November 28th, 2017

BACK TO BASICS: ASPHALT BINDER

Wisconsin Asphalt Pavement Association
2017 Annual Meeting

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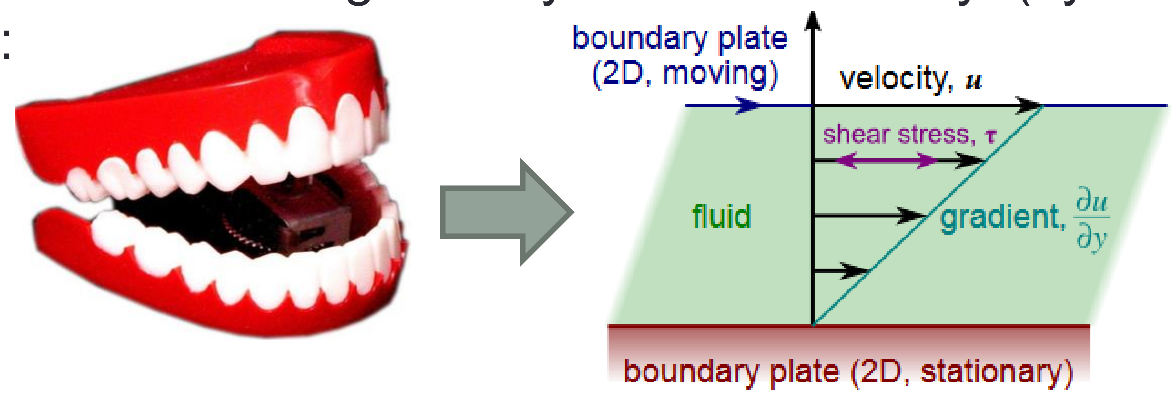
"What is Quality Asphalt?":*

From Chewing to Fourier Transform Infrared Spectroscopy

- 1893, "Report on Asphaltum", Pavement life depends on:
  - The amount of traffic
  - The skill with which pavement is laid
  - The **materials** of which it is constructed
- Earliest asphalts (before ~1900) were natural deposits cut with petroleum flux
  - Practitioners knew that heating stability and "consistency" (by chewing) were important:

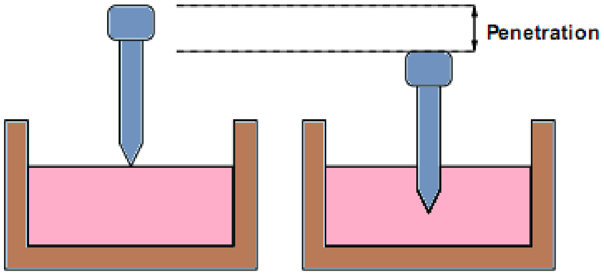


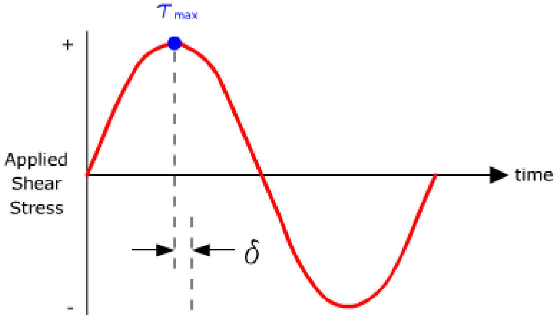
- So, *why* do we need a DSR that costs more than a new car?

*From: Welborn, J.Y. "What is Quality Asphalt" 1961

Just what is asphalt?

- It's <u>complicated</u>.
  - Co-product of refinery operations:
    - Crude source (naturally occurring material)
    - Distillation (refinery) practices, advances
    - Many thousands of molecular species (Structure vs. Interaction)
    - Now additives…polymers, oils, acids,….
  - *The overall chemical structure and interaction control material response.*
- Is it practical (or possible) to specify asphalt by chemistry?
- Two "philosophies" to specify engineering materials:
  - Practical/Empirical ← Index, Observation
  - Fundamental/Rheological ← Eng. Principles (modulus), Direct Measure





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Walk before you run…

- Things we know about asphalt:
  - Asphalt is ‘visco-elastic’ (actually all materials are to some degree)
    - Some important phenomena associated with viscoelastic materials:
      - Materials exhibit CREEP response
      - Materials exhibit stress RELAXATION
      - Materials show loading RATE dependency
      - Materials exhibit HYSTERESIS (energy loss) under cyclic loading
  - Material response is (extremely) temperature sensitive within the expected range of service temperatures:
    - Stiffness: 6-7 orders of magnitude
    - Elasticity: Nearly viscous to nearly elastic

