Implementation of the Bitumen Performance Grading System in Estonia

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Outline

- How US has reached to currently valid Superpave standards.
- On-going research in bitumen and asphalt mixtures.
  - What should be the bitumen properties in pavements.
  - What should be the composition of asphalt mixtures to ensure a 20-30 year long lifespan of pavements.
- Comments on study of bitumen sources used in Estonia
- Concluding Remarks

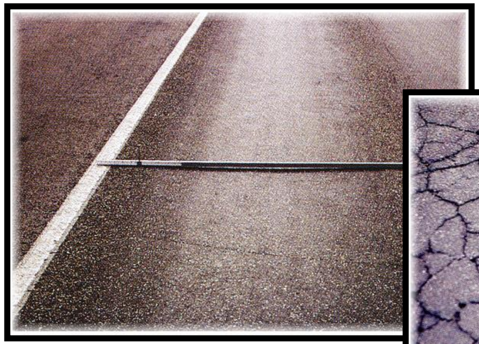
Bitumen Standards – USA Overview

- 1930's – Pen grading
- 1960's – Viscosity grading
- 1993 - Superpave testing system proposed
- 1996- PG grading implemented
- 2000- PG (Plus) – more complex
- 2002- Damage Resistance Testing – NCHRP 9-10:
  - 2008 (MSCR)
  - 2011 (BBS)
  - 2013 (LAS)
  - 2014 (SENB, BYET, DSR-ER)

Common Targets for Bitumen Specifications - Performance Based Grading

- Constructability

- Performance



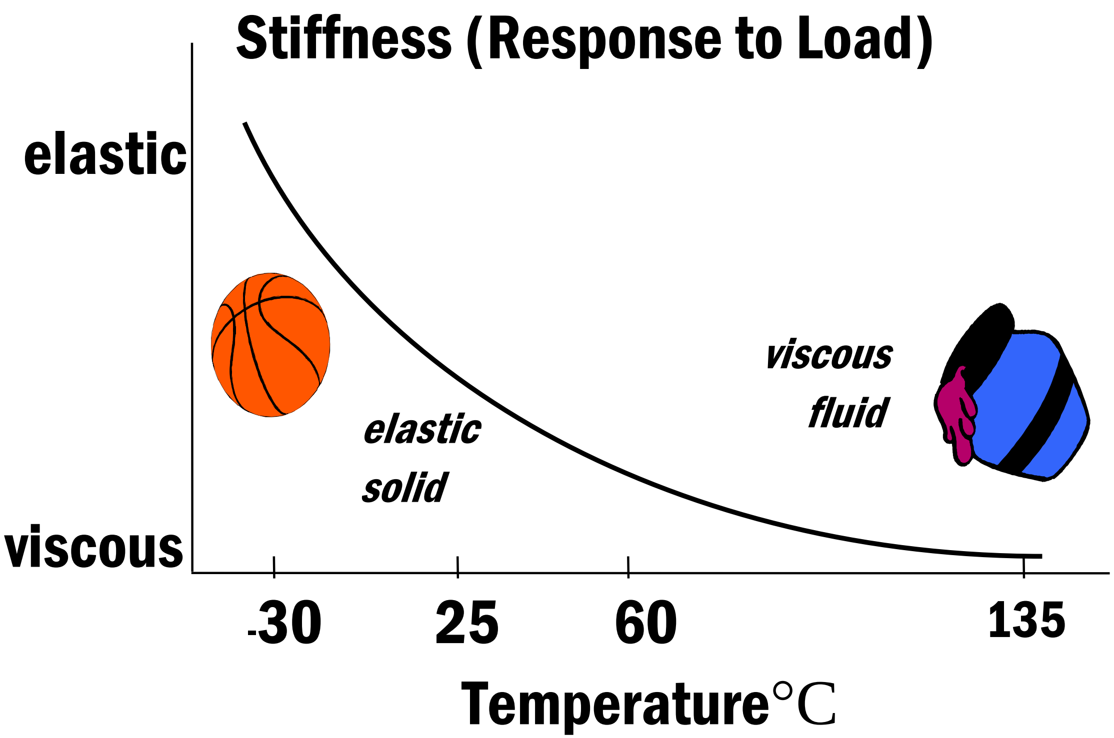
Rutting

Fatigue Cracking

Thermal Cracking

- Durability

Properties of Asphalt Binders

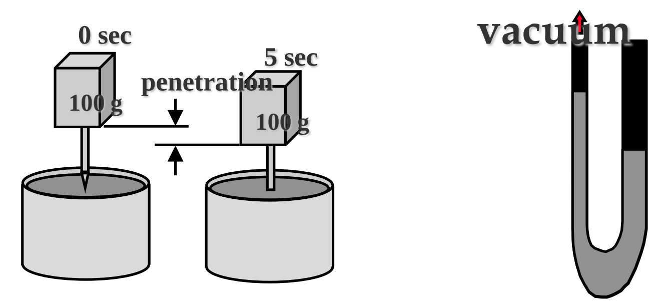


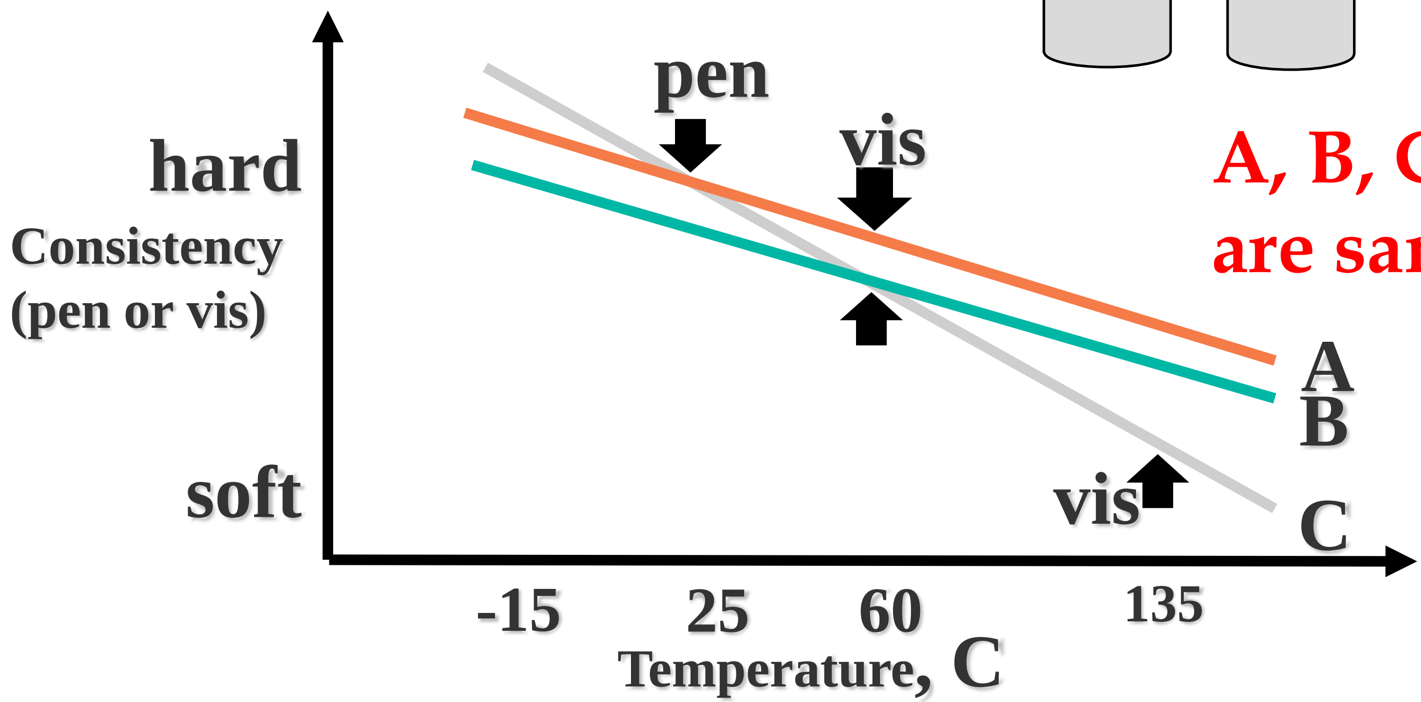
Cold climates ==> use soft-grade asphalts

Warm climates ==> use hard-grade asphalts

- Asphalt binder is a **temperature-susceptible viscoelastic material**
- **Change in stiffness** with temperature dictates in-service response to loading .
- **High strain/stress behavior** dictates performance.

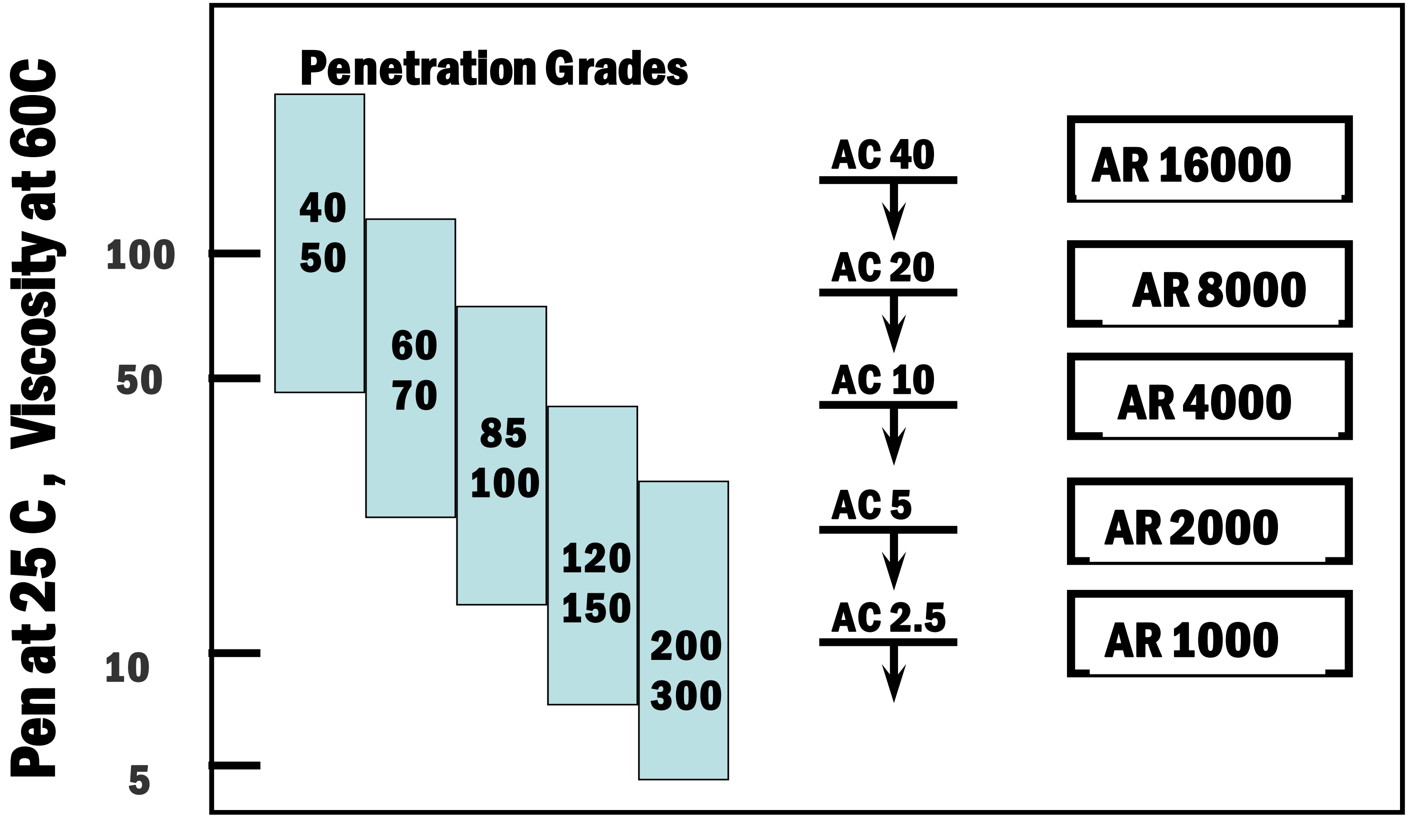
Historical Specifications – Pen & Vis





A, B, C are same grade!

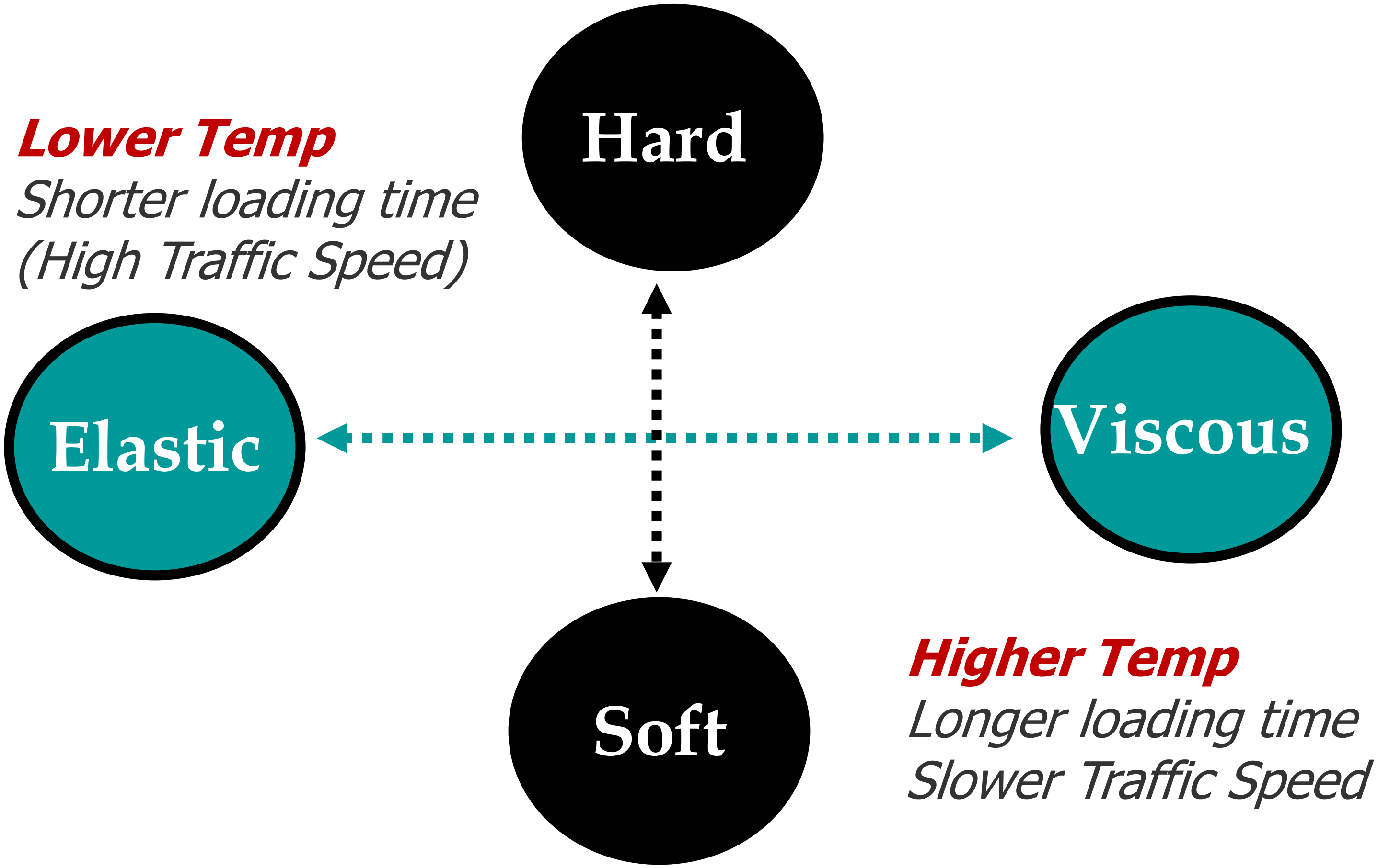
Conventional Asphalt Grades- 1930s – 1990s



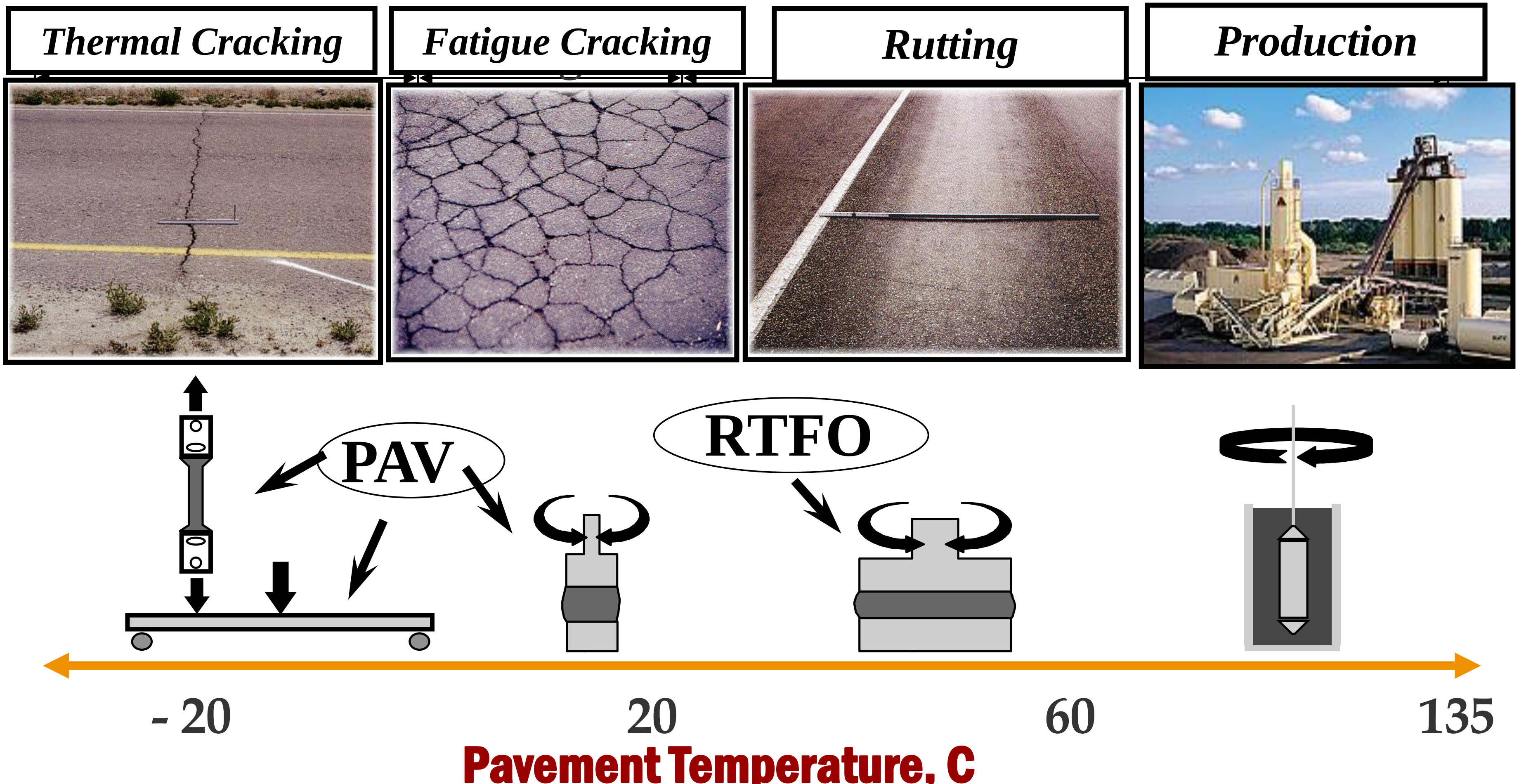
Performance Grading Should:

- Include measures describing stress-strain relationships under field climate and loading.
- Consider pavement conditions:
  - Temperature (pavement)
  - Traffic speed and volume,
  - Pavement structure, and aging.
- Include acceptance limits derived from factual field performance/experience.

