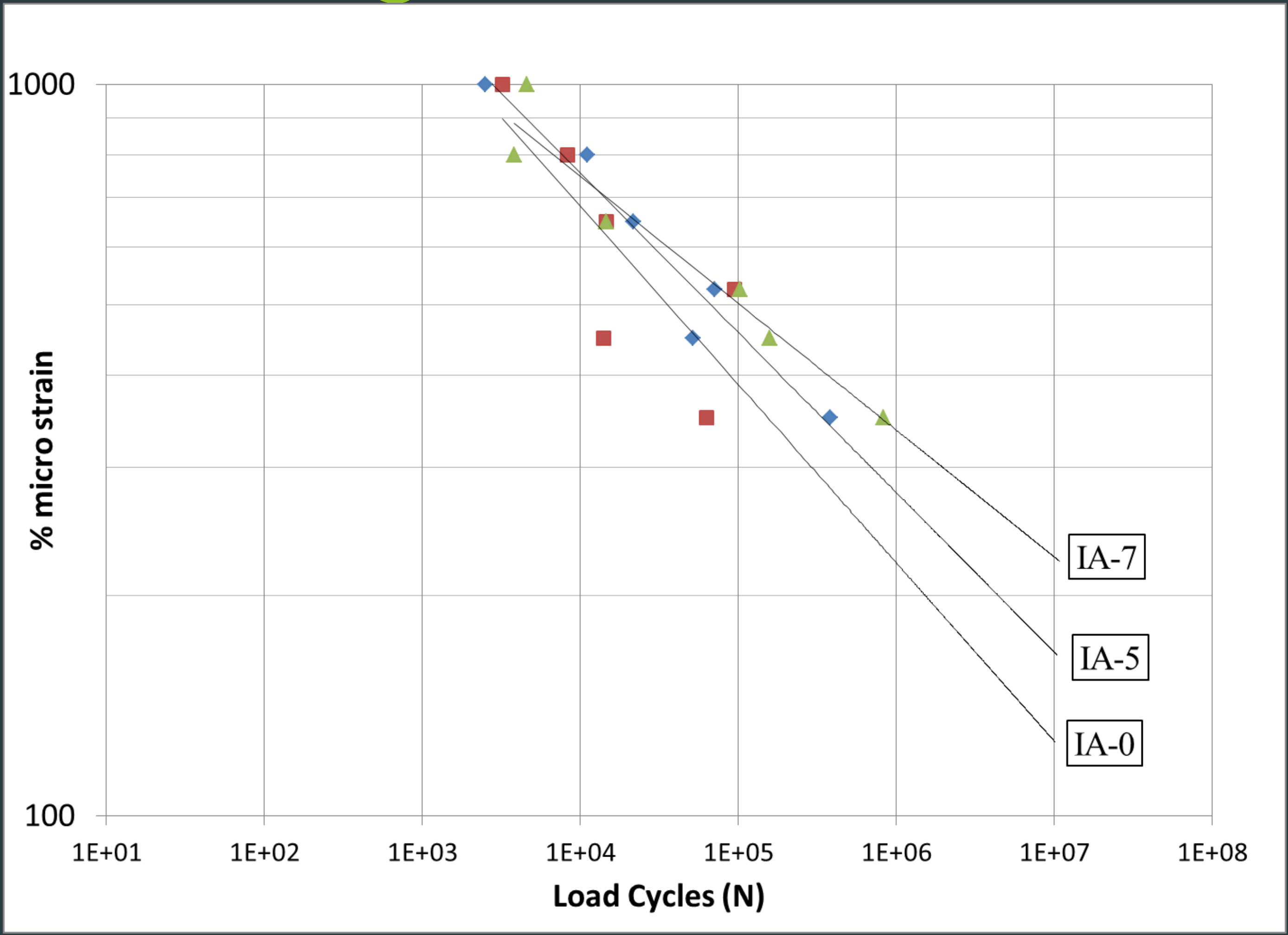
K1 = regression constant; and

K2 = regression constant

- Parameters used to estimate the fatigue endurance limit – strain level at which the material can withstand 50 million load cycles

Mix ID	% RAS	% RAP	K1	K2	R^2	Endurance Limit (Micro-strain)
IA-0	0	20	2.67E-05	2.72	0.982	16
IA-5	5	13	2.80E-10	4.35	0.975	75
IA-7	7	6	1.13E-13	5.43	0.971	114