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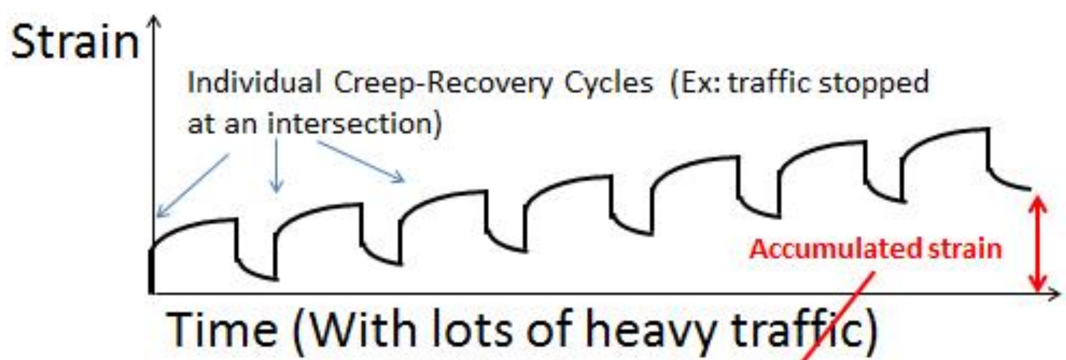
A quick applied engineering example:

Consider a bus stop where one bus after another pulls up, stops to unload passengers, then drives away, over and over for many thousands of stops.



"Rutting"

This is the same phenomenon we observe in parking lots, intersections, and even on the interstate. The only thing different in these examples is the magnitude and rate of loading.

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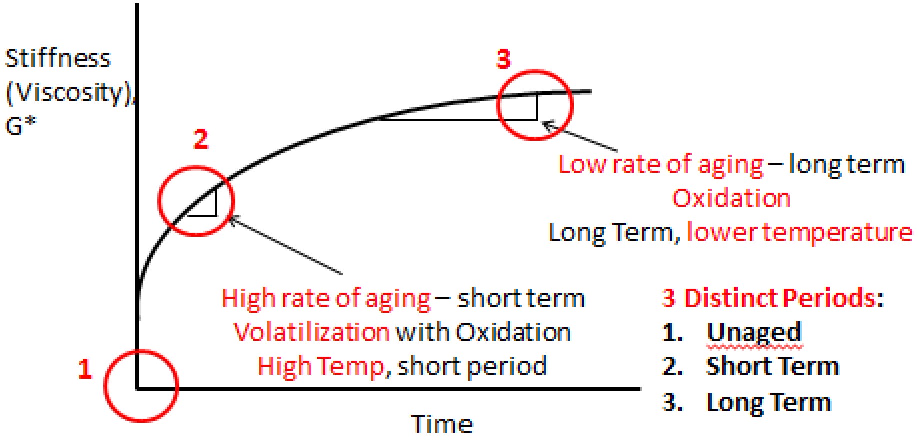
Wait, there's more: **Aging**

- Components within asphalt binder will react with air (oxygen), thereby changing either (or both):
  - Chemical Structure
  - Chemical Interaction

Remember, if you change one or both of these, you change the performance.

- This process (both rate and extent) is dependent on:
  - Asphalt Source,
  - Additives,
  - Aggregate source and size,
  - Temperature, plant & ambient,
  - Pavement Density, and
  - ….**Time**

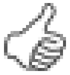
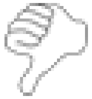
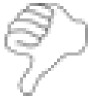


- We usually break aging into three
  1. Unaged: This is asphalt before it has been mixed with aggregate.
  2. Short Term: Aging that happens at high temperature, thin films at the plant.
  3. Long Term: Aging that happens at ambient temperature over time in the field.

Ramifications of aging

In general, the following are true with increased asphalt binder oxidation ('aging'):

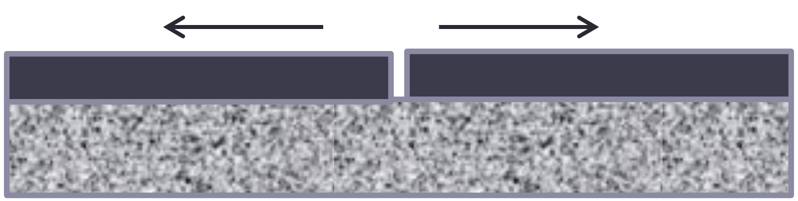
- Binder becomes stiffer (higher modulus)
  - Advantages / Disadvantages?
- Ability to relax stresses decreases
  - Advantages / Disadvantages?
- Binder becomes more "brittle"
  - Advantages / Disadvantages?