Asphalt Behavior – Visco-elastic



Fundamental Rheology Tests – PG System



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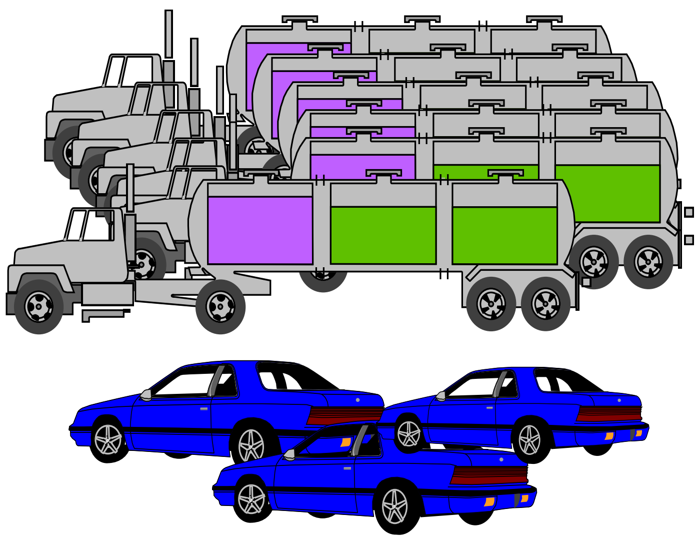
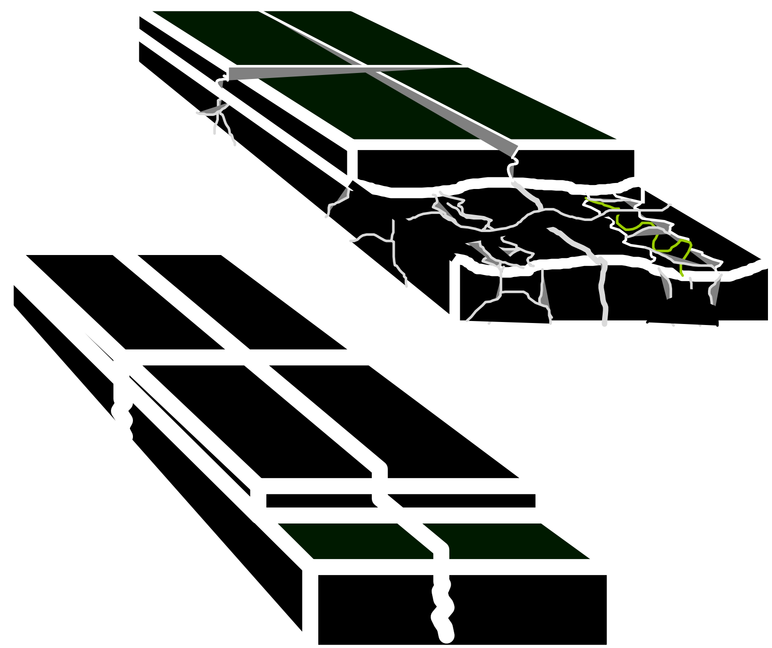
Important Considerations:
Traffic and Pavement Structure

Effect of traffic Volume & Speed



ESALS and Speed limits !

Pavement Damage



Weak vs. Strong base!

Current Performance Grading System- PG

1. *Climate*
2. *Traffic conditions- Indirectly*
3. *Reliability*

PG 64-22

Performance Grade

Summer
Average 7-day max pavement design temp

Winter
Min pavement design temp

PG Grades and Binder Modification

High Temperature, °C

Low Temperature, °C	52	58	64	70	76
-16	52-16	58-16	64-16	70-16	76-16
-22	52-22	58-22	64-22	70-22	76-22
-28	52-28	58-28	64-28	70-28	76-28
-34	52-34	58-34	64-34	70-34	76-34
-40	52-40	58-40	64-40	70-40	76-40

= Crude Oil

= High Quality Crude Oil

= Modifier Required

Reasons for Modified Binders

1. Extreme Climates (i.e. AZ or WI)
2. Slow/Standing Traffic
3. Poor subgrade Support

http://www.pavementinteractive.org/article/superpave-performance-grading/

The New Grading System- MP19 – PG xx(z)-yy

1. *Climate: xx-yy*
2. *Traffic conditions- Trucks (S,H,V,E)*
3. *Reliability , and*
4. *Modification*

Traffic
Volume & Speed

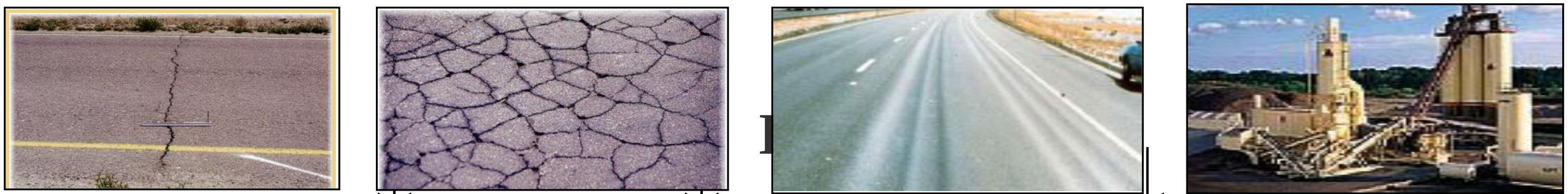
PG 64(V)-10

Performance Grade

Summer
Average 7-day max pavement design temp

Winter
Min pavement design temp

New / advanced testing needed for modified asphalts

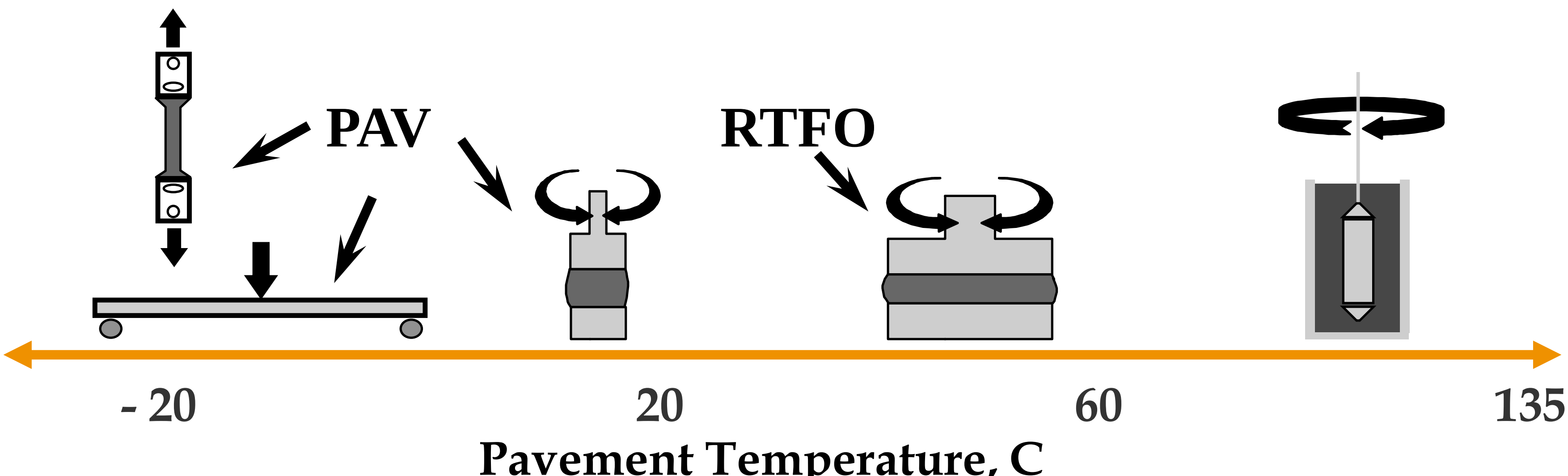


4. Fracture **(SENB)** glass transition

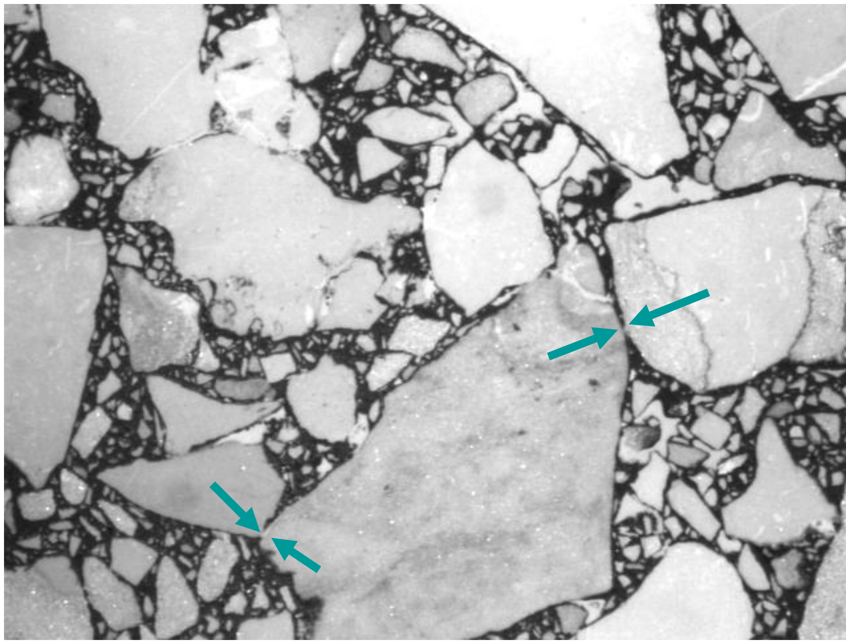
3. Binder fatigue- **LAS**
5. **DSR - Ductility**

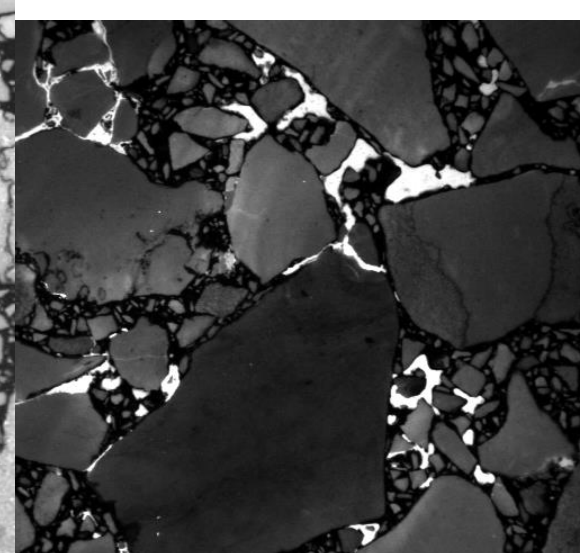
2. Binder repeated creep - **MSCR**

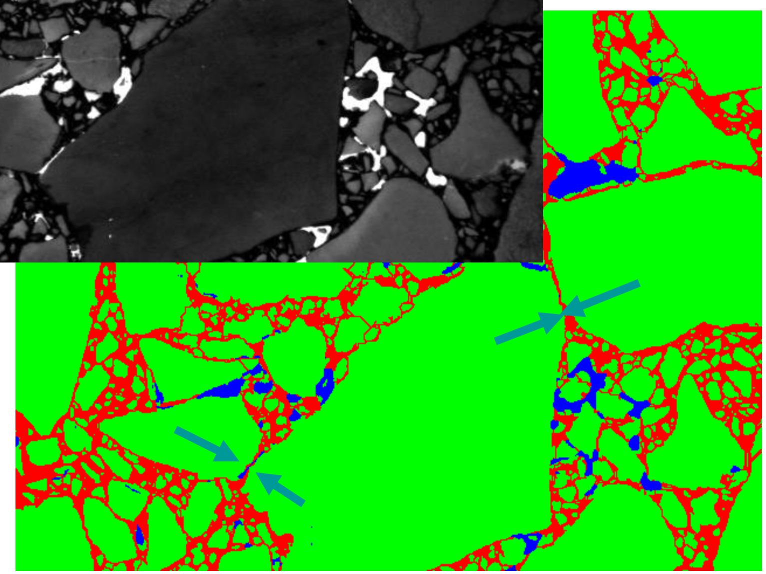
1. Viscosity at variable shear rate



HMA Basics:
Rocks + Asphalt + Air Voids





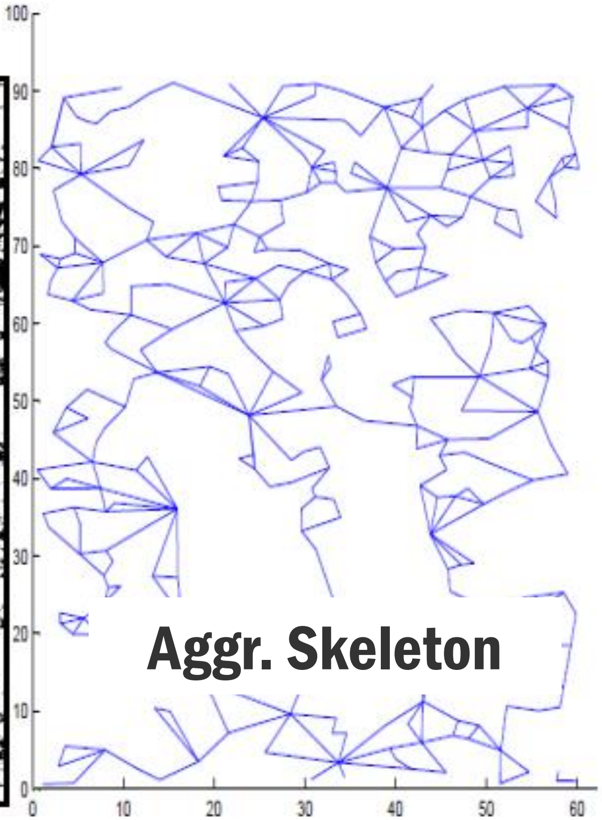


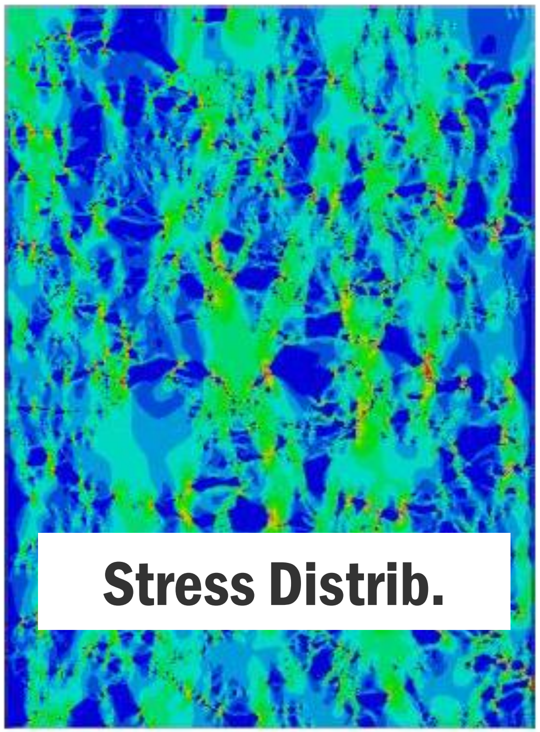
Stability of HMA:

1.Rock- to – rock contacts

2.Binder rheology

Aggregate Structure in Mix is very Important

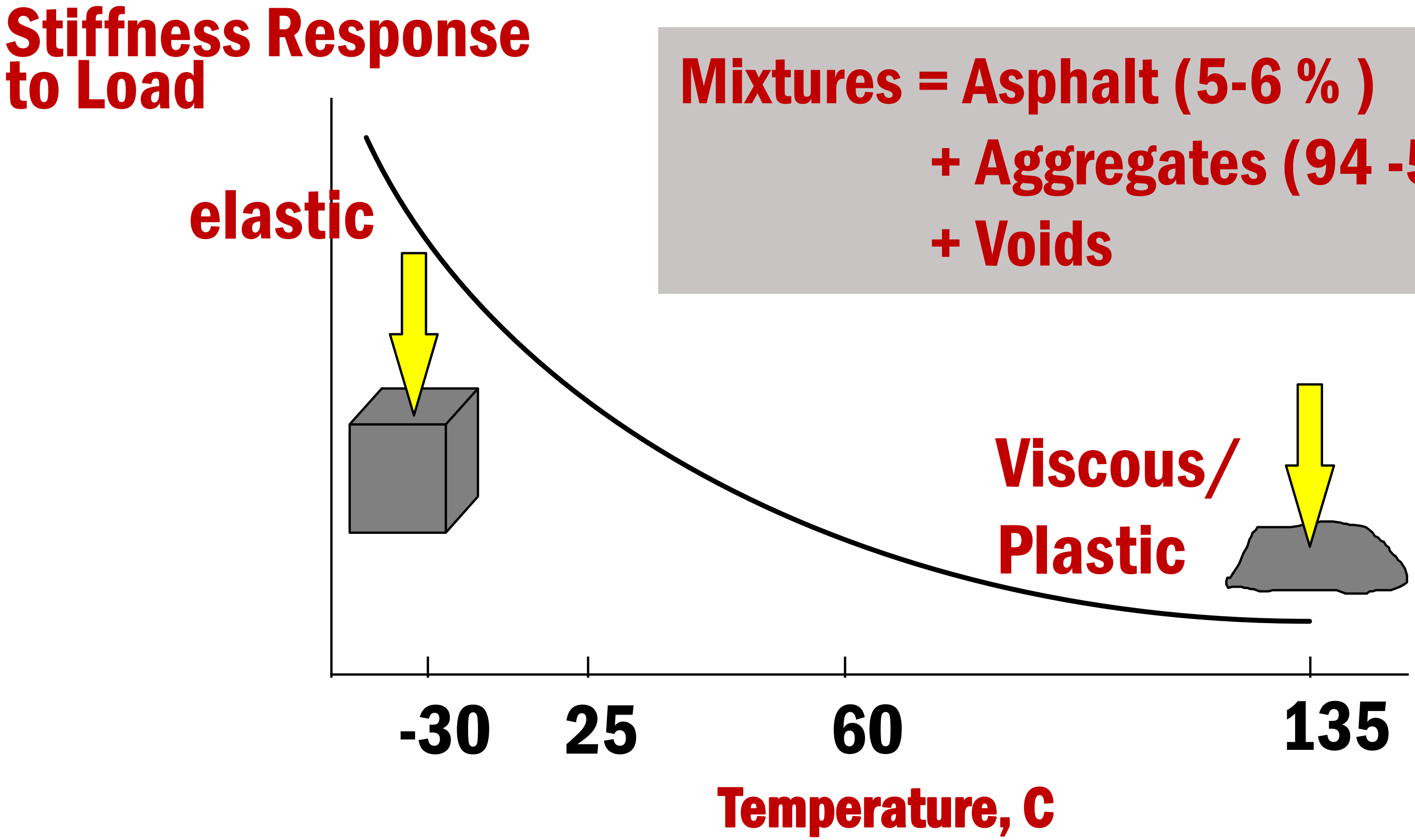




How can we measure it? Can we specify it? What factors control it?