Beam Fatigue Test



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Beam Fatigue Test

- The power law relationship between the applied strain and the fatigue life gives Nf,

$$N_f = K1(1/\varepsilon_o)^{K2}$$

N_f = cycles to failure;

ε_0 = flexural strain;

K1 = regression constant; and

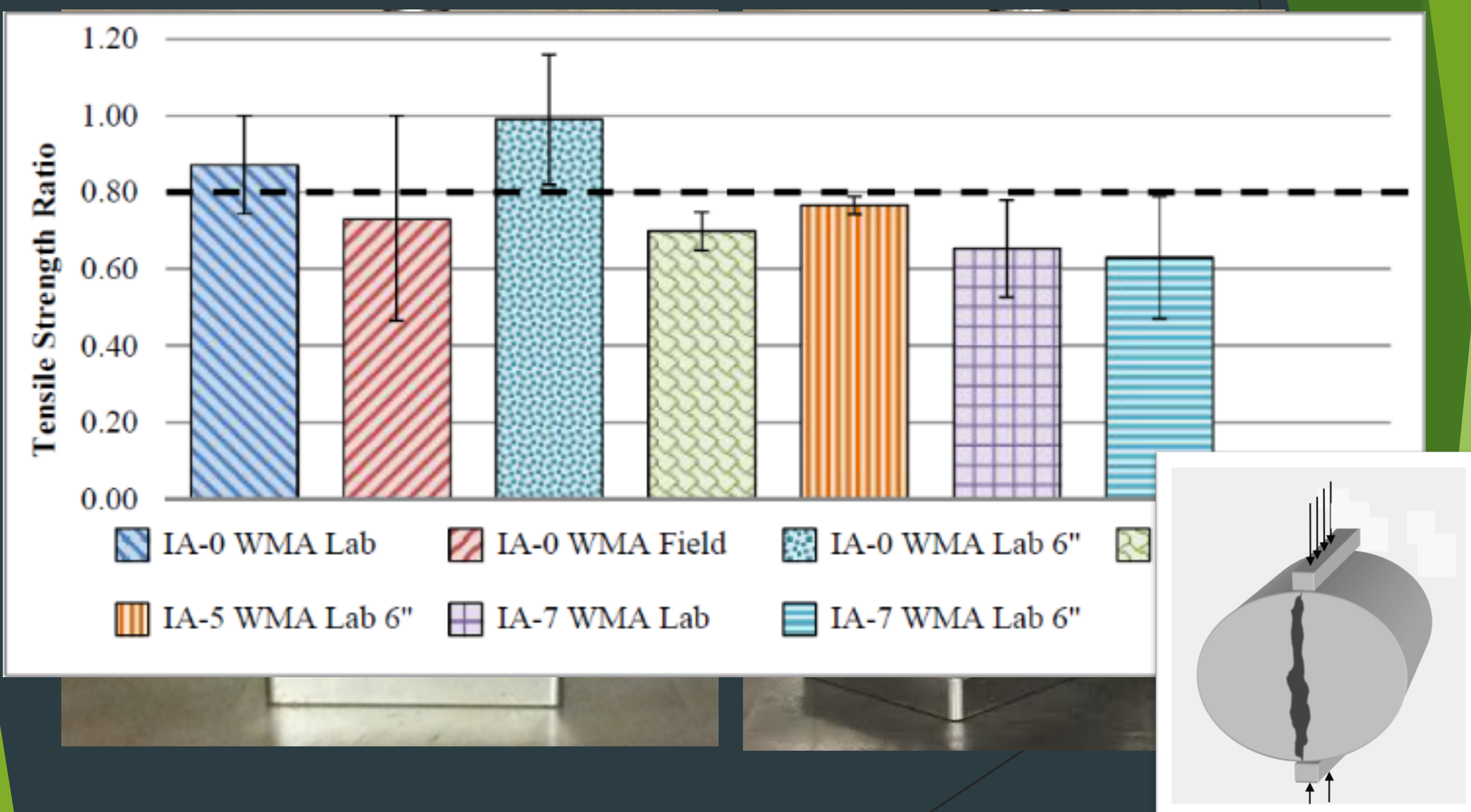
K2 = regression constant

- the intercept (K1) and the slope (K2);
- Parameters used to estimate the fatigue endurance limit