Service temperature range	General Impact of Aging on Performance	
High (Summer)		Unaged/S.T. Aged
Intermediate (F/S)		L.T. Aged
Low (winter)		L.T. Aged

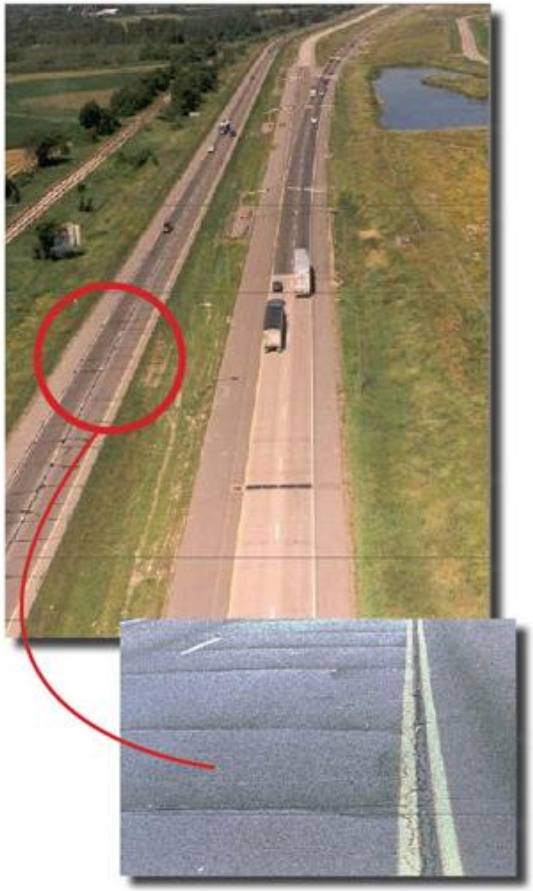
A quick applied engineering example:

Low temperature thermal cracking doesn't usually appear in asphalt pavements until several years after placement. Why is this true?

ΔT = Shrinkage (strain) = Stress Buildup



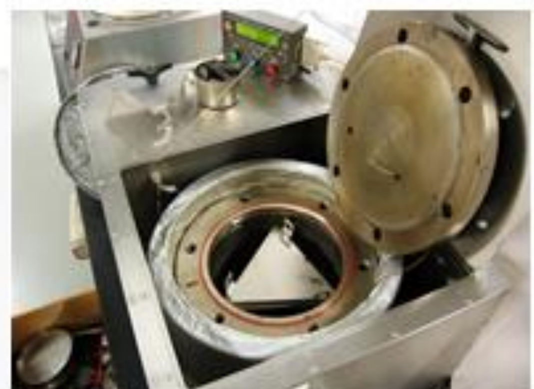
Ability to relax stresses decreases



Sidebar: We don't have all week!

- Short-term – Rolling thin film oven to simulate production/placement

- Long-term – Pressure Aging Vessel to simulate long term oxidation



- ***Is 20 hrs. in the PAV enough?***

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Let’s build a specification:

Thermal Cracking	*Fatigue Cracking*	*Rutting*	*Production*




Pavement Temperature, °C

Low Temp.	Intermediate Temp.	High Temp.	Production

Aging Condition

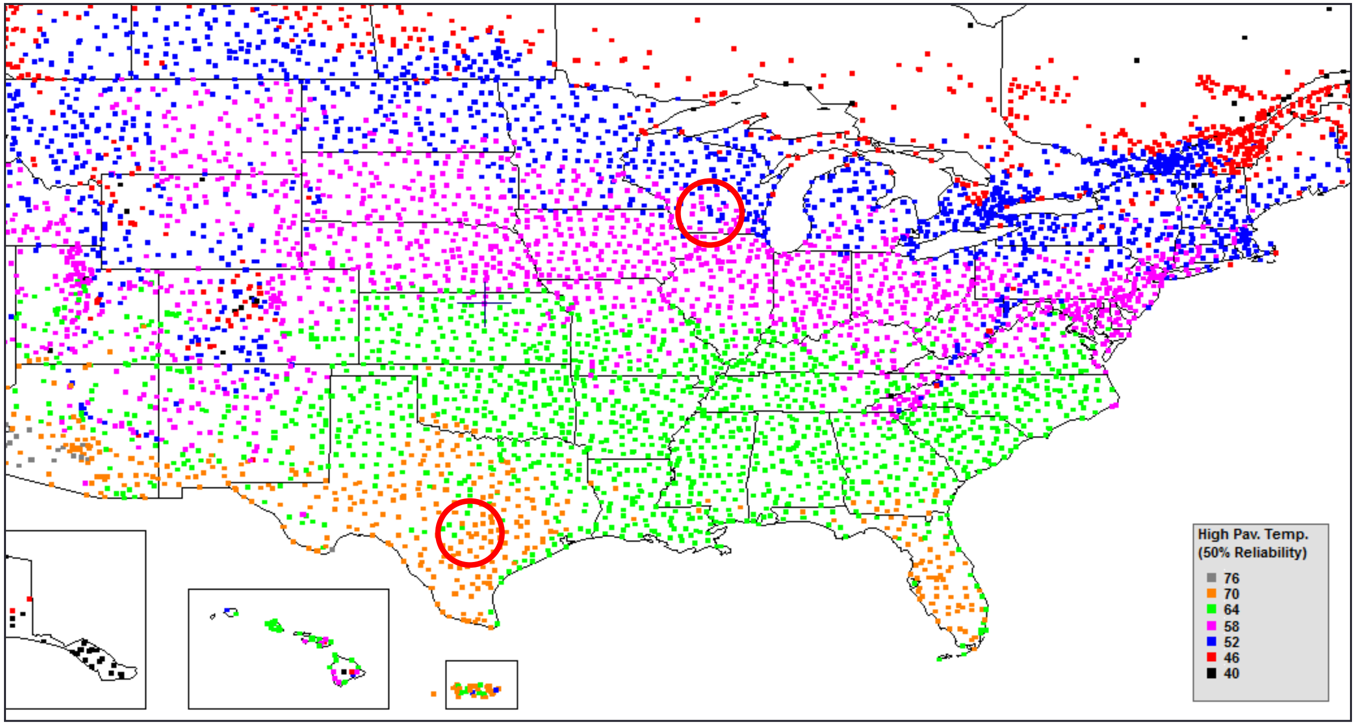
Long Term	Short Term	Unaged

Response

Low Temp.	Intermediate Temp.	High Temp.	Production
Creep Stiffness Stress Relaxation Rate	Dynamic Shear Modulus Elastic Response	Dynamic Shear Modulus Elastic Response Creep Compliance Strain Recovery	Viscosity

Badgers vs. Longhorns

- Traffic loads/frequencies/etc. are DESIGN inputs, and do not intrinsically depend on region.
  - Fundamental Concept: Limiting Criteria are the same in every location, the temperature at which the asphalt passes/fails the criteria is based on region:

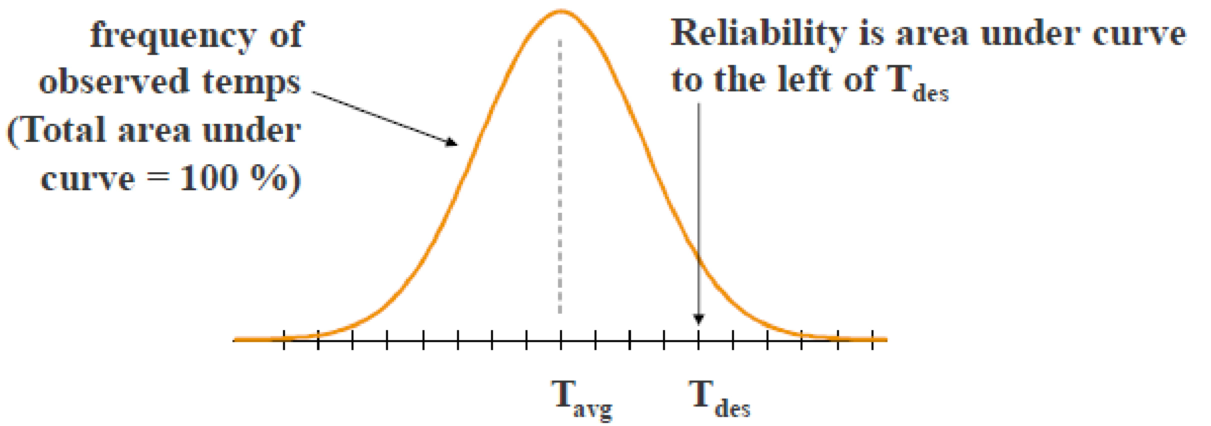


LTPPBind Weather Stations

Global Warming?