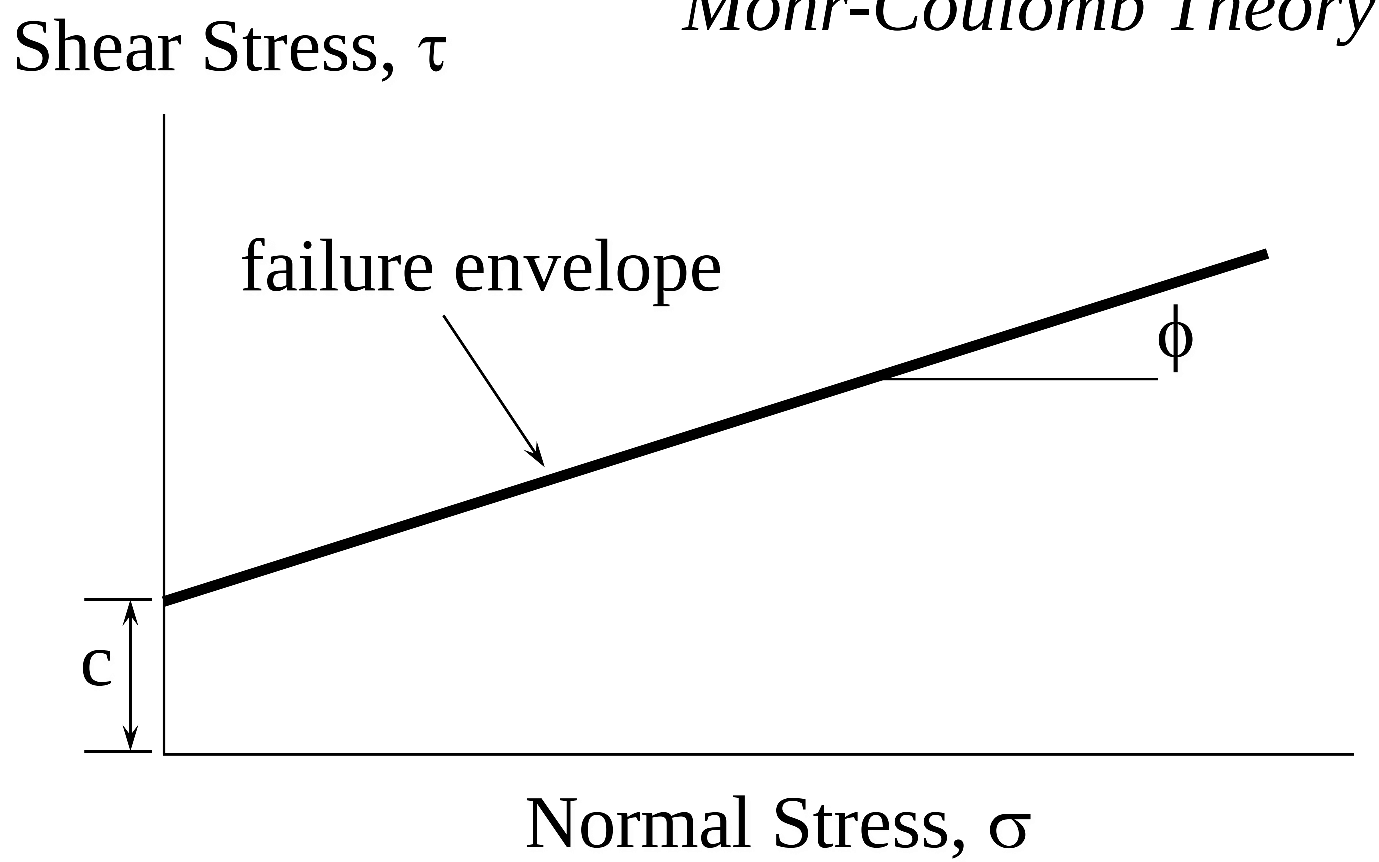
Mixture Response to Load and Climate

Mixtures = Asphalt (5-6 %)
+ Aggregates (94 -5%)
+ Voids

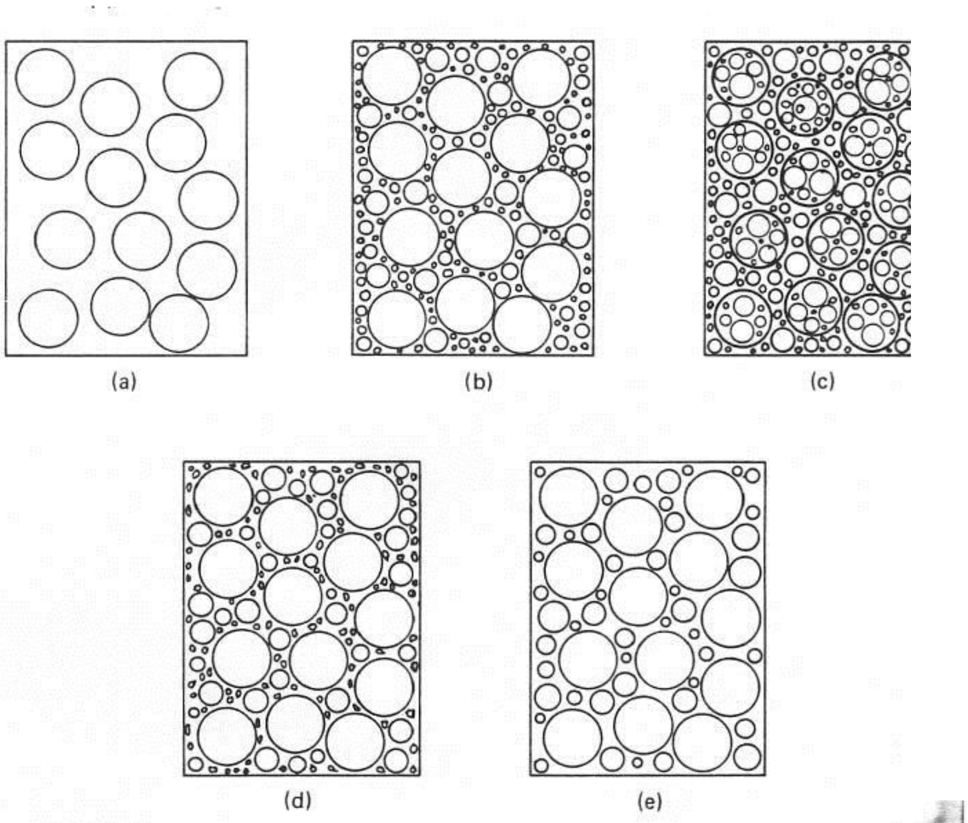


Shearing Behavior of Aggregate

Mohr-Coulomb Theory



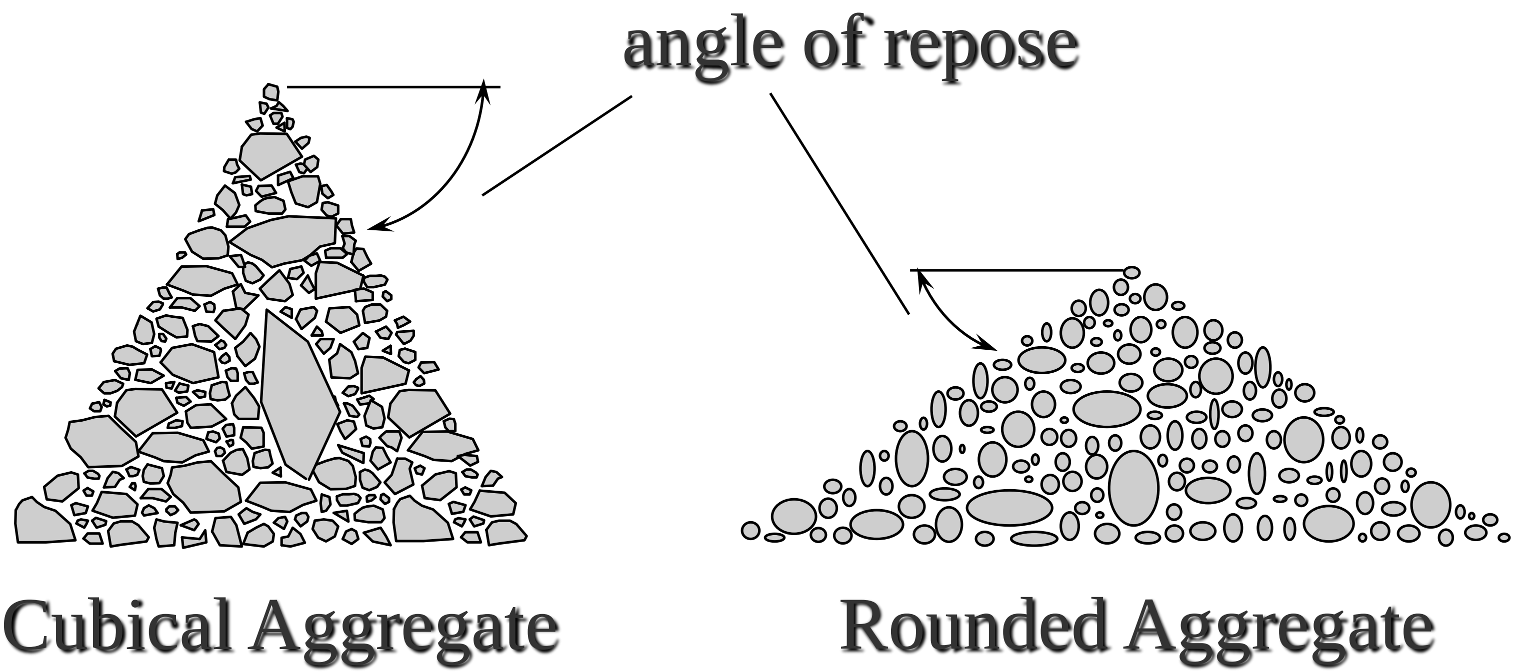
Aggregate gradation and voids between aggregates – Packing



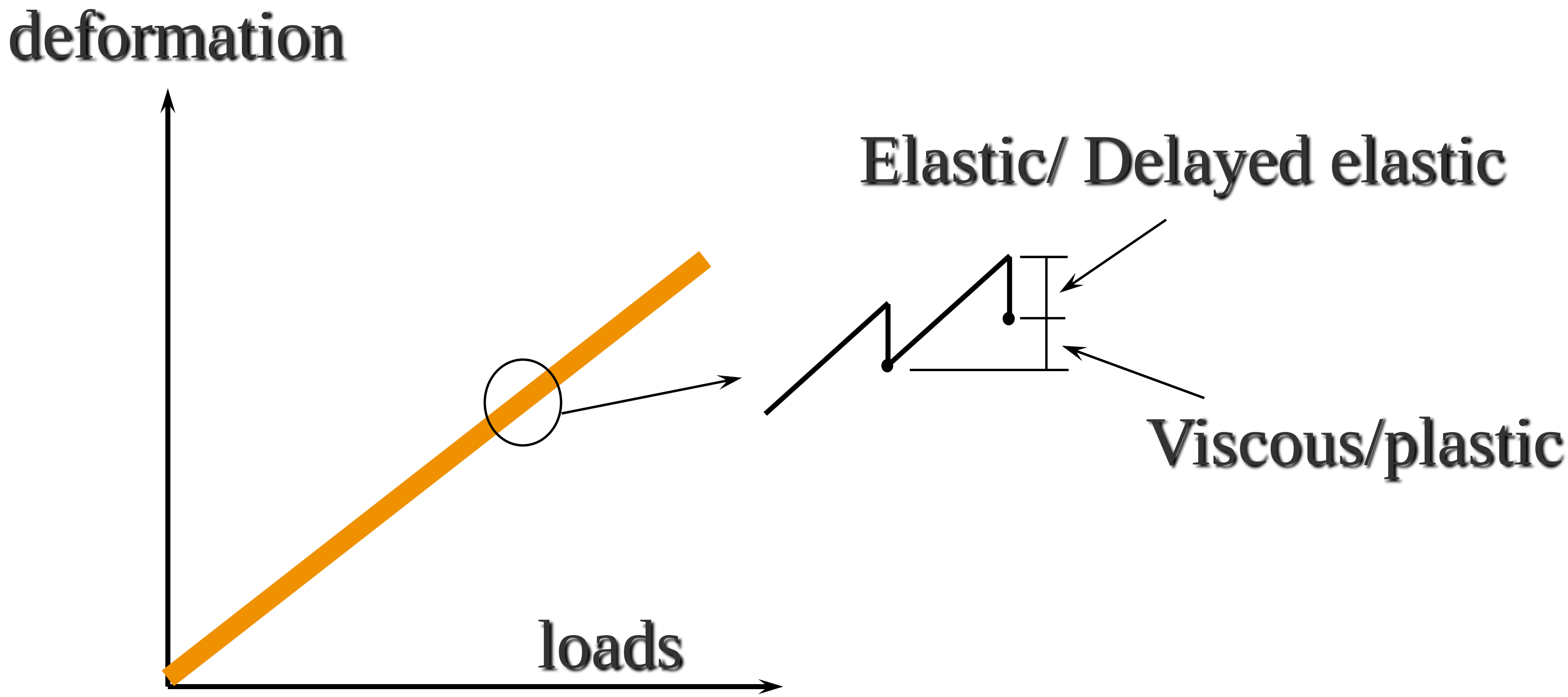
Voids will

1. **reduce stiffness (modulus)**
2. **Increase amount of cement / asphalt required (cost)**
3. **Increase permeability**
4. **Affect workability**

Shearing Behavior of Aggregate



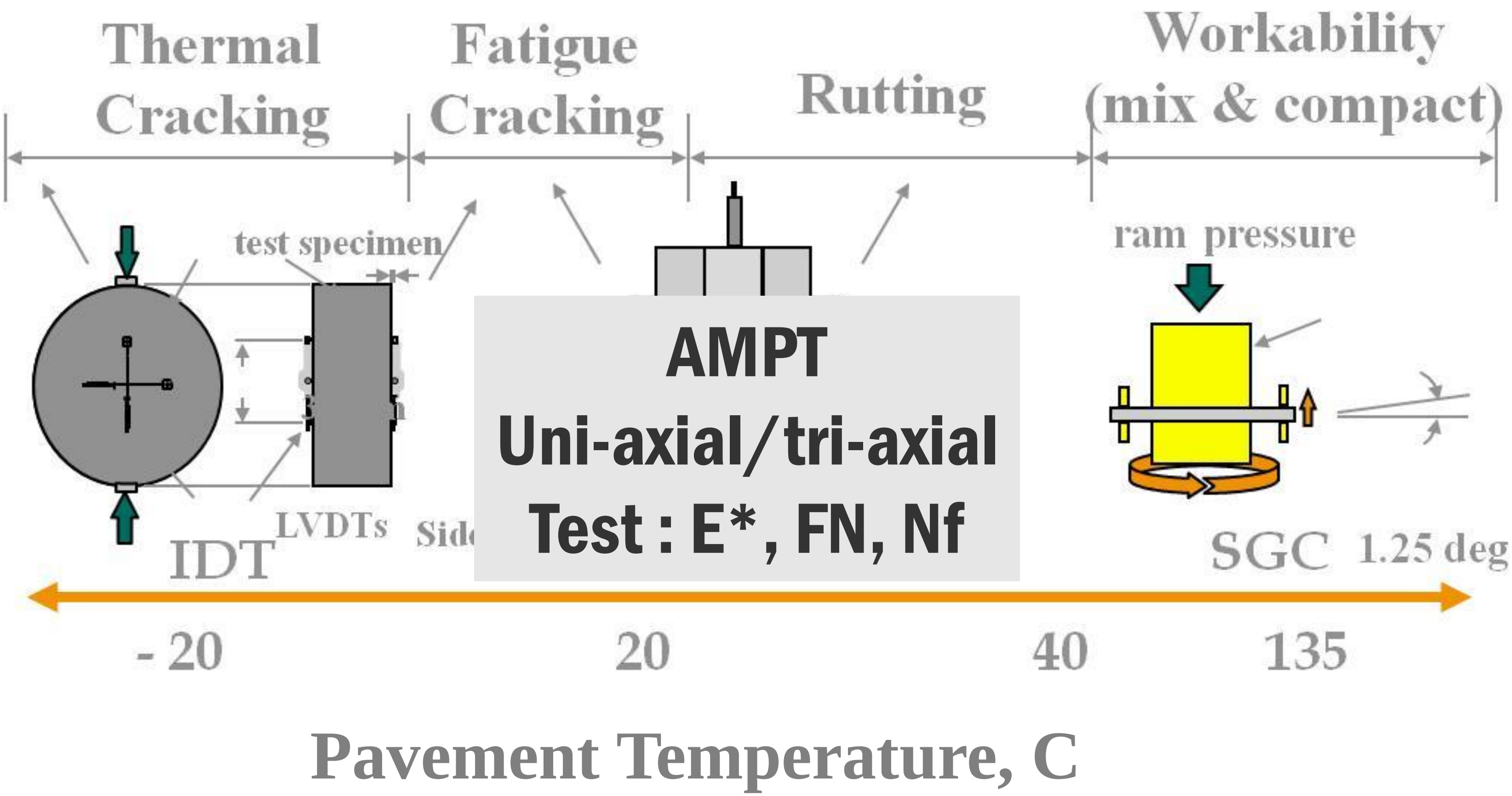
Deformation in Asphalt Layers



Mix Design and Testing Progress

- Earlier methods
  - Marshall Mix Design, Hveem Mix Design
- In the 1970-80's
  - Texas Gyratory Mix Design, other Empirical Strength Testing
- In the 1990's
  - Superpave Gyratory and Aggregate testing system (1994)
- In 2000
  - Hamburg, APA, SPT
- In 2010s
  - AMPT, Bailey Method, Imaging

Superpave Mixture Performance Tests



AMPT

Uni-axial/tri-axial

Test : E*, FN, Nf

1. Traffic

2. Aggregates Properties

3. Gyrations

4. Densification

Va @ N ini , Va @ Ndes

Va@ N max

5. Durability

Dust/Bind, VFA

TSR

TABLE 460-2 MIXTURE REQUIREMENTS

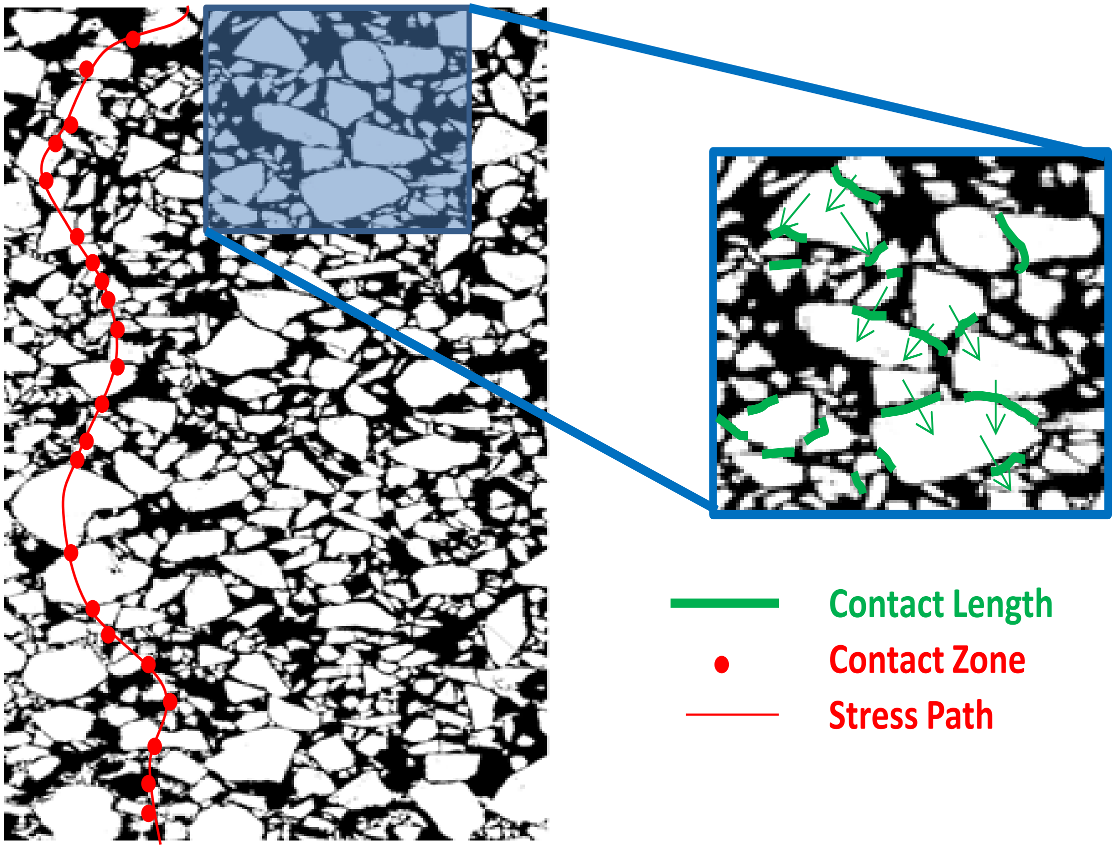
Mixture type	E - 0.3	E - 1	E - 3	E - 10	E - 30	E - 30x	SMA
ESALs x 10^6 (20 yr design life)	< 0.3	0.3 - < 1	1 - < 3	3 - < 10	10 - < 30	≥ 30	___
LA Wear (AASHTO T 96)							
100 revolutions(max % loss)	13	13	13	13	13	13	13
500 revolutions(max % loss)	50	50	45	45	45	45	45
Soundness (AASHTO T 104) (sodium sulfate, max % loss)	12	12	12	12	12	12	12
Freeze/Thaw (AASHTO T 103) (specified counties, max % loss)	18	18	18	18	18	18	18
Fractured Faces (ASTM 5821) (one face/2 face, % by count)	60 / ___	65 / ___	75 / 60	85 / 80	98 / 90	100/100	100/90
Thin or Elongated (ASTM D4791) (max %, by weight)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	20 (3:1ratio)
Fine Aggregate Angularity (AASHTO T304, method A, min)	40	40	43	45	45	45	45
Sand Equivalency (AASHTO T 176, min)	40	40	40	45	45	50	50
Gyratory Compaction							
Gyrations for N_{ini}	6	7	7	8	8	9	8
Gyrations for N_{des}	40	60	75	100	100	125	100
Gyrations for N_{max}	60	75	115	160	160	205	160
Air Voids, $\%V_a$ ($\%G_{mm}$ @ N_{des})	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)
% G_{mm} @ N_{ini}	≤ 91.5[1]	≤ 90.5[1]	≤ 89.0[1]	≤ 89.0	≤ 89.0	≤ 89.0	___
% G_{mm} @ N_{max}	≤ 98.0	≤ 98.0	≤ 98.0	≤ 98.0	≤ 98.0	≤ 98.0	___
Dust to Binder Ratio[2] (% passing 0.075/P_{be})	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	1.2 - 2.0
Voids filled with Binder (VFB or VFA, %)	70 - 80 [4] [5]	65 - 78 [4]	65 - 75 [4]	65 - 75 [3] [4]	65 - 75 [3] [4]	65 - 75 [3] [4]	70 - 80
Tensile Strength Ratio (TSR) (ASTM 4867)							
no antistripping additive	0.70	0.70	0.70	0.70	0.70	0.70	0.70
with antistripping additive	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Draindown at Production Temperature (%)	___	___	___	___	___	___	0.30

[1] The percent maximum density at initial compaction is only a guideline.