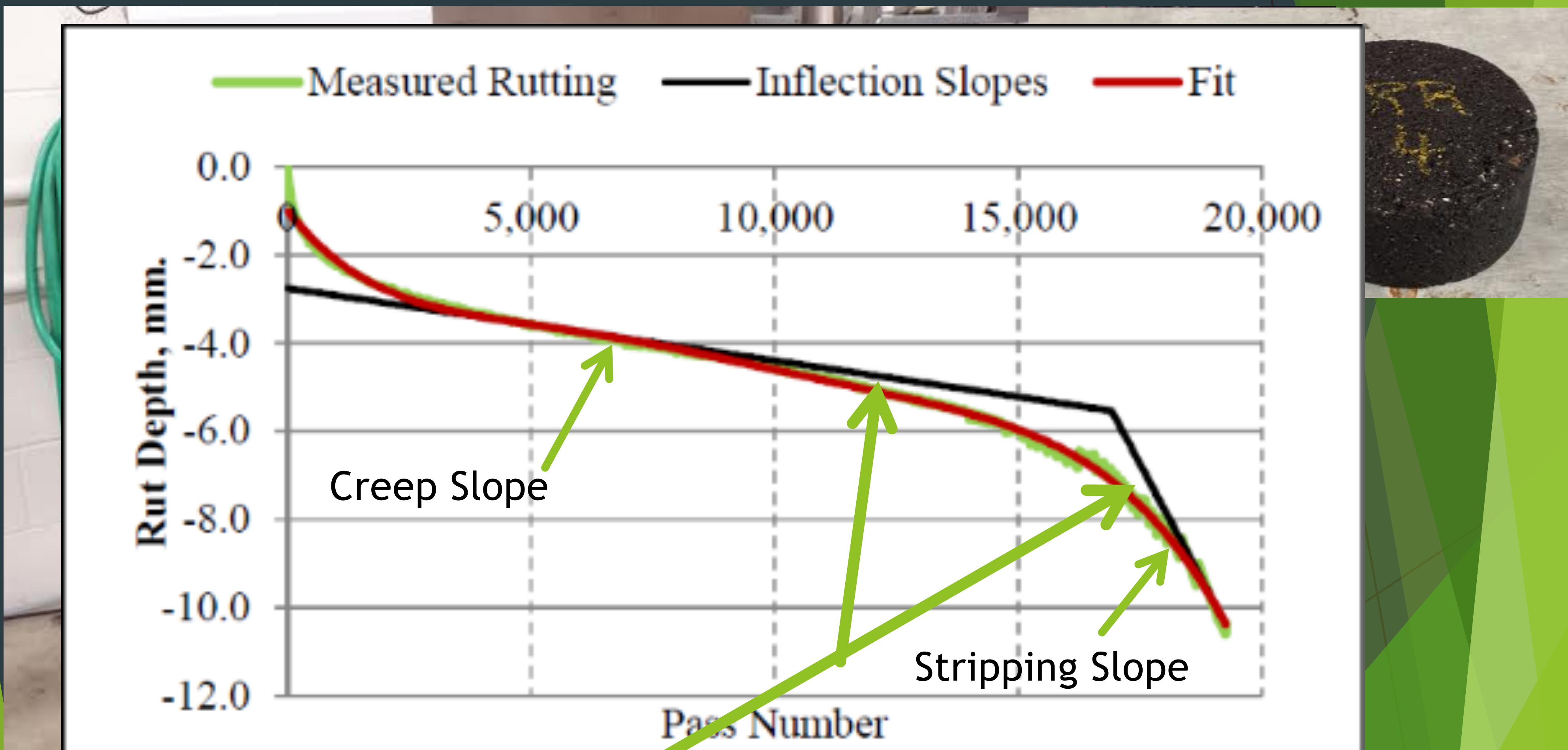
$$Lower\ Prediction\ Limit = \hat{y}_o - t_\alpha s\sqrt{1 + 1/n + (x_0 - \bar{x})^2/S_{xx}}$$

- $\hat{y}_o$ = the one-sided lower 95% prediction interval at the micro-strain level corresponding to 50,000,000 cycles;
- t_α = value of t distribution for *n*-2 degrees of freedom for a significance level of 0.05;
- s = standard error of the regression analysis; *n* = number of samples;
- S_{xx} = sum of squares of the x values;
- x_o = log 50,000,000; and
- $\bar{x}$ = average of the fatigue life results