- Weather stations stationed throughout US:
  - We measure AIR temp and convert to pavement temp.
  - Collect data over many years and conduct reliability analysis based on normal distribution:

=> using Normal Distribution



- We choose the reliability that we want:
  - Higher Reliability in a Region = Higher High Temp, Lower Low Temp = Increased Cost

Superpave Performance Grading (PG), M332 Method

- Binder is assigned a “Performance Grade”:

PG HT T – LT (PG 58H-28, for example)

PG = Performance Grade

HT* = 7-day average maximum pavement temperature for which this binder is certified for use. (52, 58 typical in WI, MN), considering reliability

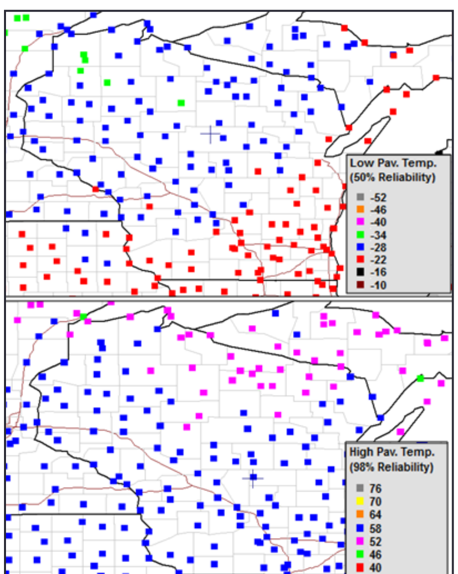
T = Traffic level designation (S, H, V, E)

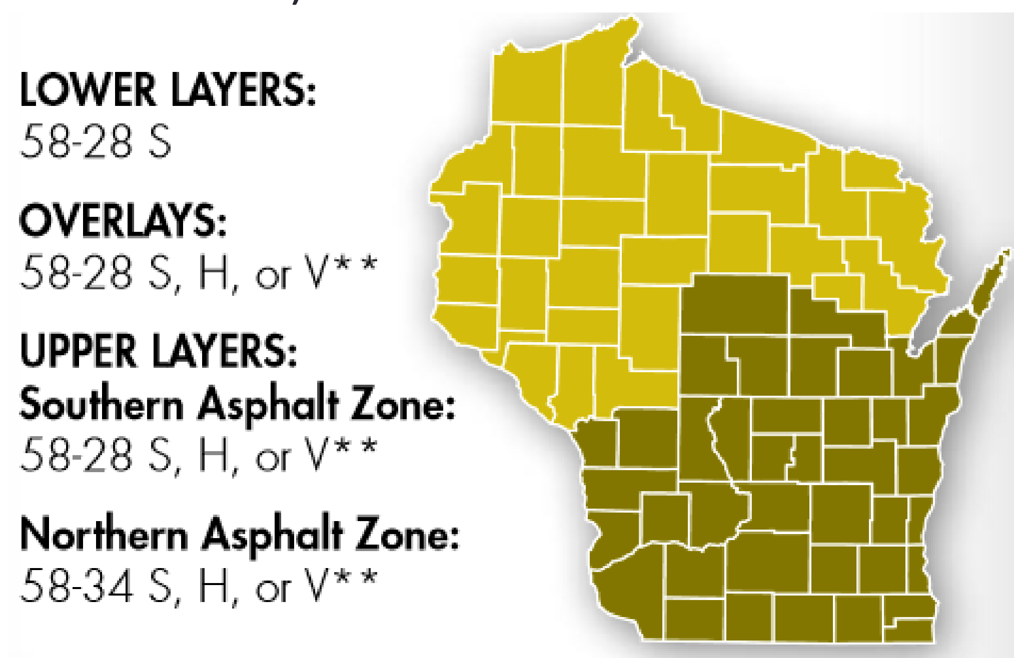
LT* = single minimum pavement temperature for which this binder is certified for use. (-28 or -34 typical for WI, MN), considering reliability

***We also use LT, MT, and HT to describe ESALs for WisDOT mix designs, but for this presentation we’re talking temperature….**