Example of Mixture Specification Wisconsin DOT

MARC studies: We Measure aggregate structure
iPas1 … iPas2 … (Image Processing and Analysis Software)

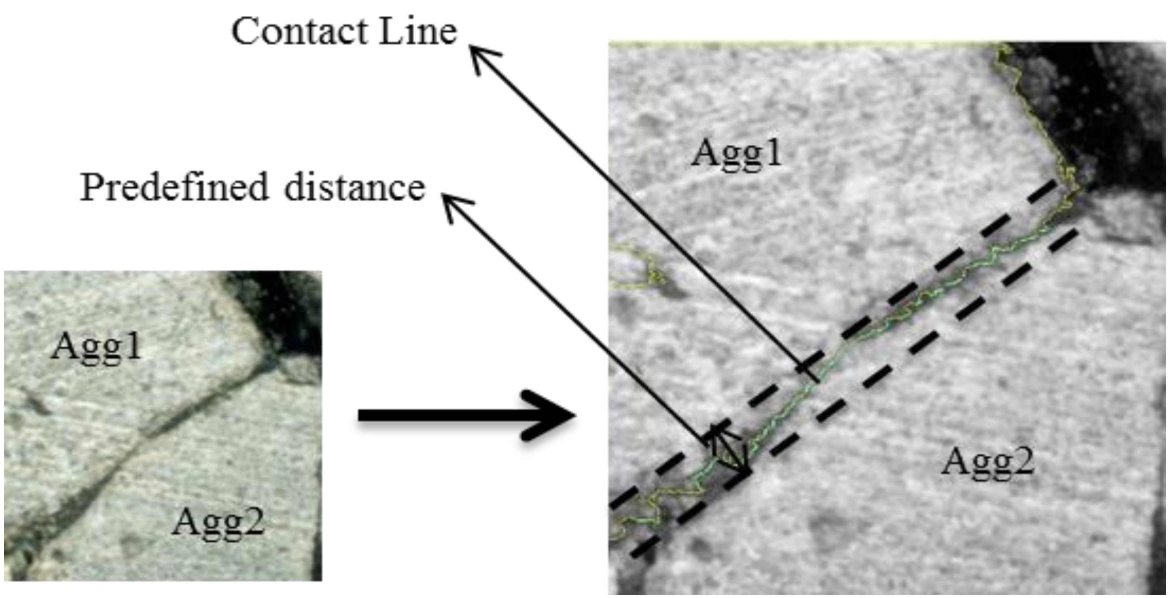
- iPas: A tool to identify aggregate structure.
- Give statistics about
  - Packing
  - Connectivity
  - Orientation
  - Spatial segregation

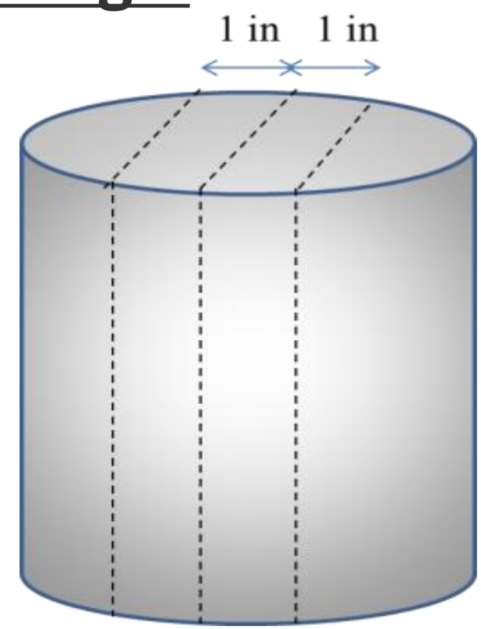


Aggregate Packing Characterization
2D to represent 3D - Stereology

iPas2 output used to quantify packing: Aggr. Proximity Index

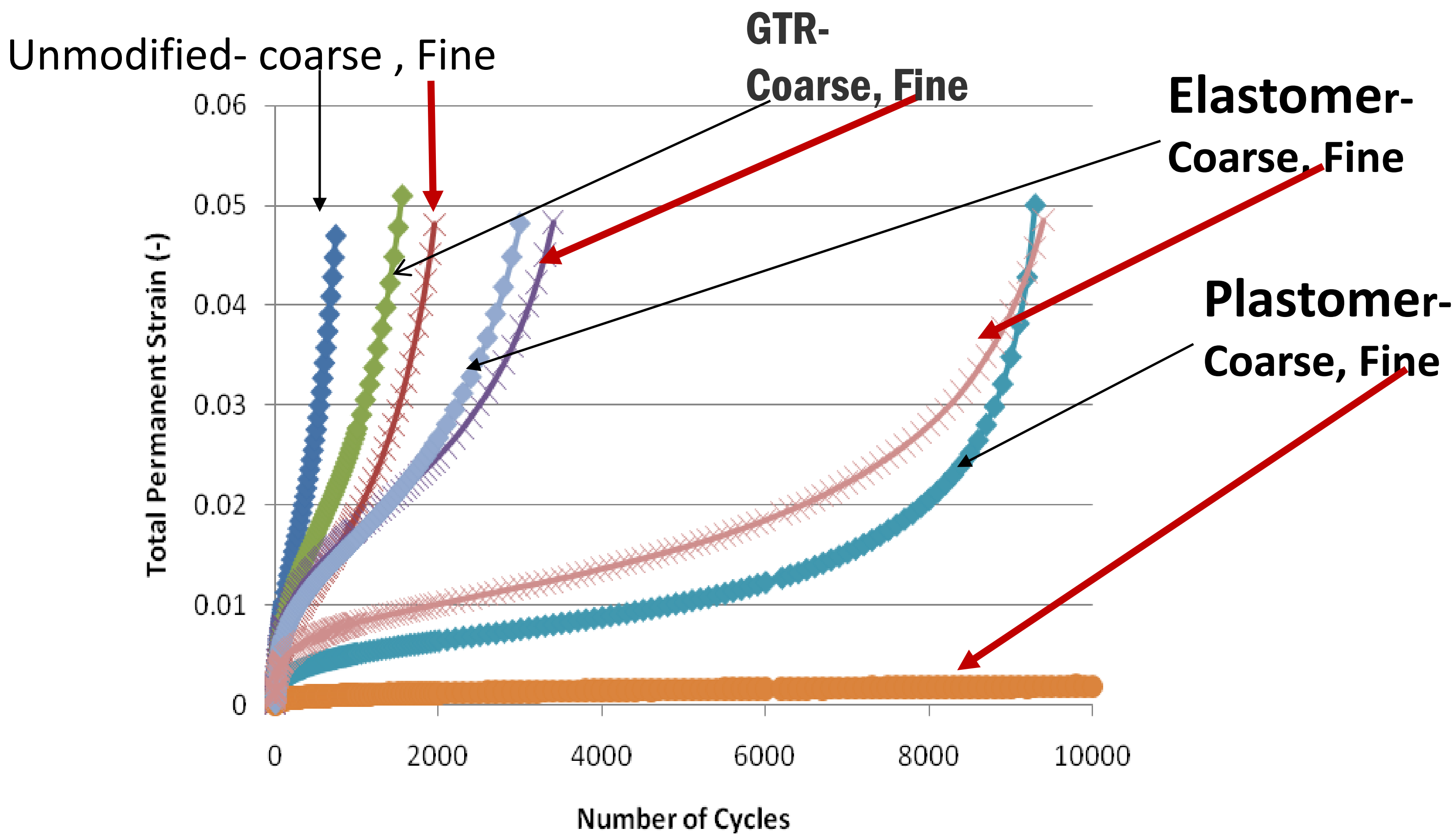
API= Total aggregate to aggregate Proximity length



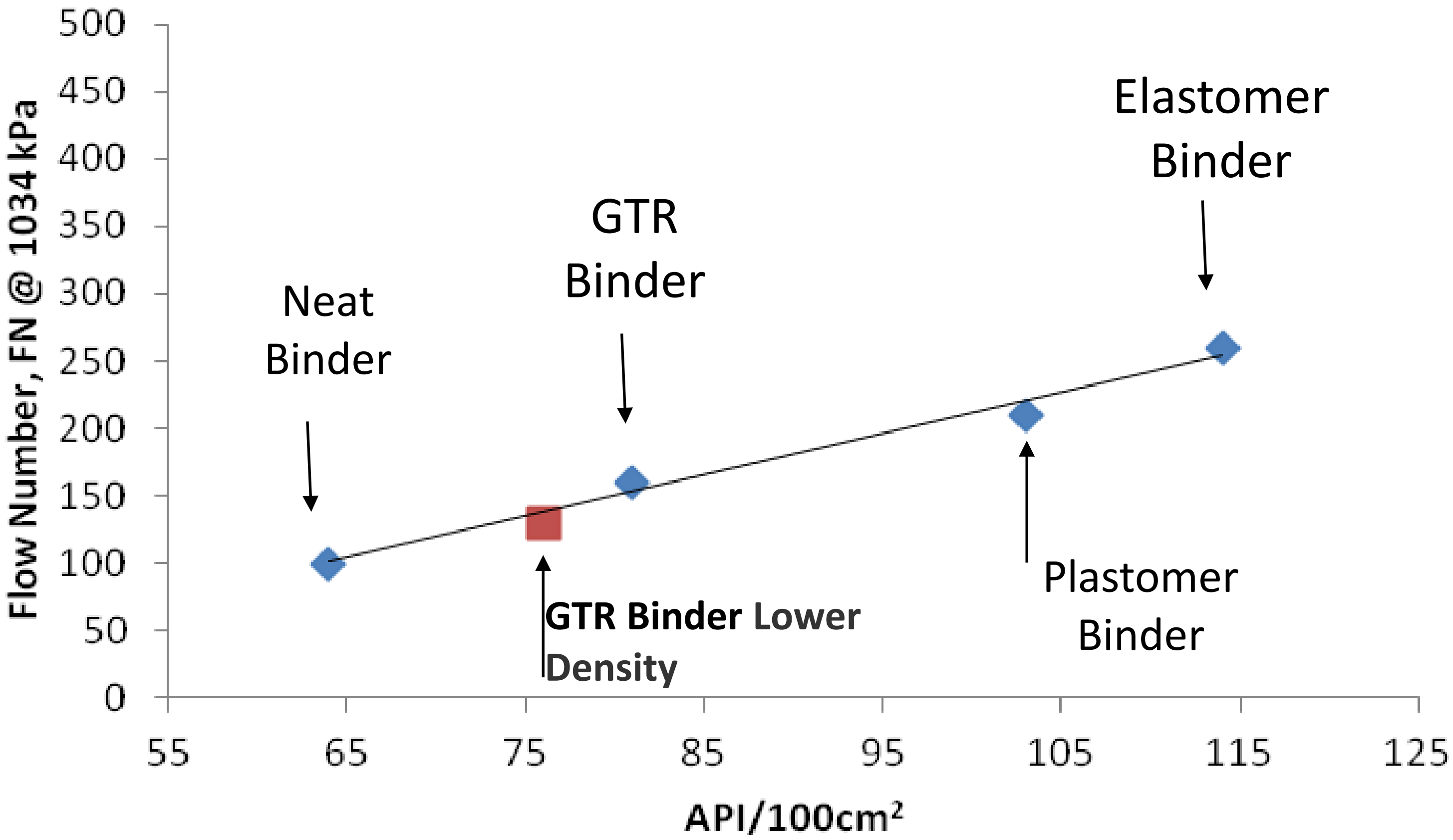


Cutting sections

Can we control Mixture Rutting:
Effect of Aggregate Gradation and Binder Modification

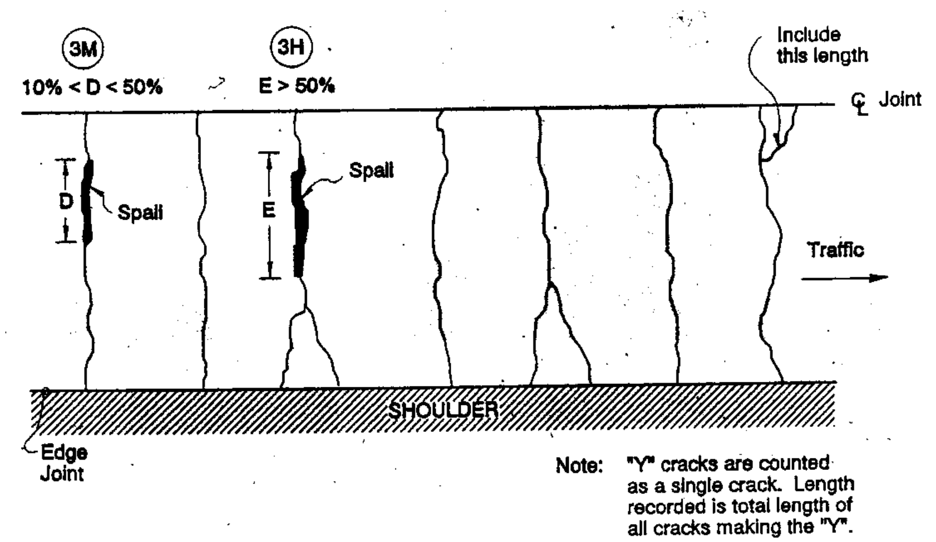


Internal Aggregate Structure (API) Can explain the differences in FN

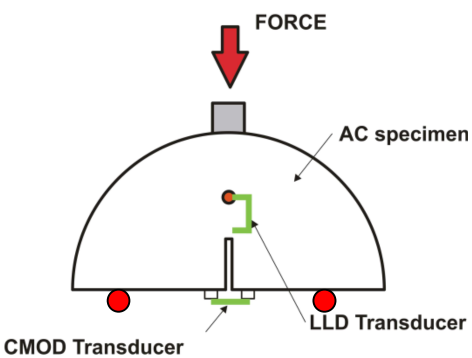


Estonia Cold Climate – Thermal Cracking

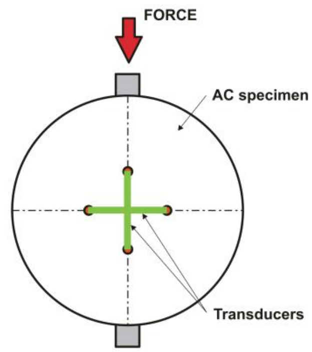
- Thermal cracking of pavements **remains one of the most challenging distress** in pavements to predict, and reduce, in North America.



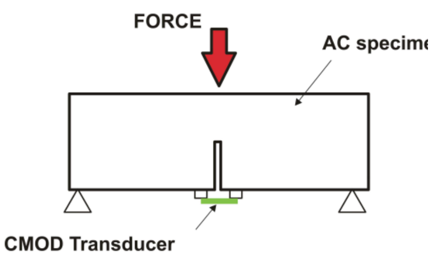
Cold Temperature Mixture Test Methods:
Two types



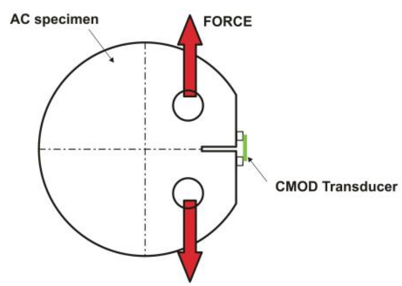
SCB



IDT*

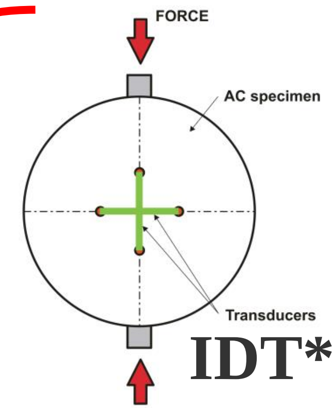


SENB



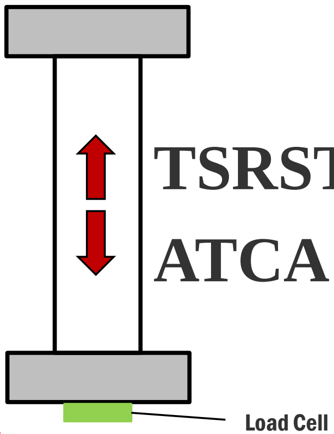
DCT

1. Fracture Tests



IDT*

2. Modulus & Failure Tests



TSRST

ATCA

*IDT can be performed with notch (fracture), without notch (failure) or in creep mode.

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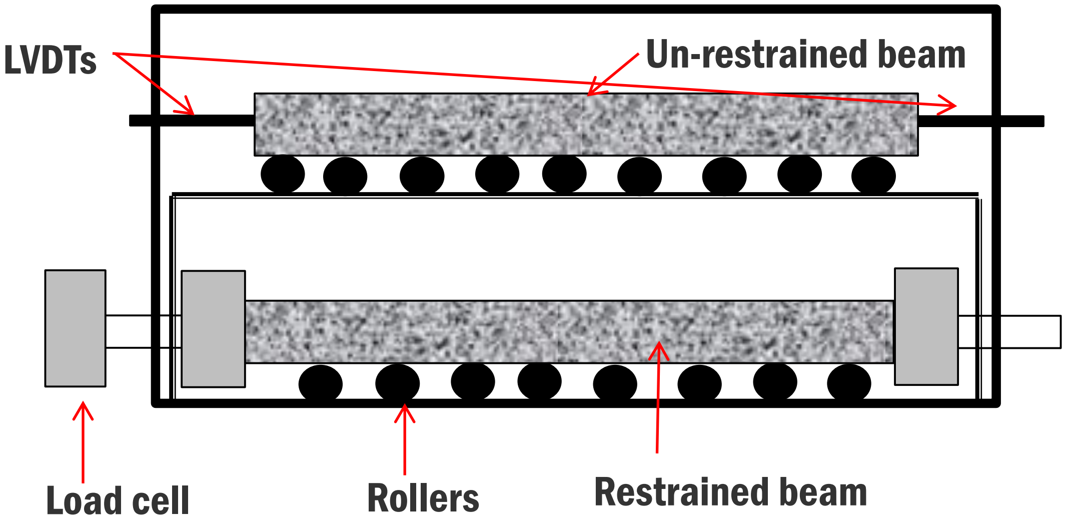
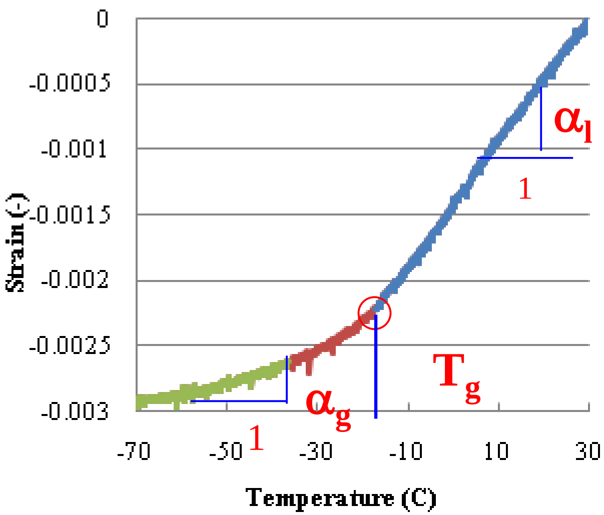
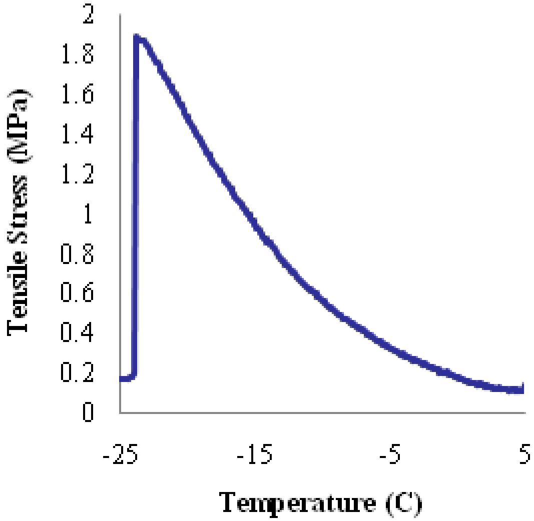
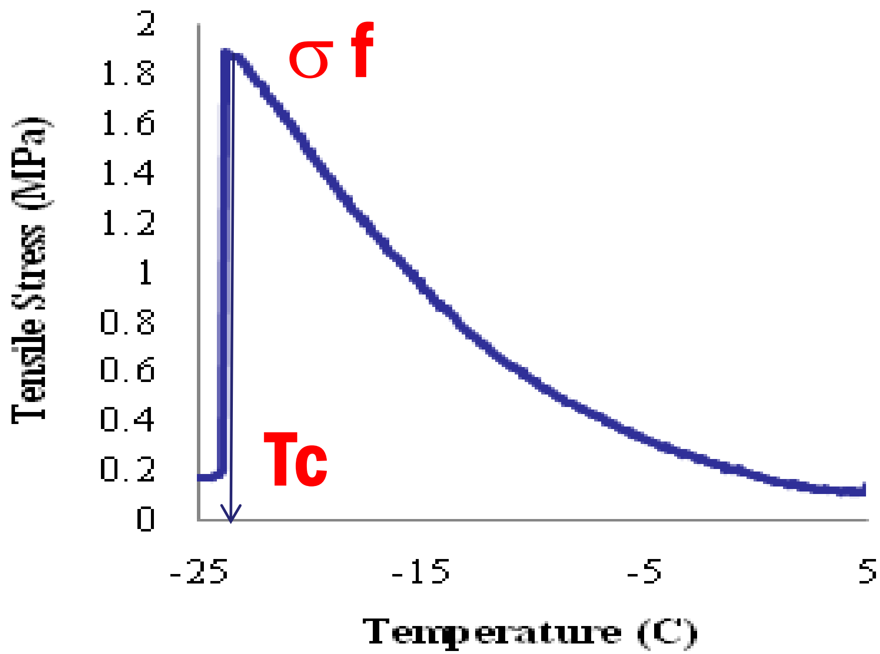
ATCA: Asphalt Thermal Cracking Analyzer