Warm Mix Asphalt and RAS results for AASHTO T-283

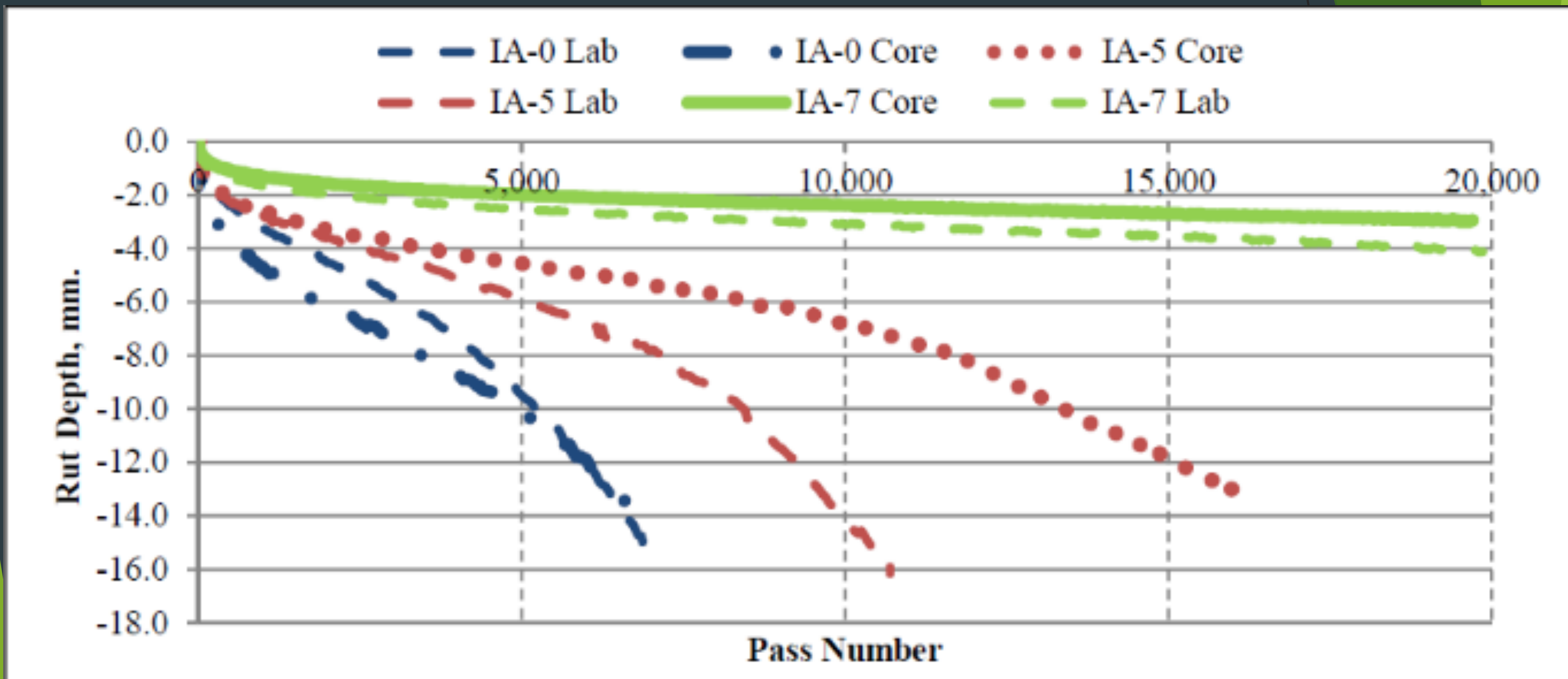


Hamburg Wheel Track Test