Notes on interpreting PG

- The HT number is the 7-day average maximum pavement temperature
  - Maximum because stiffness of AC ↓ with ↑ Temp
  - Average because failure at HT is cyclic and load related (non-recoverable creep) –occurs over time
- The LT number is the single minimum pavement temperature
  - Minimum because LT failure (thermal crack) is climate-related – occurs at a single event (theoretically)





M332 Specification: CSBG Modified

Test procedure and criteria – NEVER CHANGES

Pavement temperatures – changes based on YOUR LOCAL CLIMATE and reliability

Level of aging – changes with test method

Test Temperatures

Performance Grade[a]				PG 46			PG 52							PG 58				
Average 7-day max pavement design temp, °C[b]				46			52							58				
Min pavement design temp, °C[b]	Spec Base	Spec w/Tol	Tol	-34	-40	-46	-10	-16	-22	-28	-34	-40	-46	-16	-22	-28	-34	-40
Flash Point Temp, T 48, min °C	230	221	9	230			230							230				
Viscosity, T 316:[c] max 3 Pa•s test temp, °C	3.0	3.2	7.3%	135			135							135				
Dynamic Shear, T 315:[d] G*/sinδ, min. 1.00 kPa test temp @ 10 rad/s, °C	1.00	0.93	7%	46			52							58				
				Rolling Thin Film Oven (T 240)														
Mass change, max, percent[f]				1.00														
				MSCR, T 350: (Test Temperature °C)														
Standard Traffic "S" Jnr@3.2 kPa, max 4.5 kPa[-1] Jnrdiff, max 75%	4.5	5.49	22%	46			52							58				
Heavy Traffic "H" Jnr@3.2 kPa, max 2.0 kPa[-1] Jnrdiff, max 75%	2.0	2.44	22%	46			52							58				
Very Heavy Traffic "V" Jnr@3.2 kPa, max 1.0 kPa[-1] Jnrdiff, max 75%	1.0	1.39	39%	46			52							58				
Extremely Heavy Traffic "E" Jnr@3.2 kPa, max 0.5 kPa[-1] Jnrdiff, max 75%	0.5	0.695	39%	46			52							58				
% Recov. @3.2 kPa (Min). Heavy Traffic "H"	30	24.6	18%	46			52							58				
% Recov. @3.2 kPa (Min). Vary Heavy Traffic "V"	55	45.1	18%	46			52							58				
% Recov. @3.2 kPa (Min). Extremely Heavy Traffic "E"	75	61.5	18%	46			52							58				
				Pressure Aging Vessel Residue (R 28)														
PAV Aging Temp[g], °C				90			90							100				
Dynamic Shear, T 315: "S" G*(sinδ), max. 5000 kPa[e] test temp @ 10 rad/s, °C	5000	5600	12%	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Dynamic Shear, T 315: "H," "V," "E" G*(sinδ), max. 6000 kPa[e] test temp @ 10 rad/s, °C	6000	6720	12%	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Creep stiffness, T 313:h S, max. 300 MPa	300	324	8%	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30
m-value, min 0.300	0.300	0.285	5%															

In-Service Temperature Ranges

- Storage and Mixing – very high temperature:
  - Flash Point: Safety
  - Focus on viscosity at 135 °C (275 °F)
    - Caution with PMA – use suppler recommendations or experience.
  - Test using a Rotational Viscometer, "RV"
    - RV measures the torque required to rotate a spindle in asphalt at 'typical' storage temperatures – torque converted to viscosity