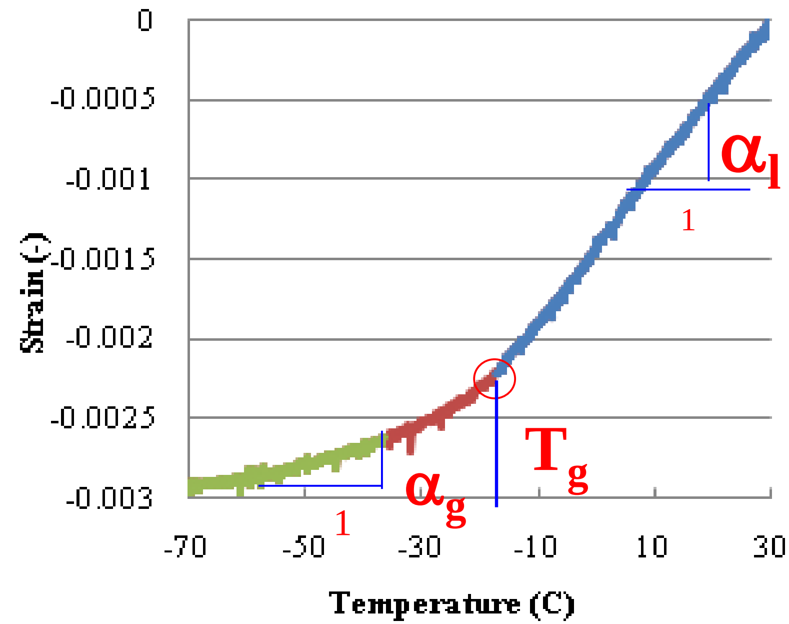


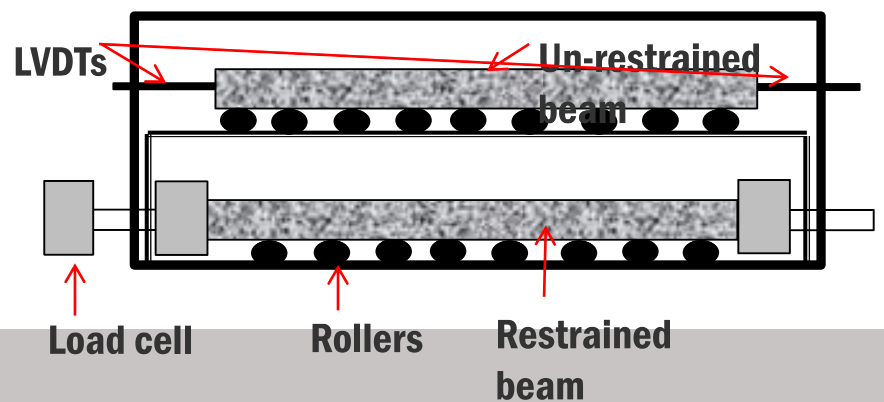




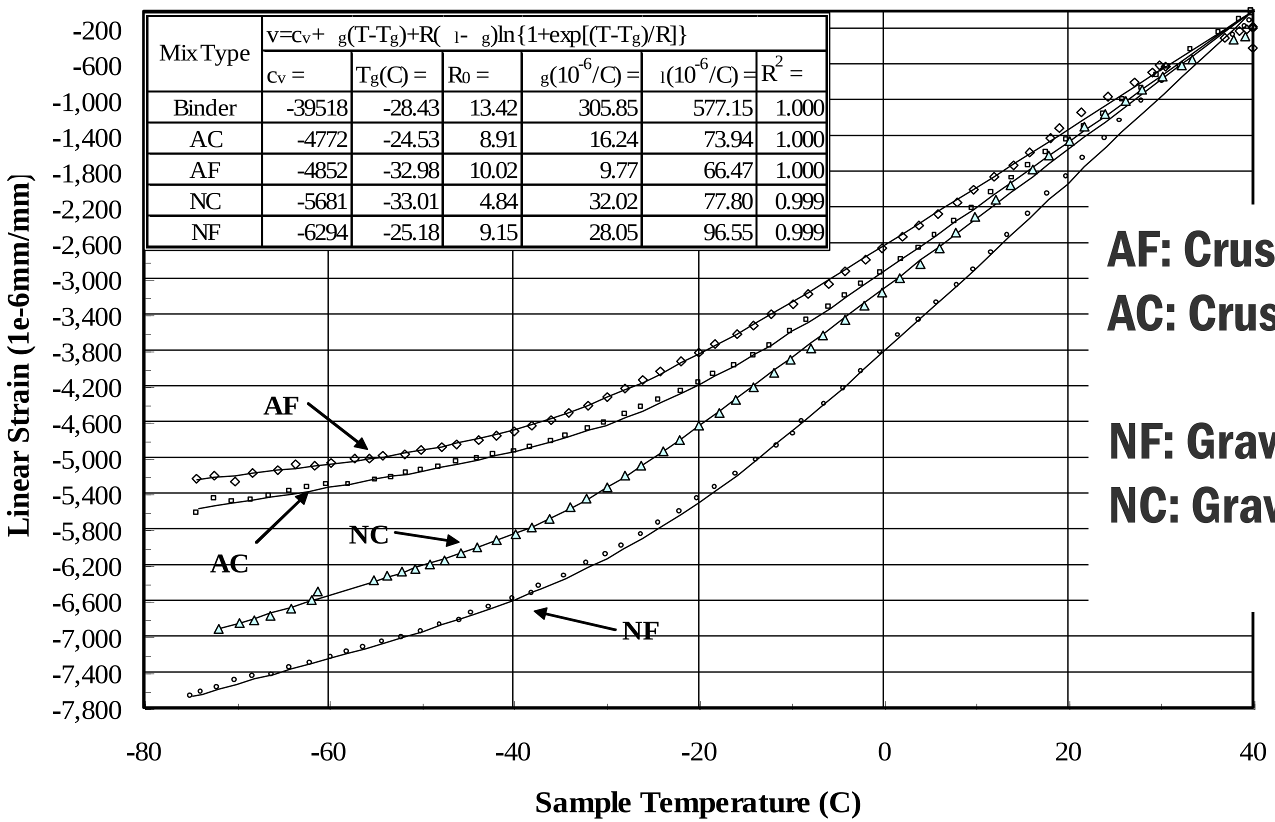
ATCA: Asphalt Thermal Cracking Analyzer







Aggregate Type Effect on Contraction Coefficients and Tg



Mix Type	$v=c_v+{}_g(T-T_g)+R({}_l-{}_g)\ln\{1+\exp[(T-T_g)/R]\}$					
	c_v =	T_g(C) =	R_0 =	${}_g(10^{-6}/C)$ =	${}_l(10^{-6}/C)$ =	R^2 =
Binder	-39518	-28.43	13.42	305.85	577.15	1.000
AC	-4772	-24.53	8.91	16.24	73.94	1.000
AF	-4852	-32.98	10.02	9.77	66.47	1.000
NC	-5681	-33.01	4.84	32.02	77.80	0.999
NF	-6294	-25.18	9.15	28.05	96.55	0.999

AF: Crushed Limestone Fine

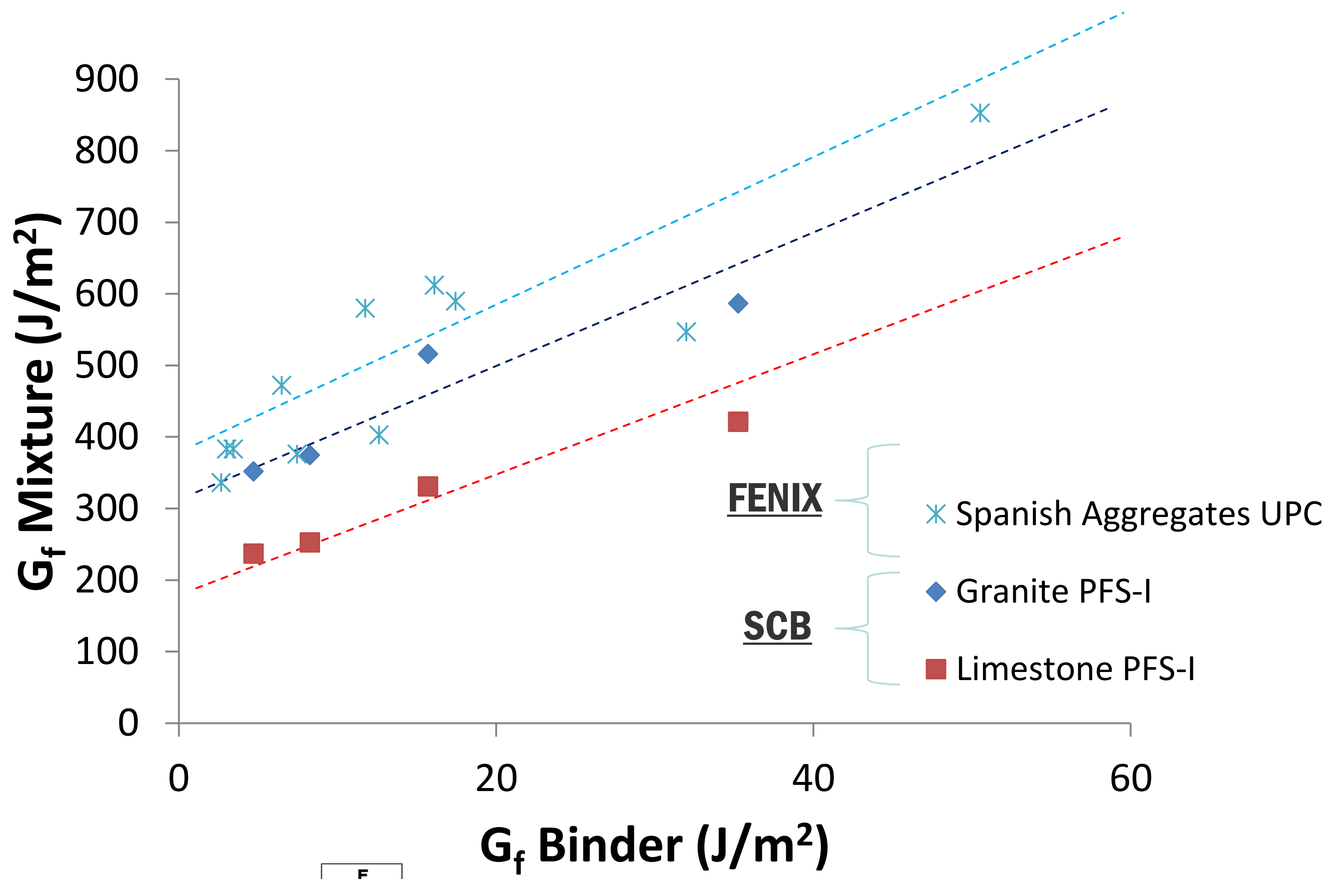
AC: Crushed Limestone Coarse

NF: Gravel Fine

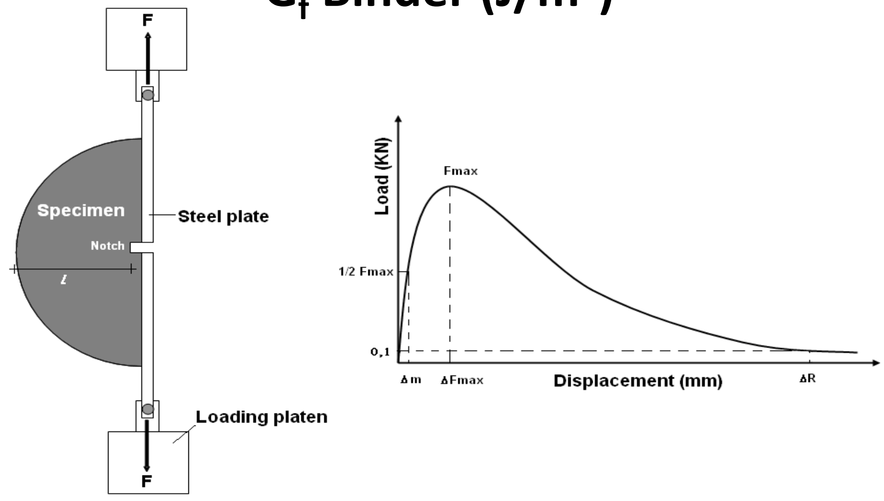
NC: Gravel Coarse

same binder and similar binder content

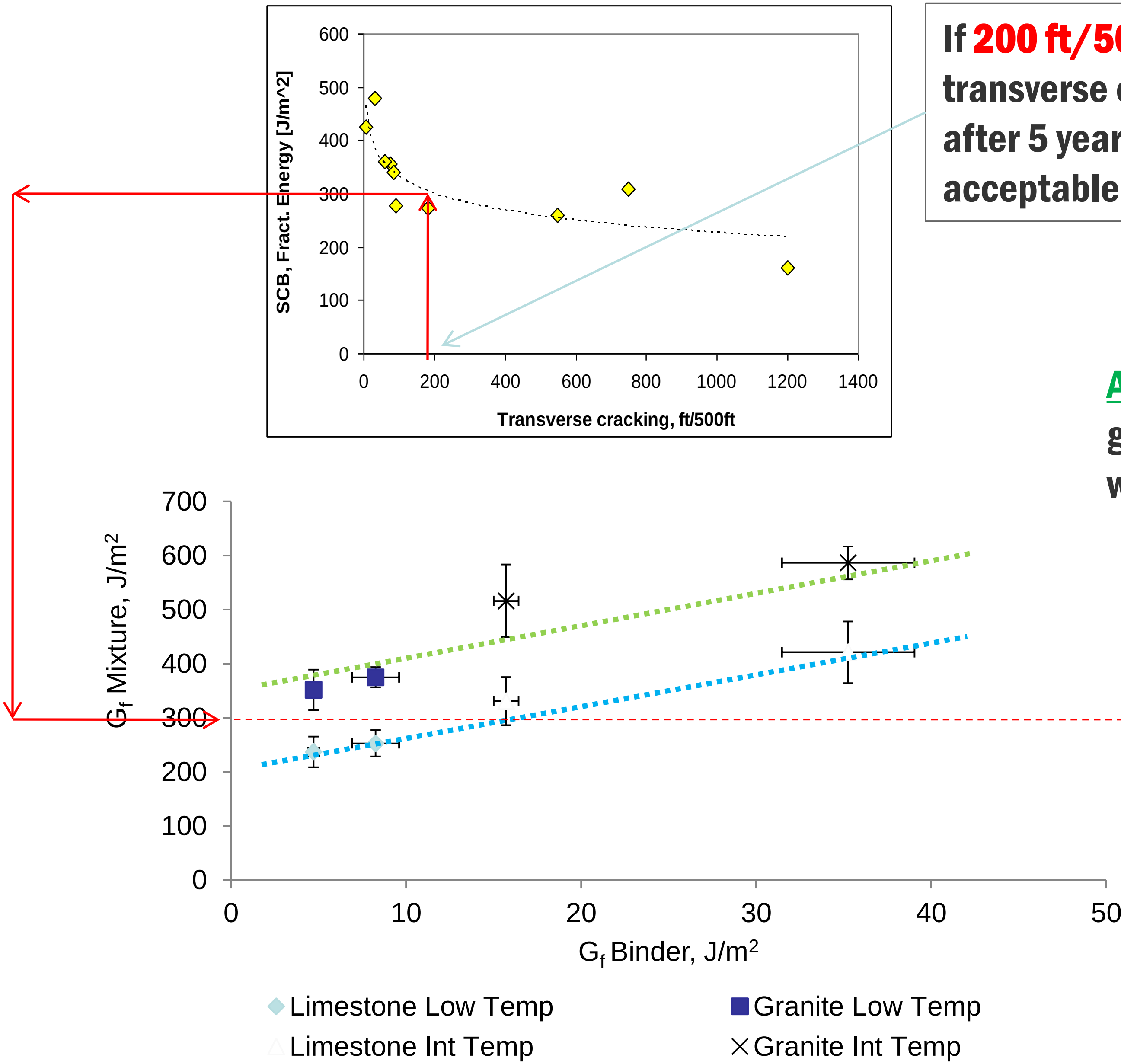
Binders vs. Mixtures



Fenix Test (Mixtures)



Developing Material Selection Criteria



If 200 ft/500 ft of transverse cracking after 5 years is acceptable

Acceptable Mixtures: All granite and limestone with binder G_f > 15 mJ/m^2

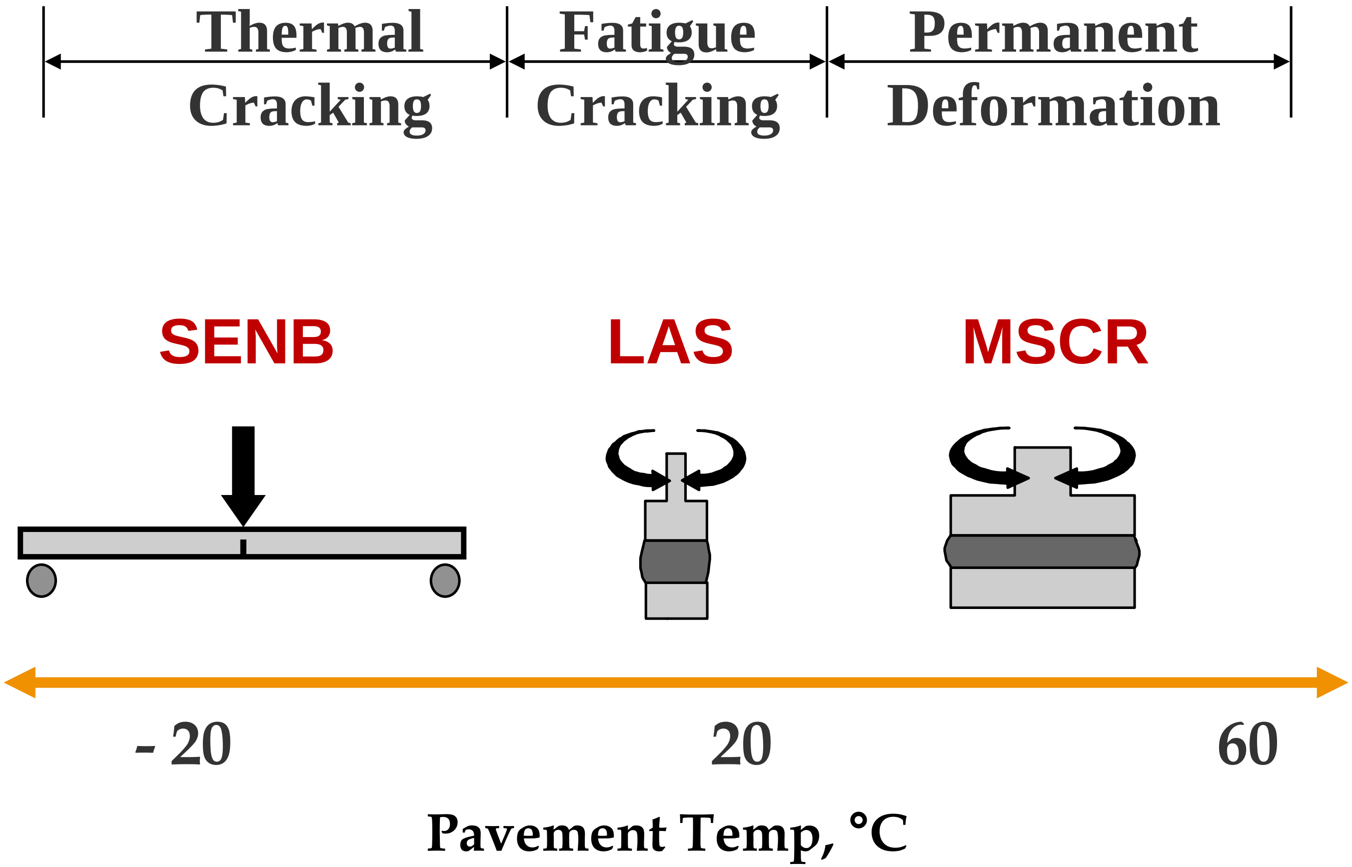
Unacceptable Mixtures: limestone with binder G_f < 15mJ/m^2

Estonia Study – Hypothesis & Objectives

- **Hypothesis:**
  - Variety of available bitumen types in Estonia does not adequately cover the varying climatic needs.
- **Objectives:**
  - Conduct Superpave performance grading testing protocol to determine the PG grades of Estonian binders.
  - Compare the grades of available binders with those required for existing climatic conditions.
  - Investigate the production of needed grades through feasible modification techniques.