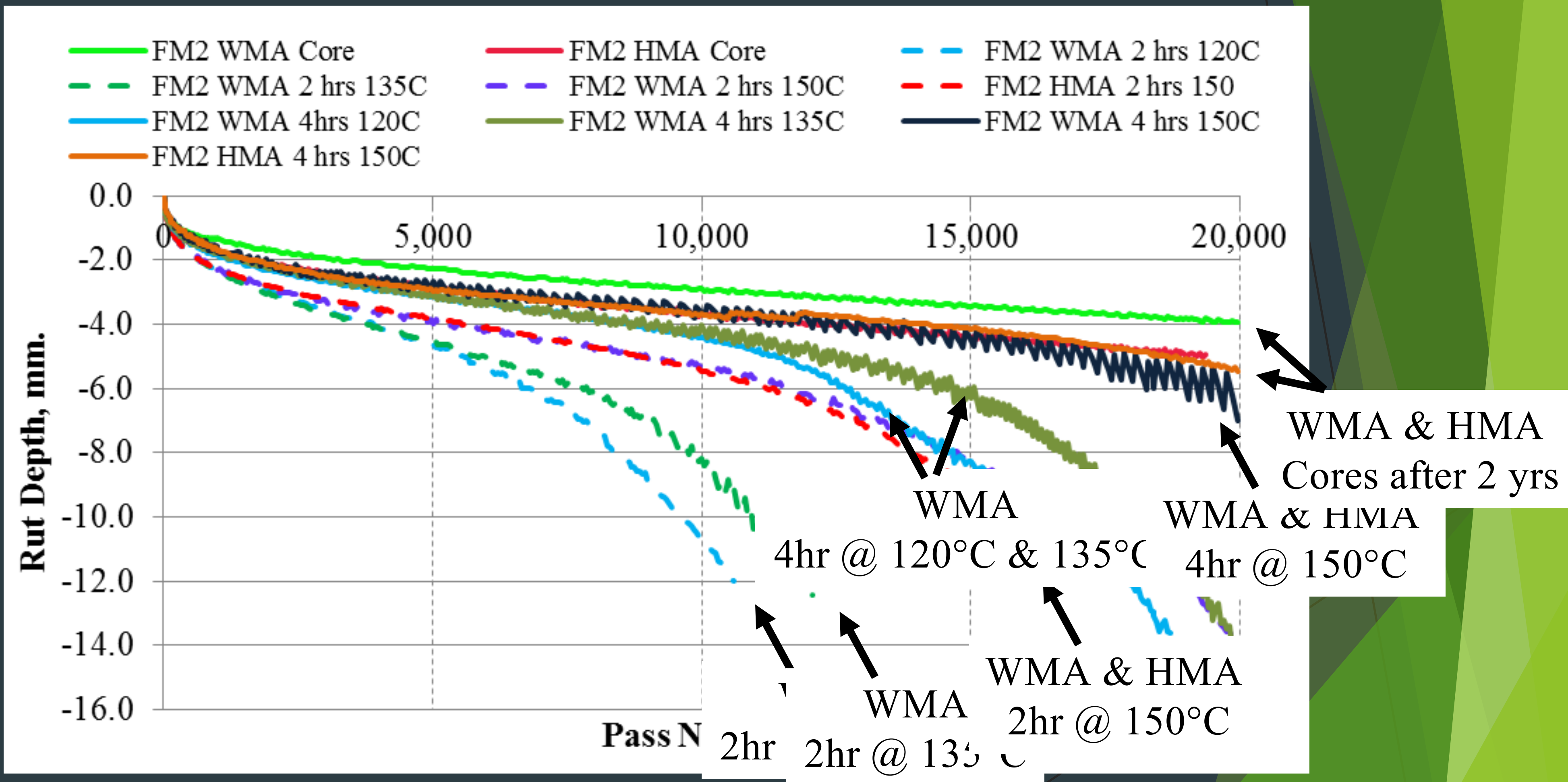


Ratio > 2 indicates stripping

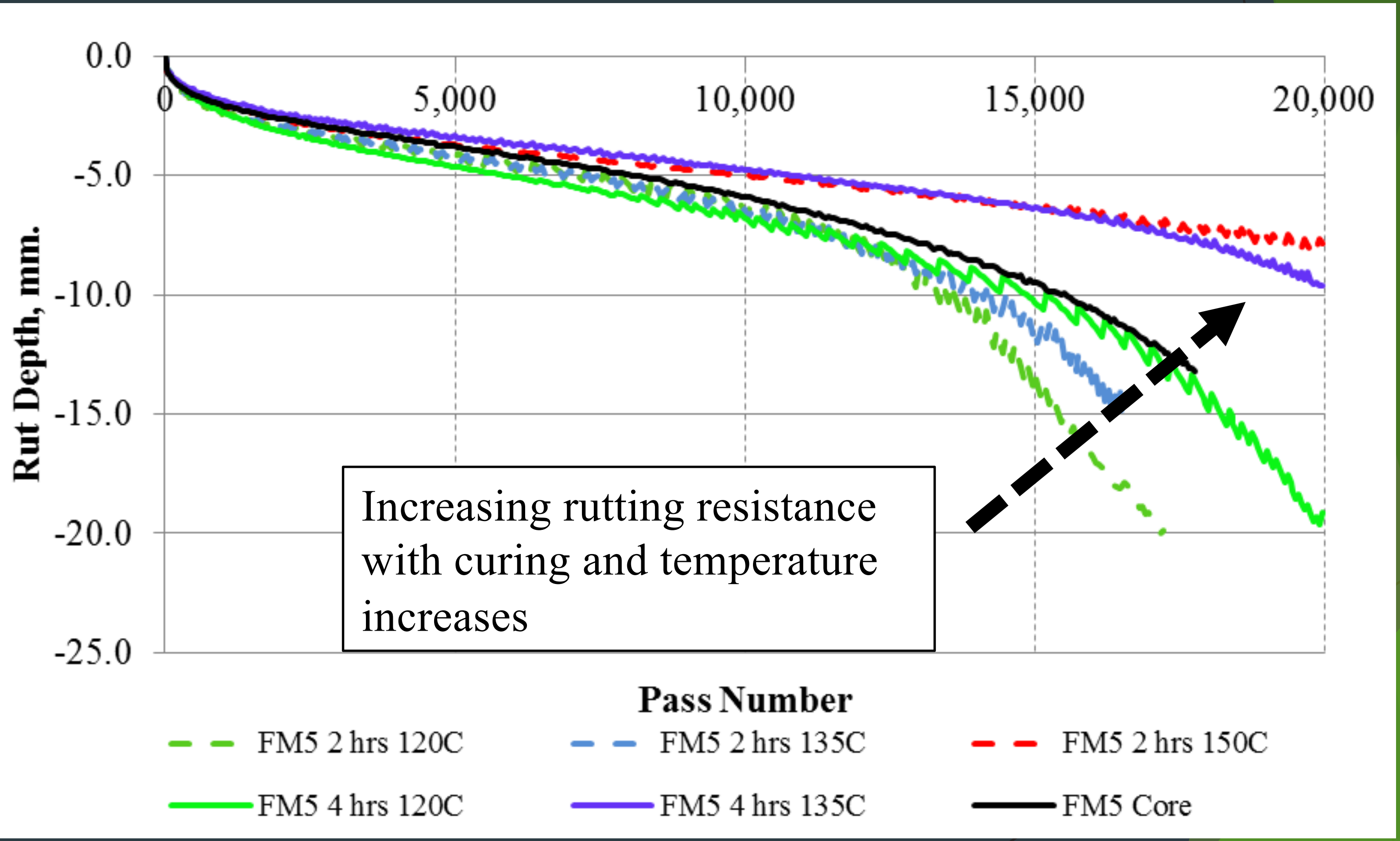