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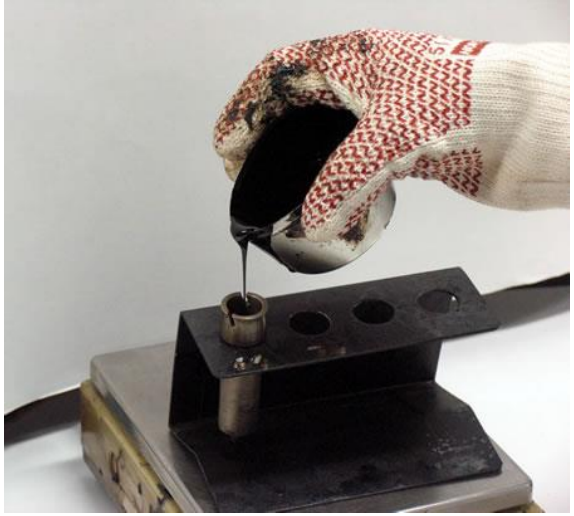
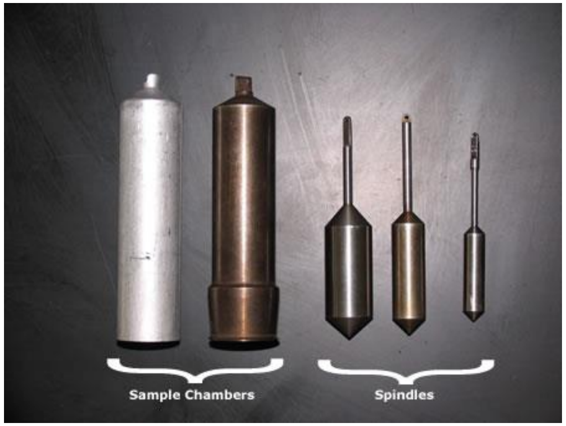
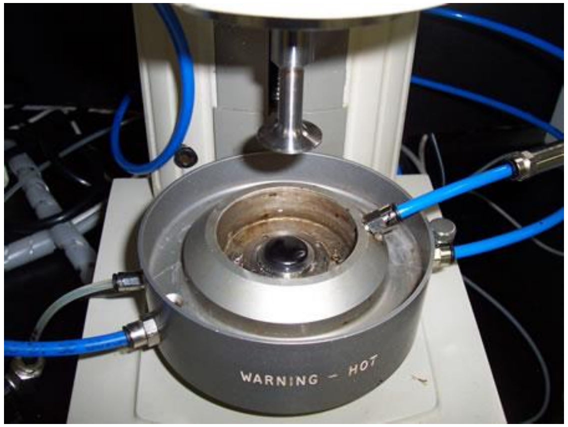
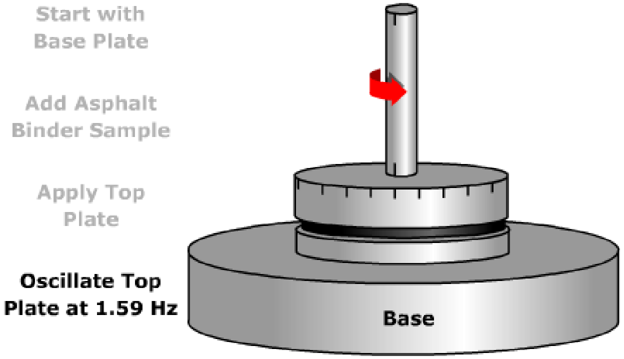




In-Service Temperature Ranges

- High service pave. temperatures (summer)
  - 2 test parameters:
  - Stiffness (G*) and elasticity (δ) – WHY?
  - Permanent def. resistance – WHY?
    - Failure at high temperature permanent deformation – repeated (cyclic) loading over time
  - Test using a Dynamic Shear Rheometer "DSR"





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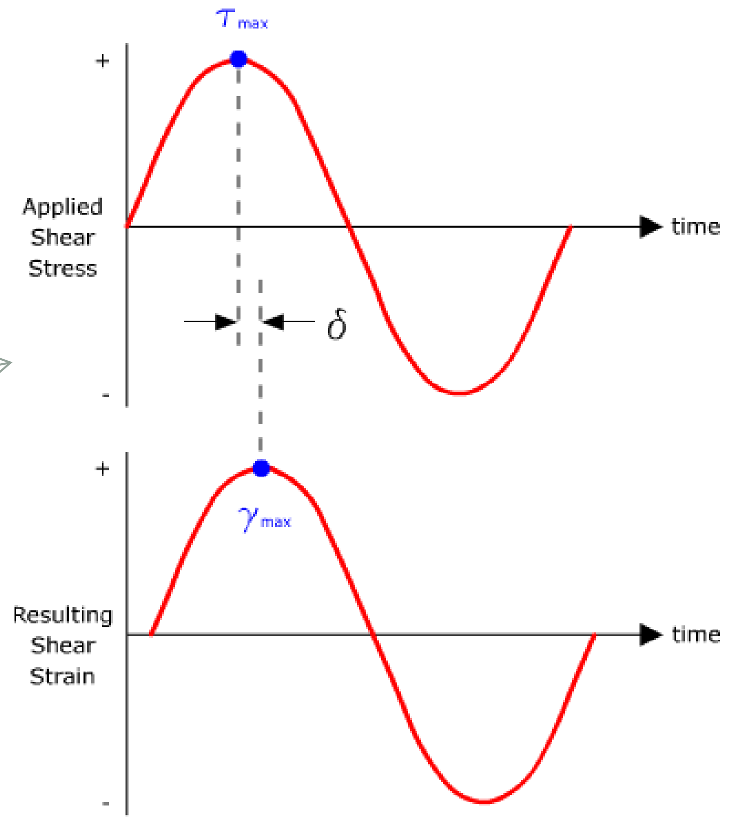
G* and δ paramters