New Methods for Modified Binder Evaluation

Damage – Based Characterization



Required PG Grades

PG 58-28

PG 58-34

PG 58-40

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Materials

Binders' designations provided from different crude sources

Binder Code	Description	Crude Oil	PG
A	Pen 70-100	Venezuela	64-22
B	Pen 70-100	Russia	58-22
C	Pen 70-100	Russia	58-22
D	Pen 70-100	Russia	58-28
E	Pen 70-100	Russia	**70-28**
F	Pen 160-220	Venezuela	52-28
G	Pen 160-220	Russia	52-28
H	Shale Oil	Estonia	**52-4**

Available vs. Required PG Grades

●	Available PG
○	Needed, Unavailable PG

		High Service Temperature			
		52	58	64	70
Low Service temperature	-22	●	●	●	
	-28		●		●
	-34		○		
	-40		○		

Modification Alternatives: Oils + Polymers

Base Binder	Modification	Modified Binder Code	PG
A	5% Oil-A	M-A	58-28
B	10% Oil-B + 2% Plastomer	M-B	58-34
C	8% Oil-B + 3% Elastomer	M-C	58-34
D	8% Oil-B + 2% Plastomer	M-D	58-34
E	11% Oil-A	M-E-1	58-34
E	8% Oil-B	M-E-2	58-40
F	8% Oil-B + 4% Plastomer	M-F	58-34
G	8% Oil-B + 5% Elastomer	M-G	58-34

- **Oil A**: Bio Oil
- **Oil B**: Refined Waste Oil
- **Elastomer**: SBSx
- **Plastomer**: Functionalized Polyethylene (Titan 7686)

Selection of the dosage of oil modifier based on the required low temperature performance grade

Test Methods

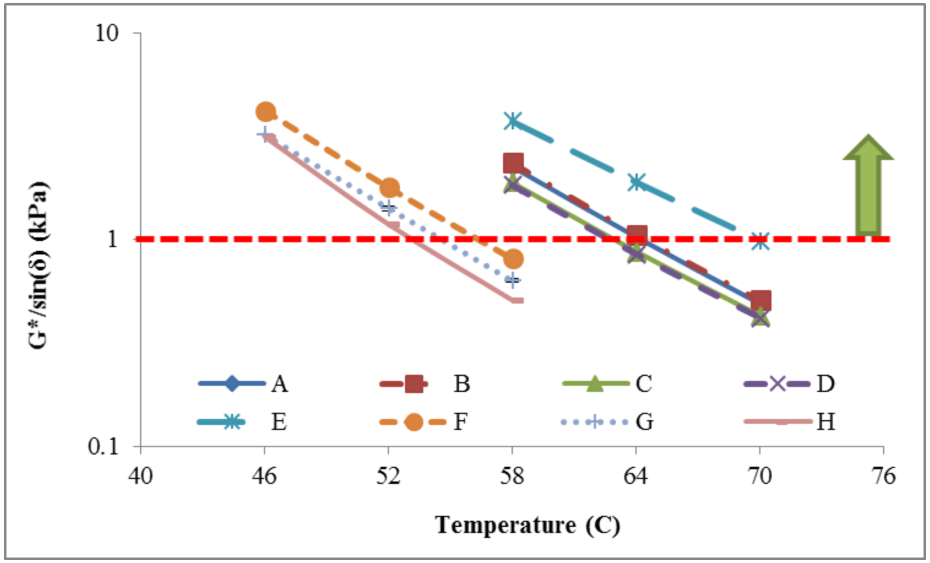
Test Methods Selected for Binder Evaluation

	Engineering Property of the Binder	Conventional Binder Test	Advanced Binder Test
1	**Rutting** resistance	DSR HT PG	---
2	**Fatigue** Cracking Resistance	DSR IT PG	Linear Amplitude Sweep (LAS)
3	**Thermal** Cracking Resistance	Bending Beam Rheometer (BBR)	Single Edge Notched Beam (SENB)
4	**Chemical** Content Spectrum	---	Gel Permeation Chromatography (GPC)

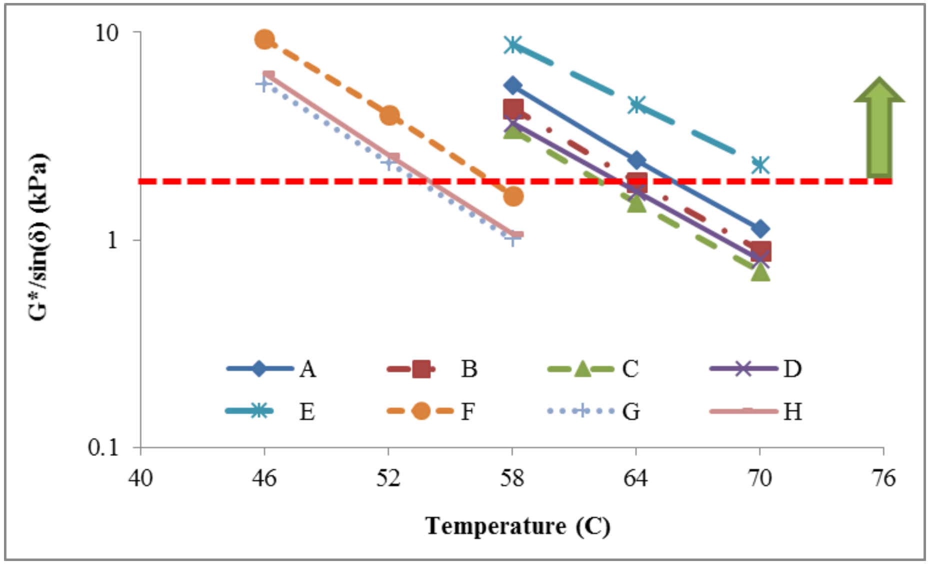
Results

High Temperature Grading-*Unmodified Binders*

Un-Aged



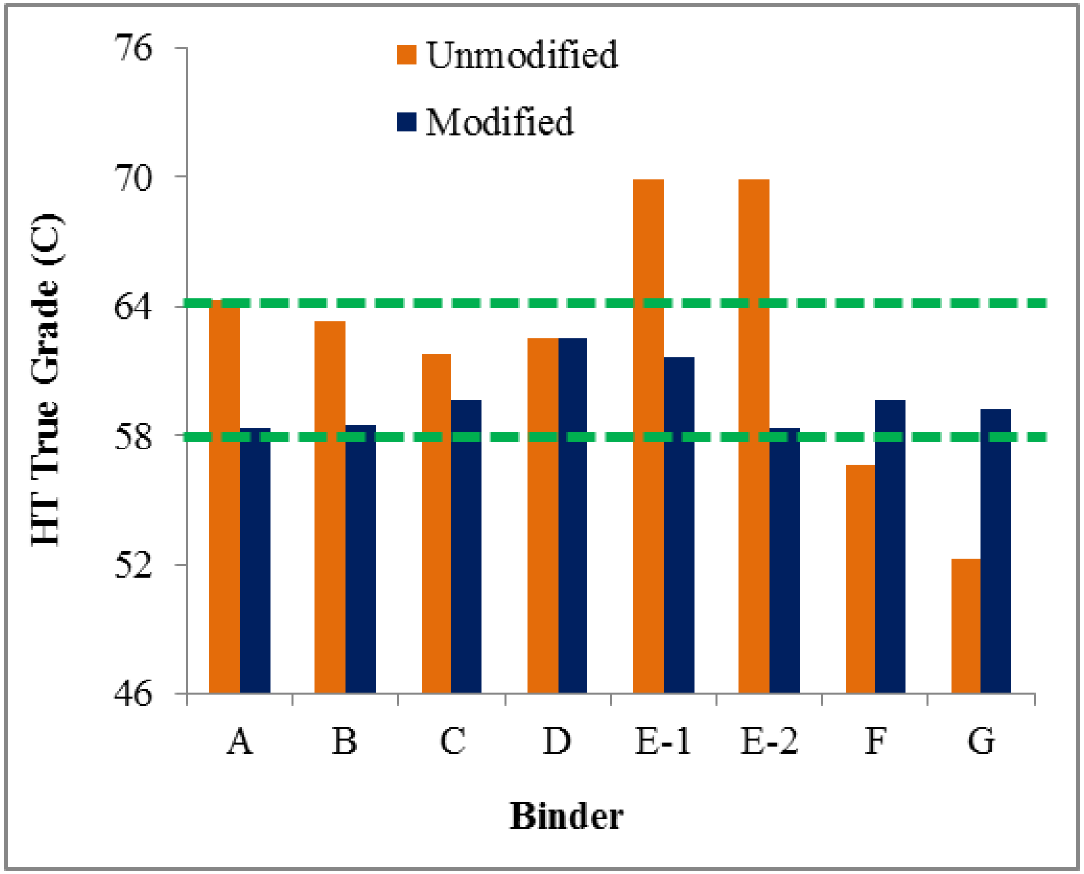
RTFO Aged



Narrow range of Performance Grades between provided Binders

Results

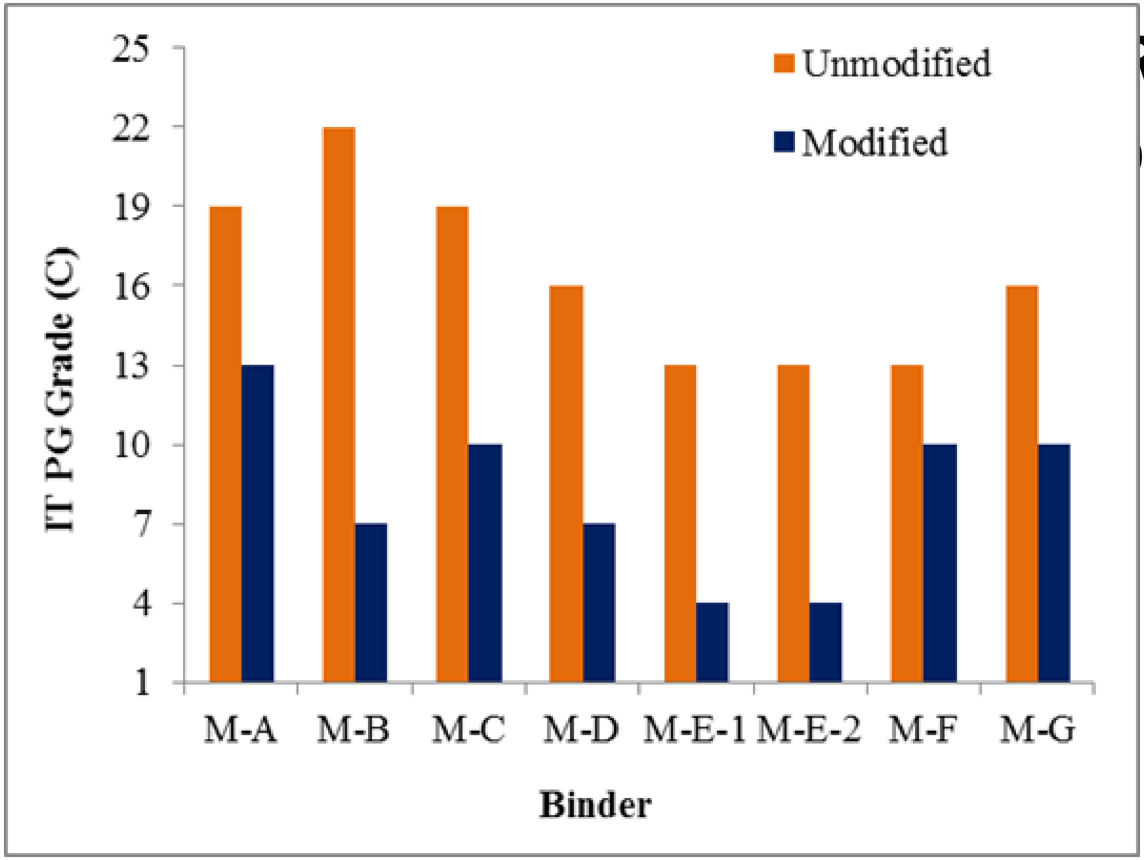
High Temperature Grading- *Continuous Grade*



- binders **with same pen grade (i.e binder A to E)** showed different behavior at high temperatures and **cover a range of three different PG grades**

- adding lubricating oils decrease the high temperature properties of the original binder

Results
Intermediate Temperature Continuous Grade

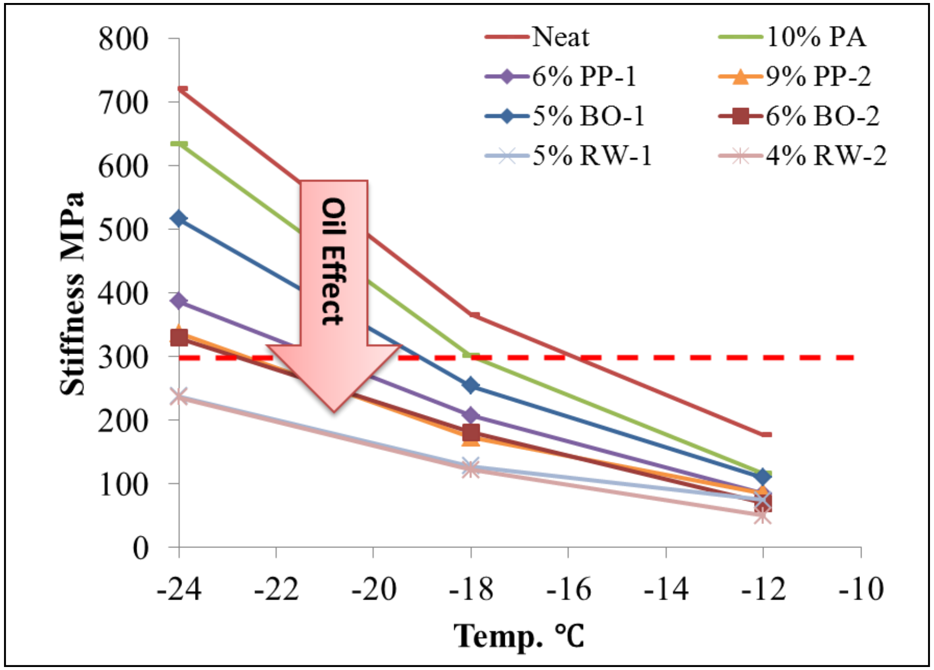


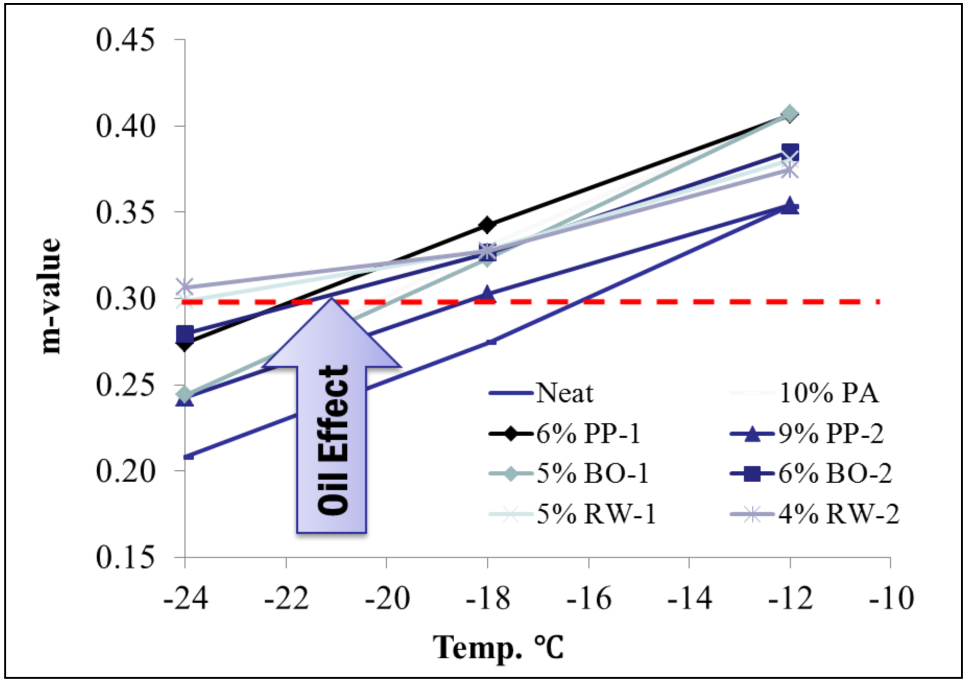
Reduction in the IT grade f binders by 6 to 15°C by binder modification

Superpave Max IT Grade:

- PG 58-28: 19°C
- PG 58-34: 16°C
- PG 58-40: 13°C

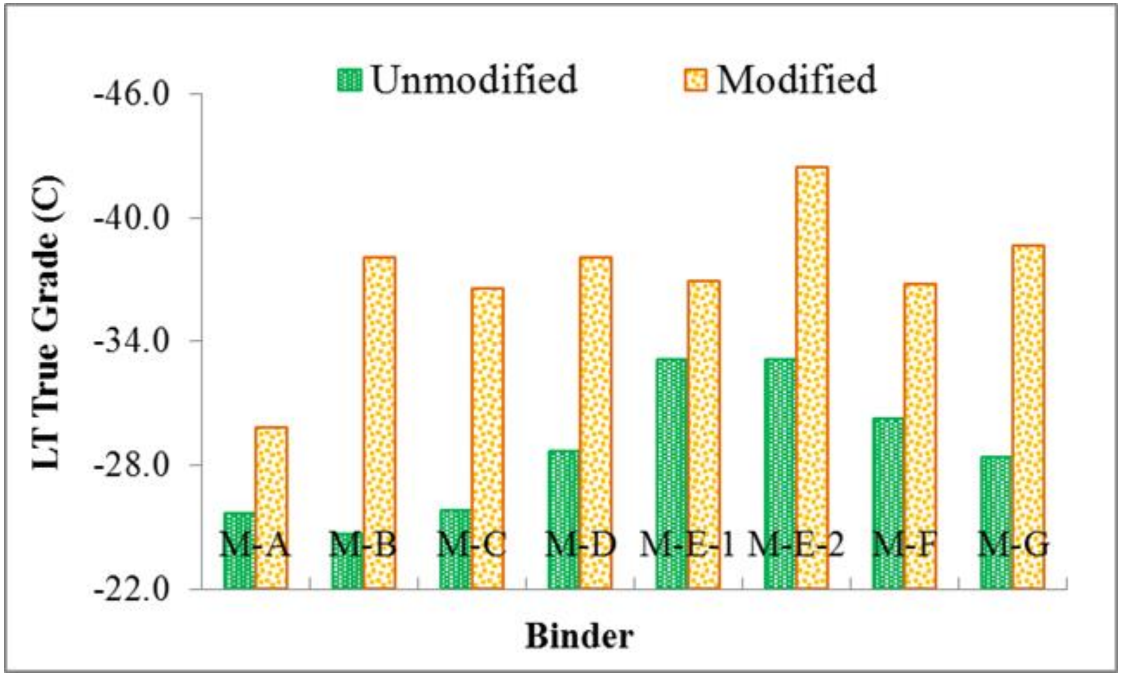
Effect of Oils on LT Binder Properties





Results

Low Temperature Grading- *Continuous Grade*

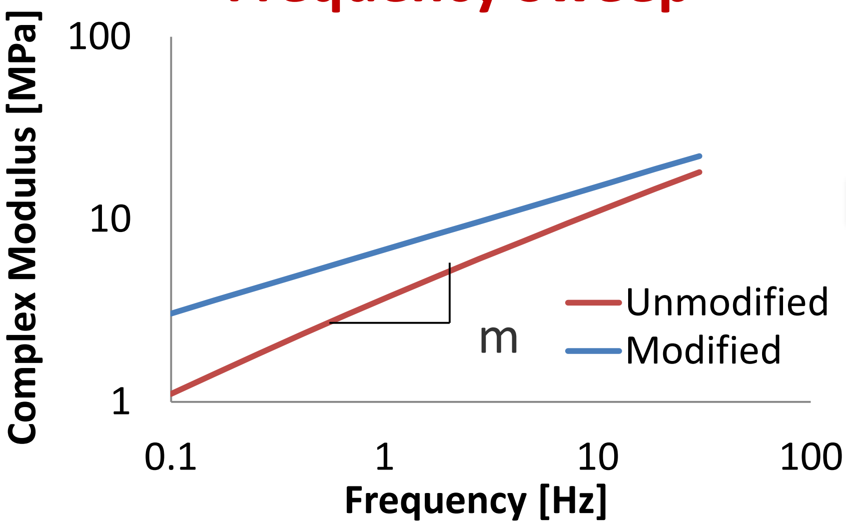


- Considering the high temperature grade of these binders to be kept the same level, **selected modifications** were capable of expanding the performance range of binders by **shifting the lower band up to 10°C**