WMA/RAS Hamburg Results



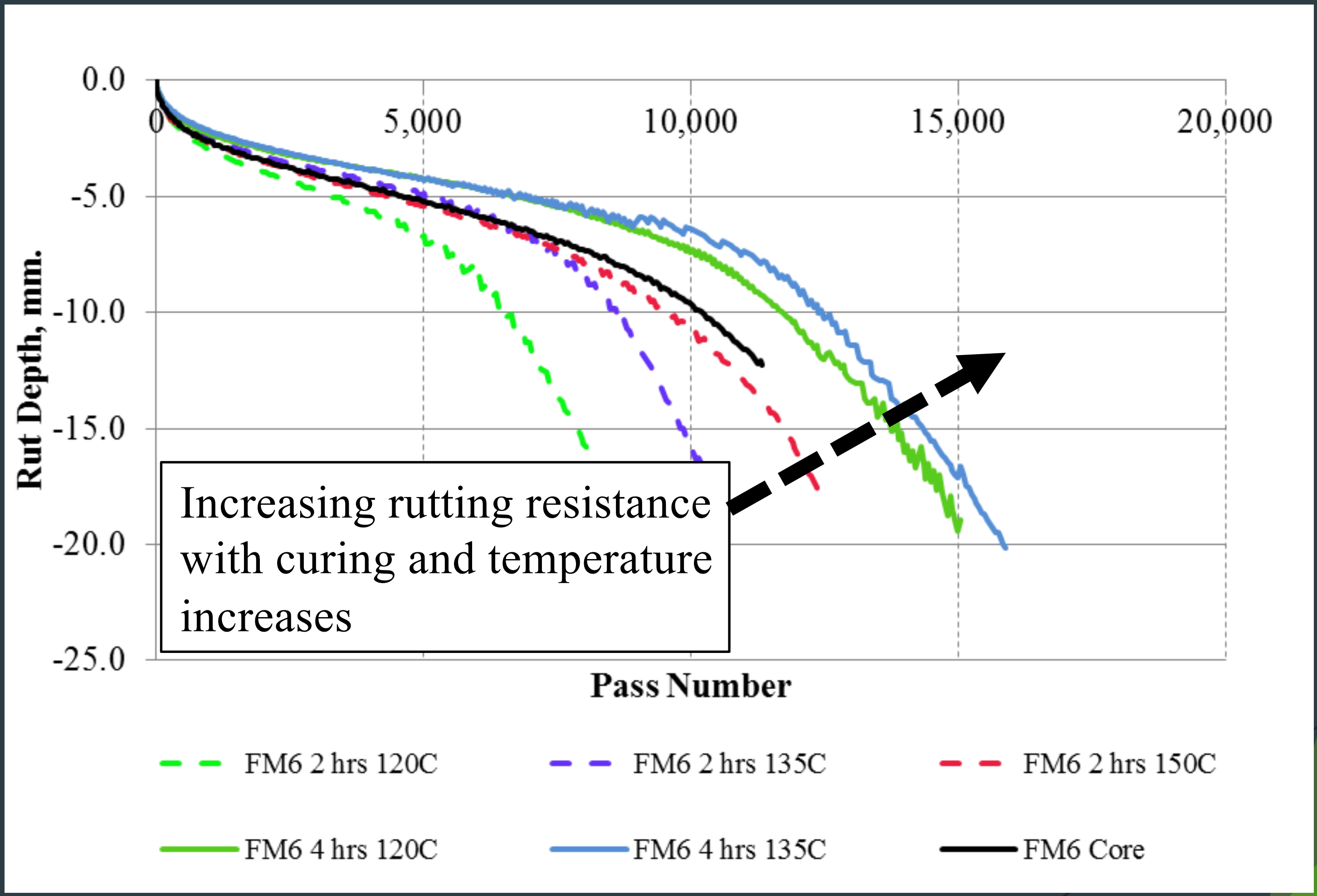
WMA Curing Study using the Hamburg



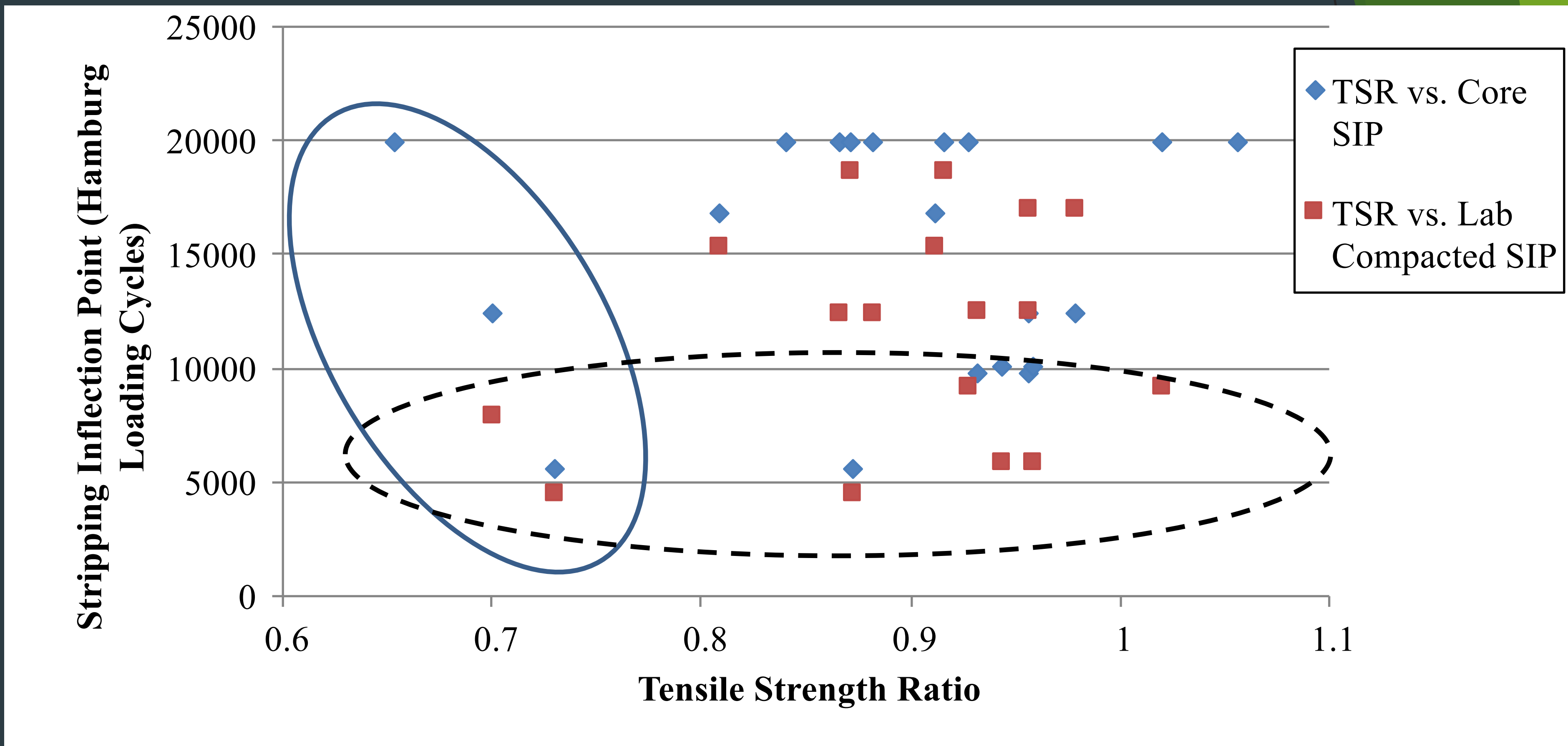
WMA curing impact on Hamburg rutting results