Fatigue Life from LAS
Specification based on Binder Nf

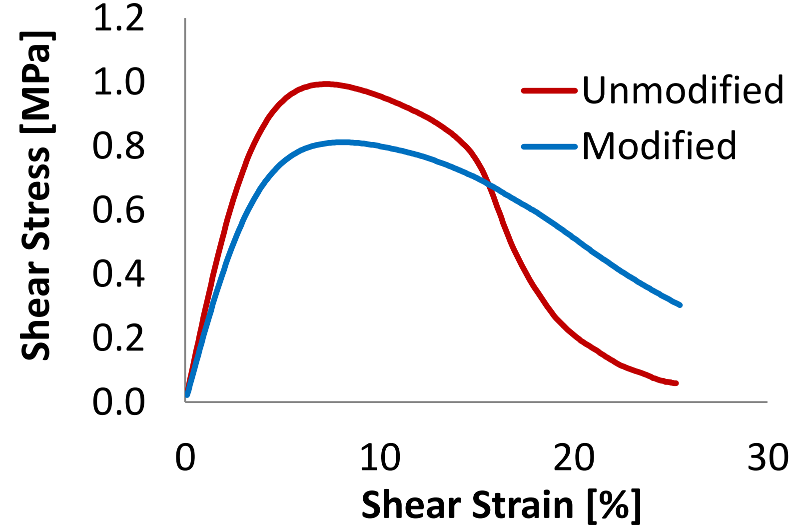
Rheology

Frequency Sweep



Damage Resistance

Continuous Amplitude Sweep



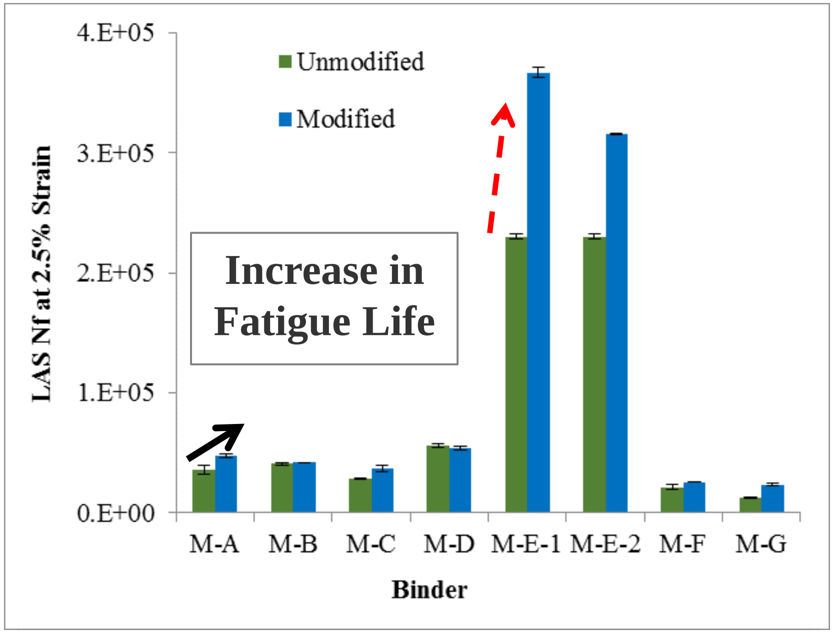
Slope → **B**

$$N_f = A\,(\gamma_{max})^B$$

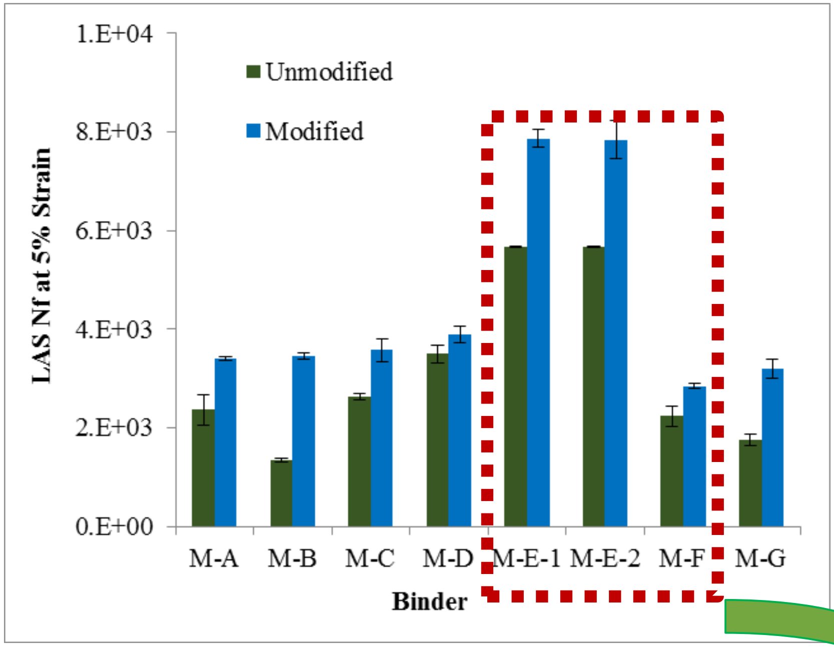
VECD → **A**

Results
Linear Amplitude Sweep (LAS) Test

2.5%Strain Amplitude



5%Strain Amplitude



Lubricating oils improve the fatigue resistance at different strain levels

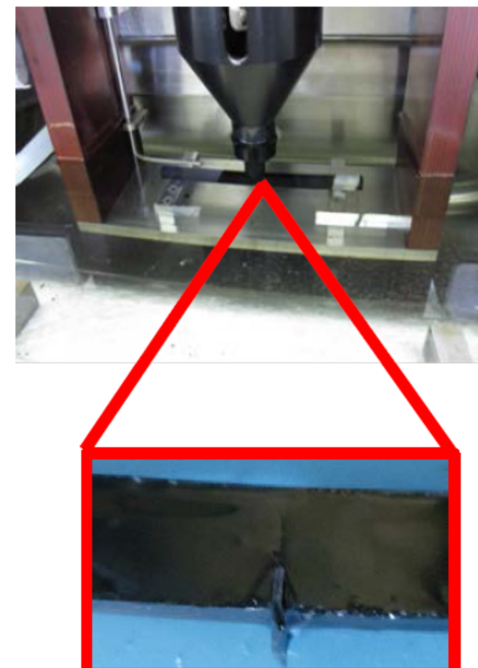
Same IT PG grade can resist fatigue significantly different

Single Edge Notched Bending (SENB)

Displacement-Controlled Mode

Step Motor

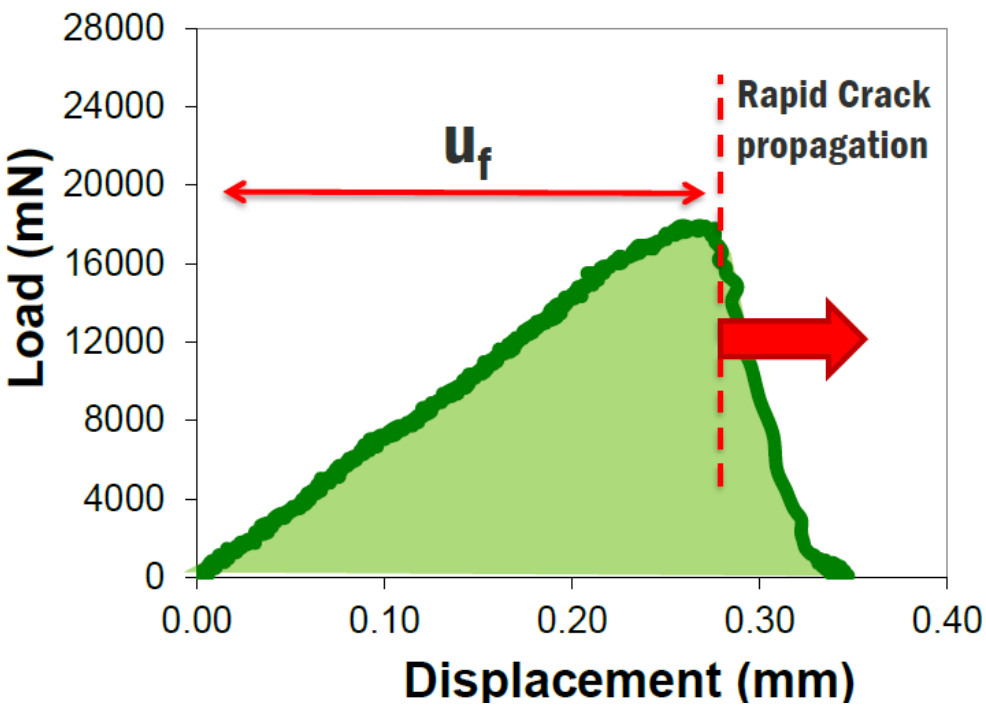
BBR system with a load cell with higher capacity

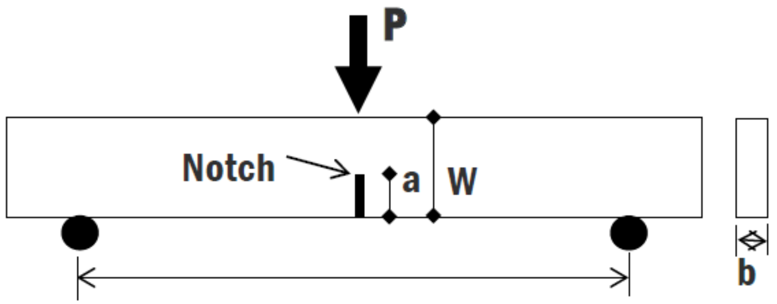


Fracture Properties and Strain Tolerance

Single-Edge Notched Beam (BBR-SENB):

- Failure Energy (G_f)
- Deflection at failure (u_f)



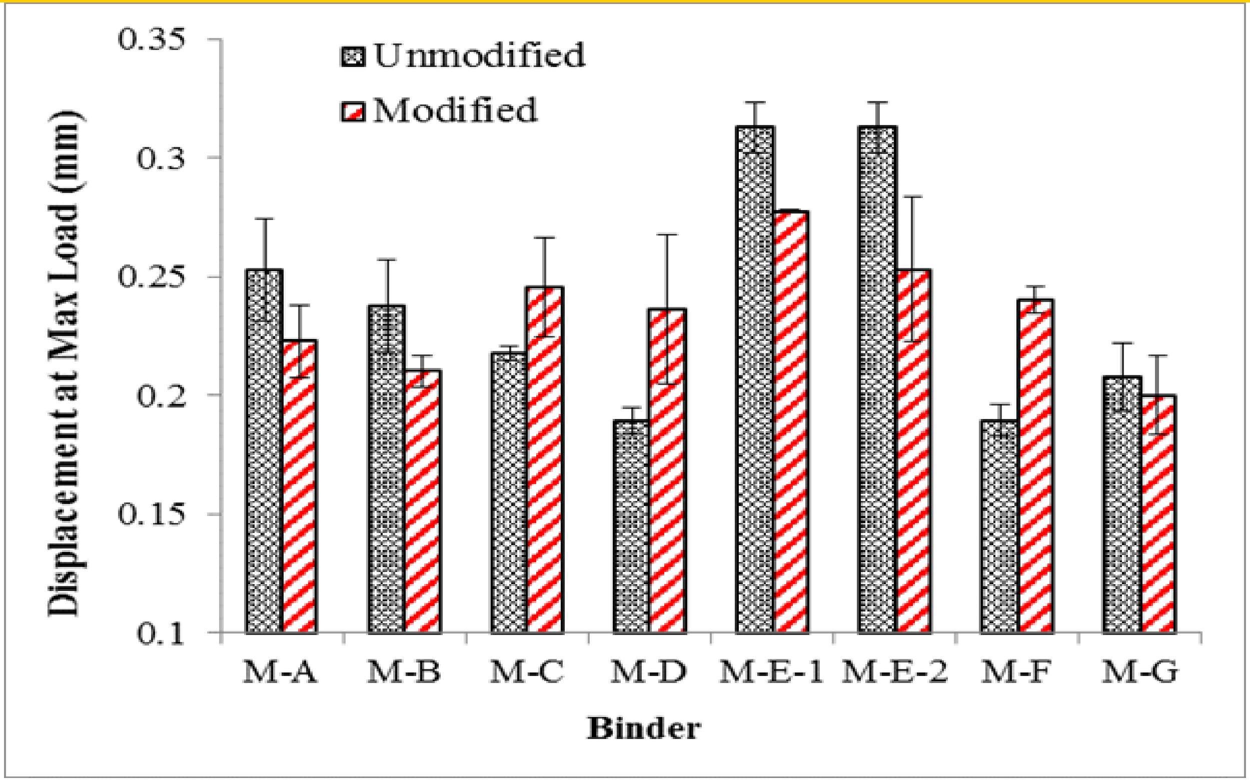


$$G_f = \frac{W_f}{A_{lig}}$$ Failure Energy

$$W_f = \int P du$$ Work

Results

Single Edge Notched Bending (SENB) @ LT Grade



- **Marginal difference between unmodified and modified binders**
- **Test is performed at LT grade of the binders**

Concluding Remarks-Binder Study

- Estonia will need to use Oil modification to improve performance of pavements
- Oils could result in lower rutting resistance; need polymers to offset this effect
- Fatigue resistance varies significantly based on oils
- Impact of oils and polymers vary based on oil type and the crude source of binder

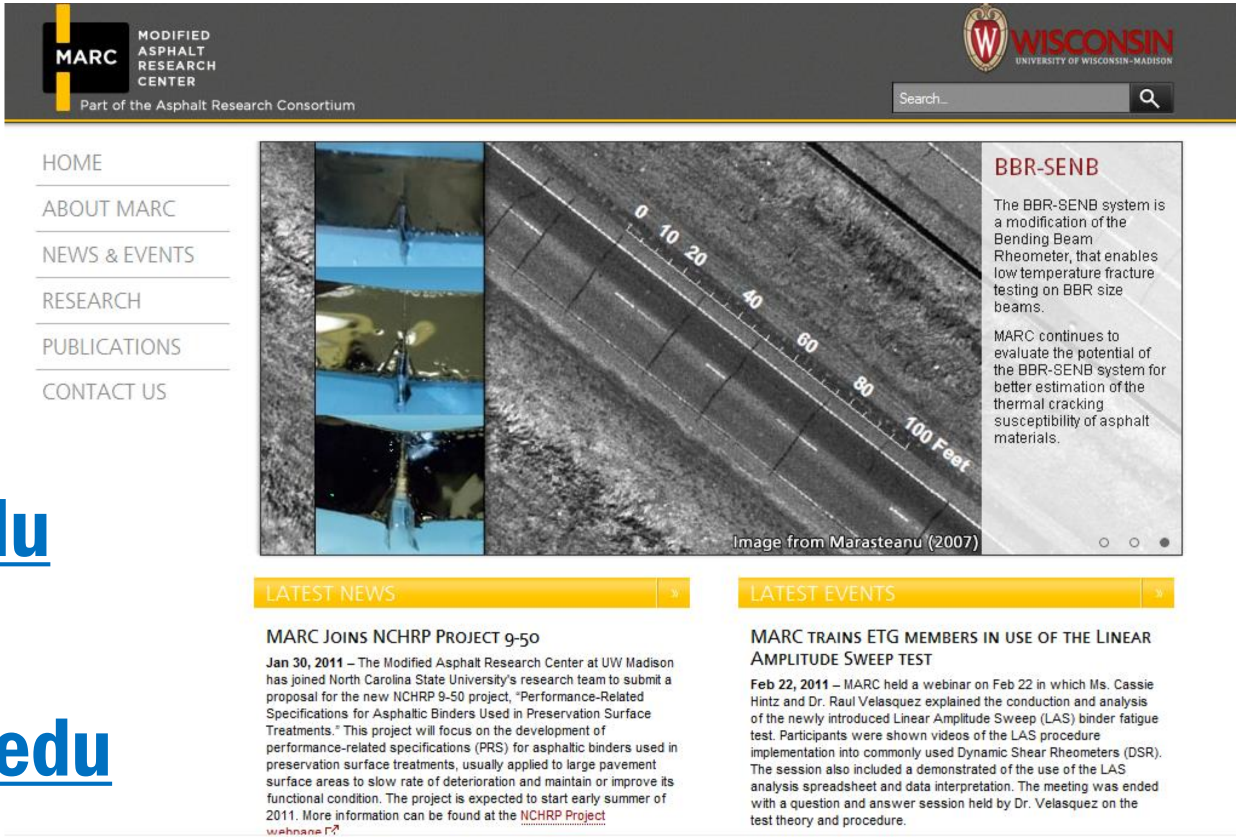
Concluding Results – General

- Roads are built with mixtures, not Binders!
- Thermal Cracking & rutting are affected by:
  - aggregate structure and binder properties.
- Suggestion for Mixture studies:
  - Internal structure and resistance to rutting
    - Ipas and FN
  - Coefficient of thermal contraction- ACTA
  - Fracture properties
  - Moisture damage – Wet Hamburg

Thank You!

Questions?

www.uwmarc.org



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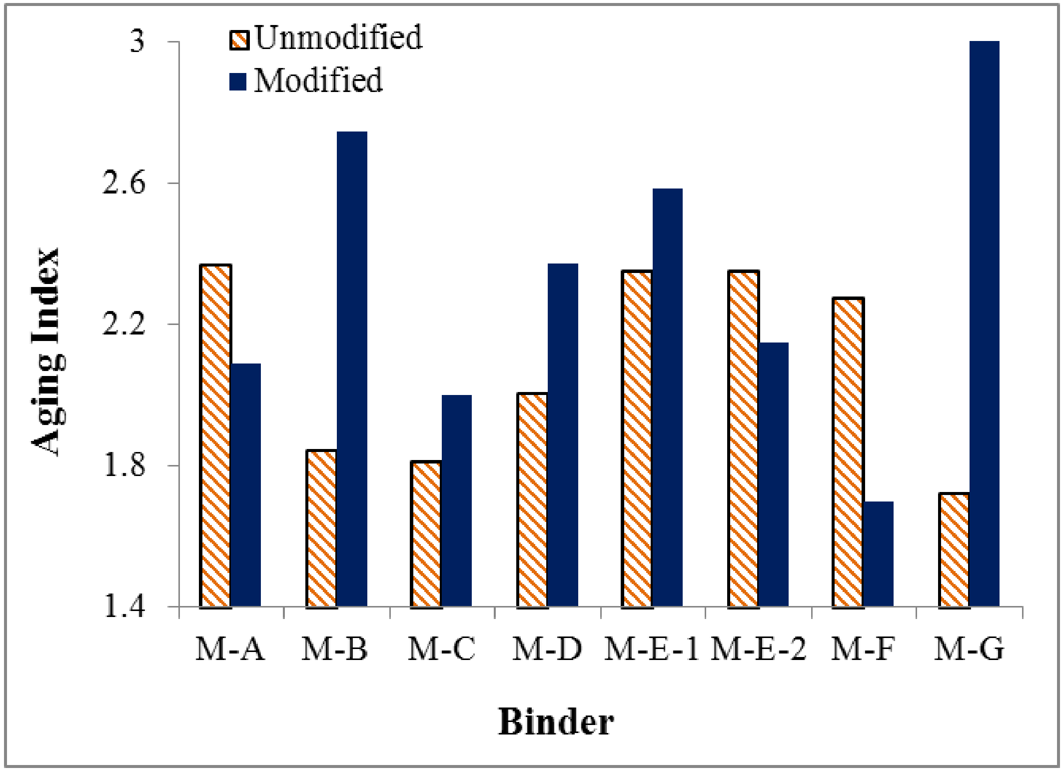
Results