WMA curing impact on Hamburg rutting results



Lack of Correlation: SIP and TSR



Warm Mix Asphalt Conclusions

- WMA additives can be successfully used with recycled asphalt shingles at reduced temperatures
- Shingles improved fatigue performance
- Curing time and temperature greatly influence Hamburg test results- important for QC/QA
- WMA more susceptible to moisture damage for a short time after construction

Warm Mix Asphalt Conclusions

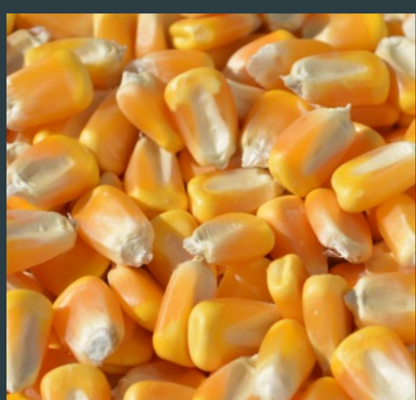
- Shingles improve the WMA mixture's Hamburg, flow number and dynamic modulus results.
- Shingles increase the binder stiffness (Grade) but performance tests indicate improved mixture performance. Likely due to higher binder content and fibers in the shingles.
- Field Surveys show excellent performance two years after construction

WMA Research Needs

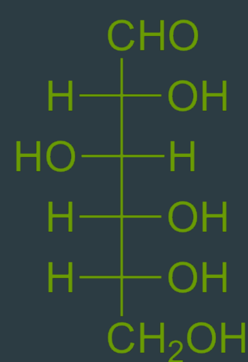
- Sensitivity of WMA and recycled asphalt materials using the Pavement Mechanistic-Empirical Design Guide
- Further study of emission reductions from using WMA additives
- Further developments of bio-based WMA additives

Ongoing WMA Research

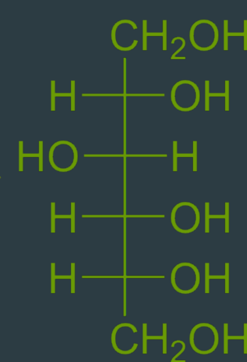
- Bio-renewable WMA additive in development
- WMA developed as co-products from bio-refineries
- Distillation bottoms have surfactant properties useful for WMA



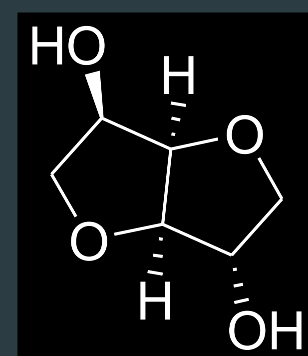
Corn



Glucose



Sorbitol



Isosorbide


Thank you!
Questions?