High Temperature Grading-*Aging Susceptibility*

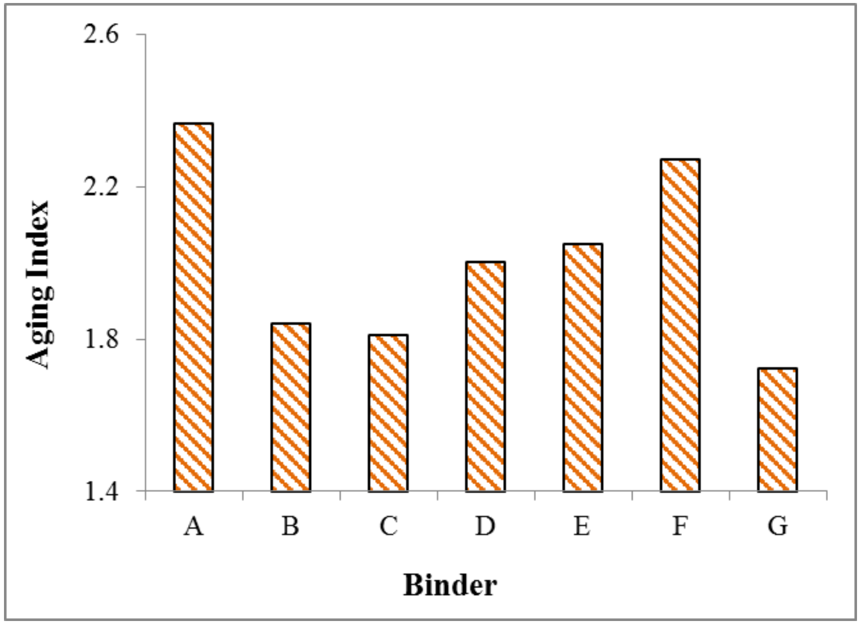


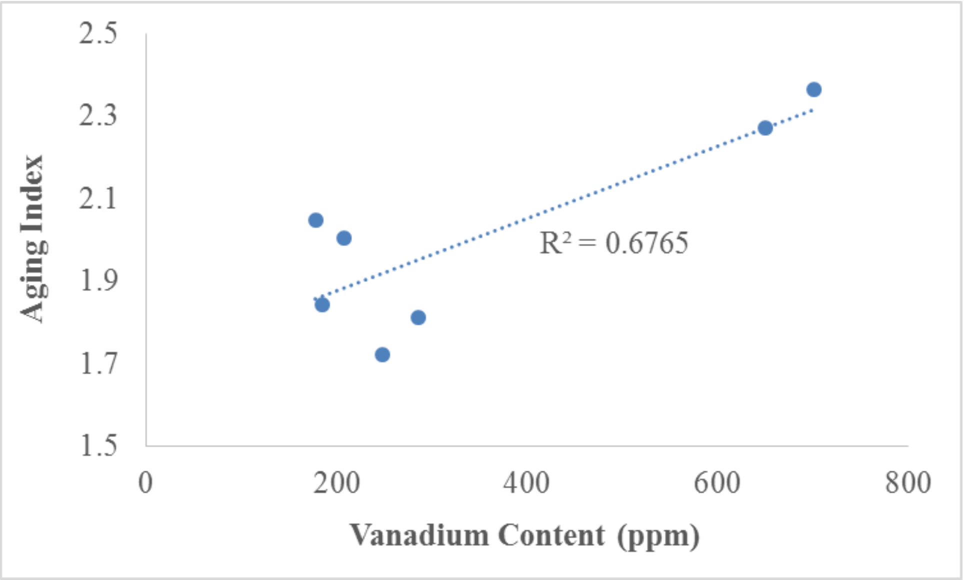
$$A.I. = \frac{\frac{G^*}{sin\delta}RTFO}{\frac{G^*}{sind\delta}OB}$$

- **Aging effect** of different recycling agents are **not the same**
- The difference in aging index for different recycling agents comes from their **different chemical components**
- Values will change if the binder is exposed to long term aging

Results

Aging Vs. Elemental Analysis





$$Aging\ Index = \frac{RTFO\ Aged\ |G*|/sin\delta}{Un-aged\ |G*|/sin\delta}$$

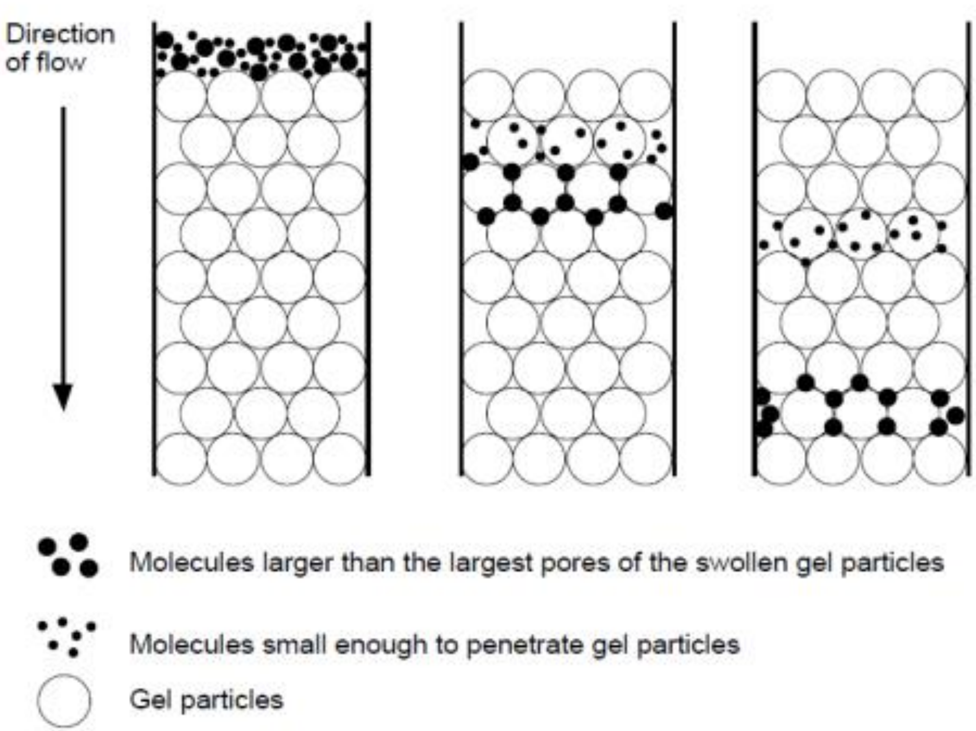
Aging Susceptibility has fair relationship to Vanadium Content

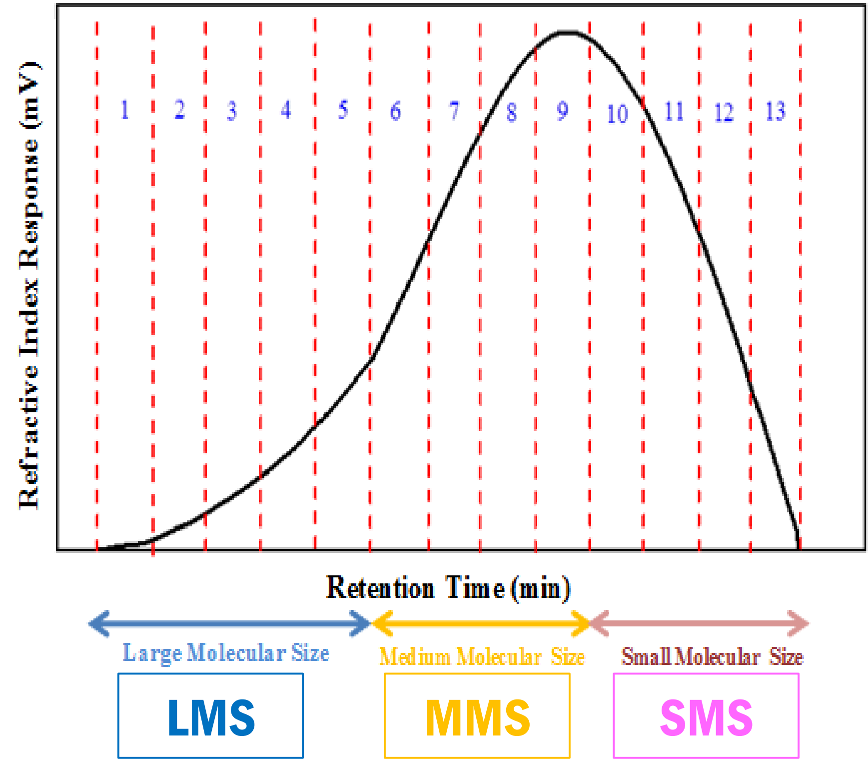
GPC Parameters

- MW: weight-average molecular weight
  - influences the bulk properties and toughness of the material
- Mn: number-average molecular weight
  - influences the thermodynamic properties of the molecule
- Mz: z-average molecular weight
- Mp: peak molecular weight

Gel Permeation Chromatograph (GPC)

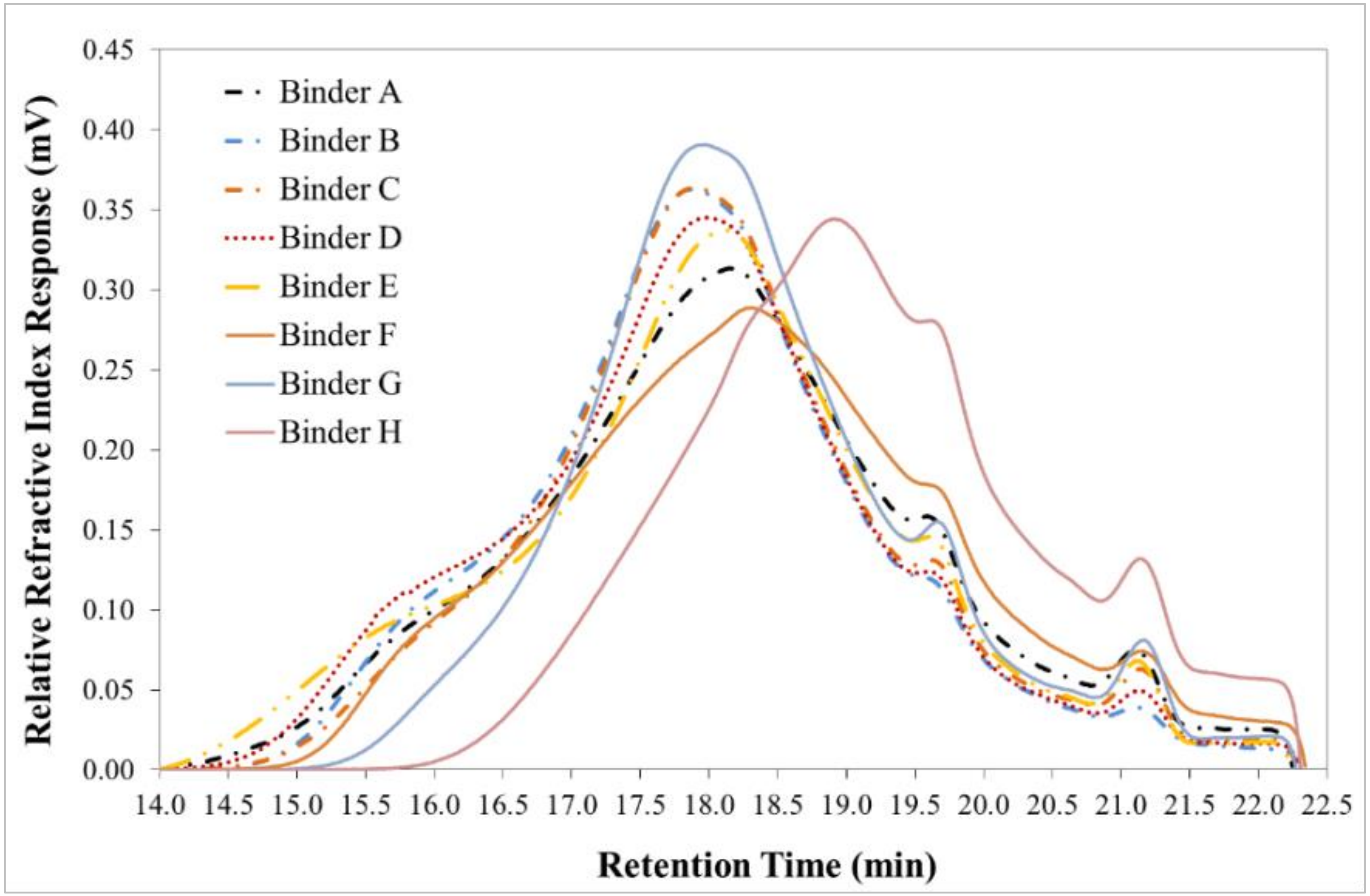
- **Simple separation technique available that responds to molecular size alone and not to chemical structure.**
  - **Analogous to a type of sieve analysis of sample.**





GPC spectrum divided into 13 equal elution time areas.

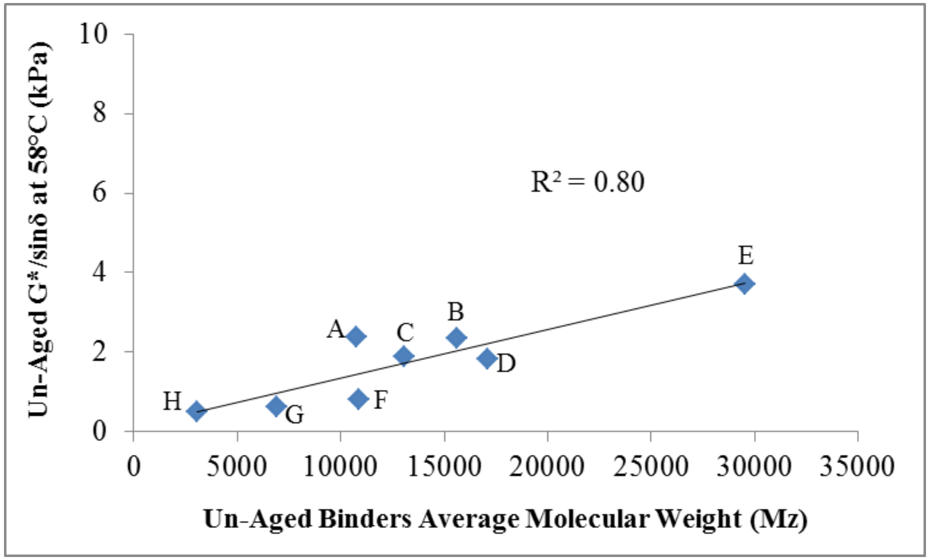
Results
GPC Results

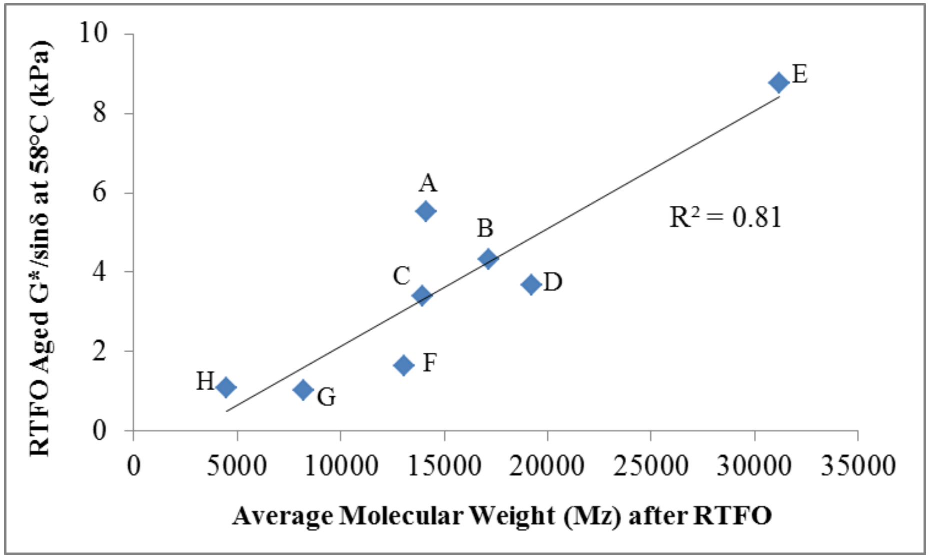


Different patterns of chromatograms and GPC clearly distinct the different molecular size distribution of different binders

Results

Rheological Vs. Chemical Properties-High Temp.

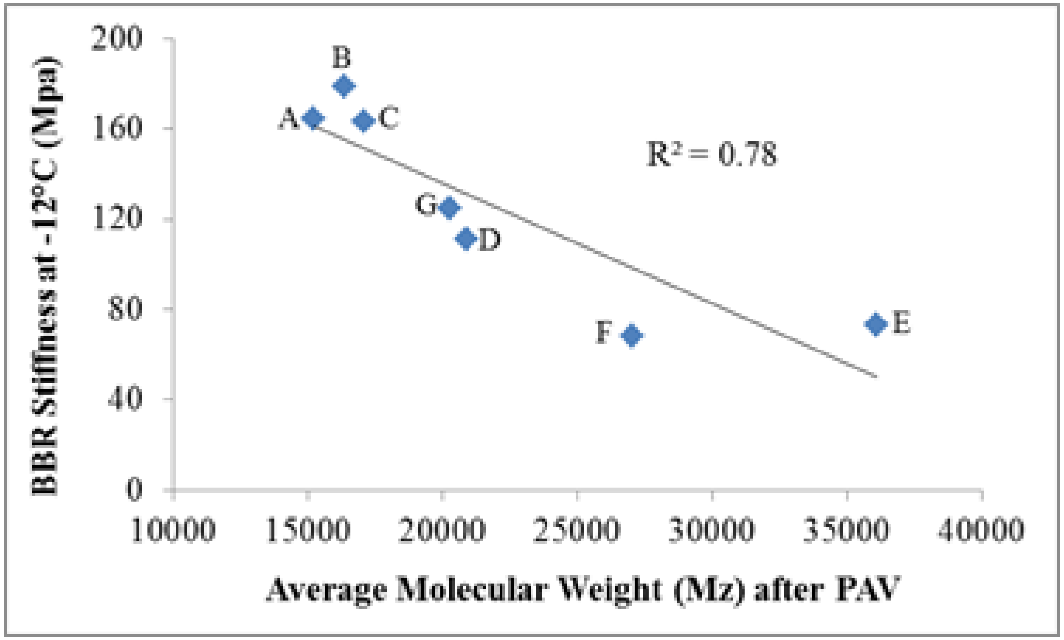




Increase in larger molecules portion of the binder

More asphaltene and higher stiffness at higher temperatures

Results
Rheological Vs. Chemical Properties-Low Temp.



- Relationship between the binder stiffness measured during BBR and the average molecular weight (Mz) in binders
- Decrease Mz corresponds to increments in lighter molecular weight components of the binders

More presence of lighter molecule sizes

Part of maltenes reach their glass transition region at higher temperatures

More brittle behavior

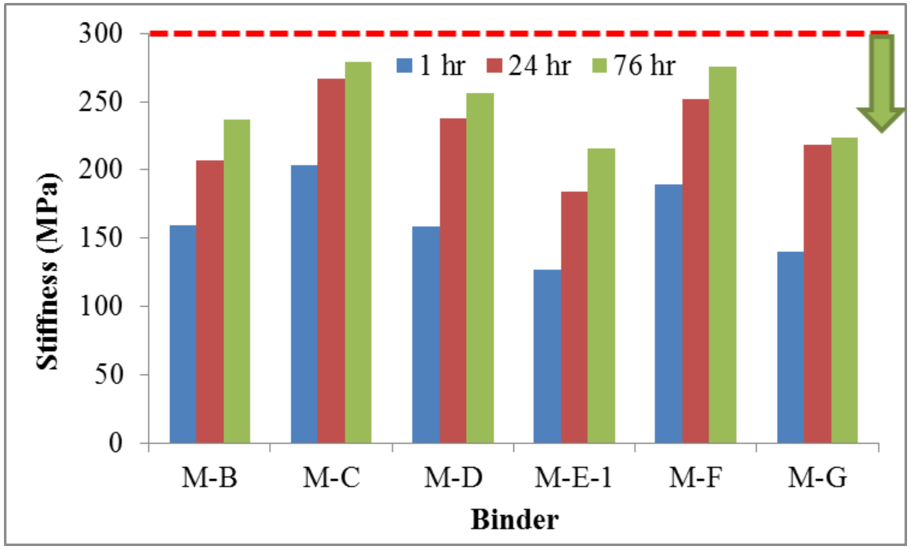
Results
Extended BBR

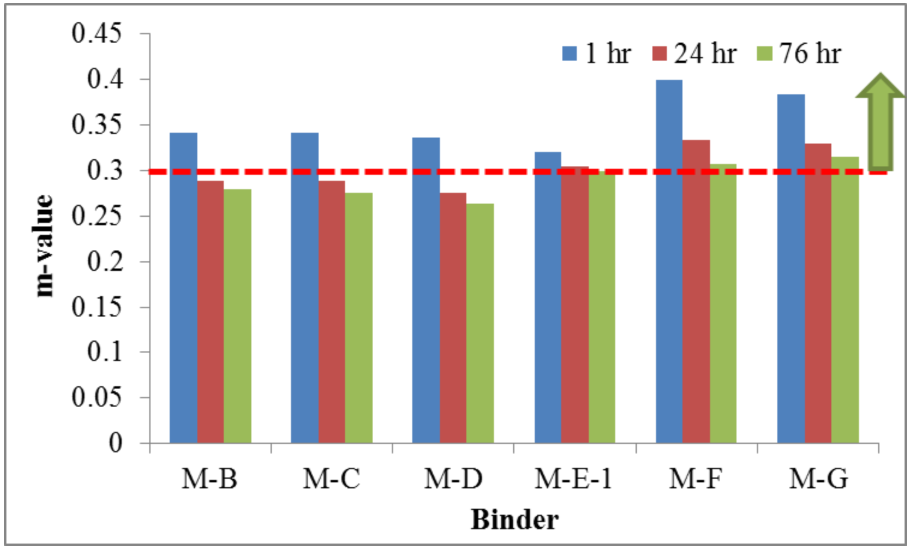
- Samples were conditioned at their LT+10°C for 72 hours
- BBR testing after 24 hr and 72 hr
- Binders tested in 3 categories based on LT grade:

-12°C	-18°C		-24°C	
• A	• D	• G	• M-B	• M-E-2
• B	• E	• M-A	• M-C	• M-F
• C	• F		• M-D	• M-G

Results

Extended BBR Results @ -24°C





- Overall performance improvement (less hardening susceptibility) by using modifications
- Higher polymer content showed to be more effective (M-F & M-G)