- We apply a cyclic load at a given frequency (to simulate traffic) and given Temp.
  - Output is shear stress and shear strain
    - We know the geometry, so we can calculate **shear modulus, G***
  - Since AC is viscoelastic, there is a time lag between stress and strain – we call that 'δ'
    - Delta is an indicator of the viscous nature of the AC
    - A δ of zero (in phase) is perfectly elastic
    - A δ of 90° (completely out of phase) is perfectly viscous

Therefore: $0° \leq \delta \leq 90°$



The parameter is G*/sin(δ) is a representation of energy dissipation through stress controlled deformation (rutting); a higher G*/sin(δ) lowers the dissipated energy (a good thing)

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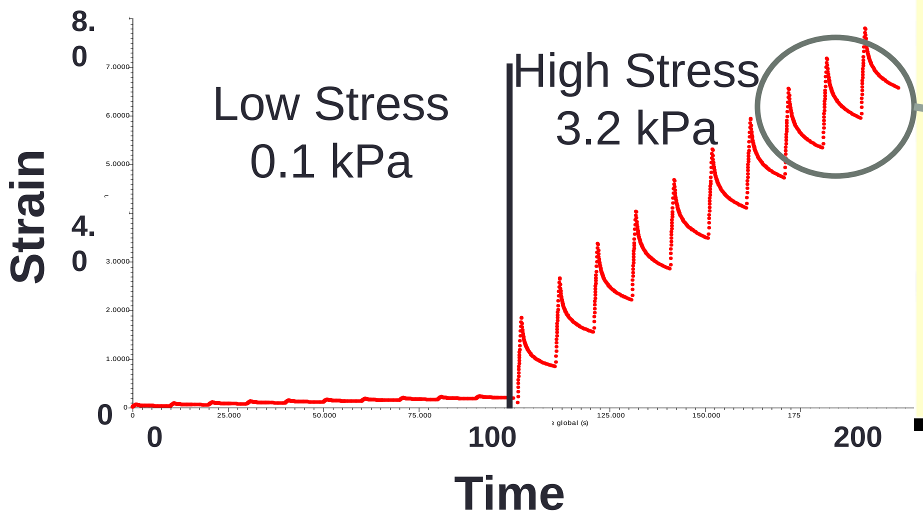
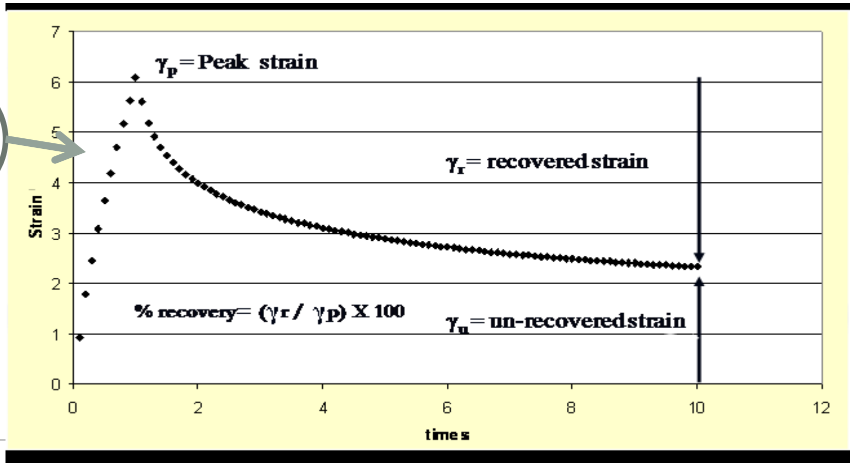
MSCR Testing

- MSCR = Multiple Stress Creep and Recovery
  - Apply several cycles of creep stress and monitor non-recoverable deformation and elastic recovery
  - 2 stress levels used to quantify sensitivity to stress





$$Non-recoverable\ Creep\ Compliance\ (J_{nr}) = \frac{Unrecoverable\ strain\ at\ end\ of\ test}{Applied\ Stress}$$

$$\%Recovery = \frac{Recovered\ strain\ at\ end\ of\ test}{Peak\ Strain}$$

M320 Grade Bumping vs. M332 Traffic Grade

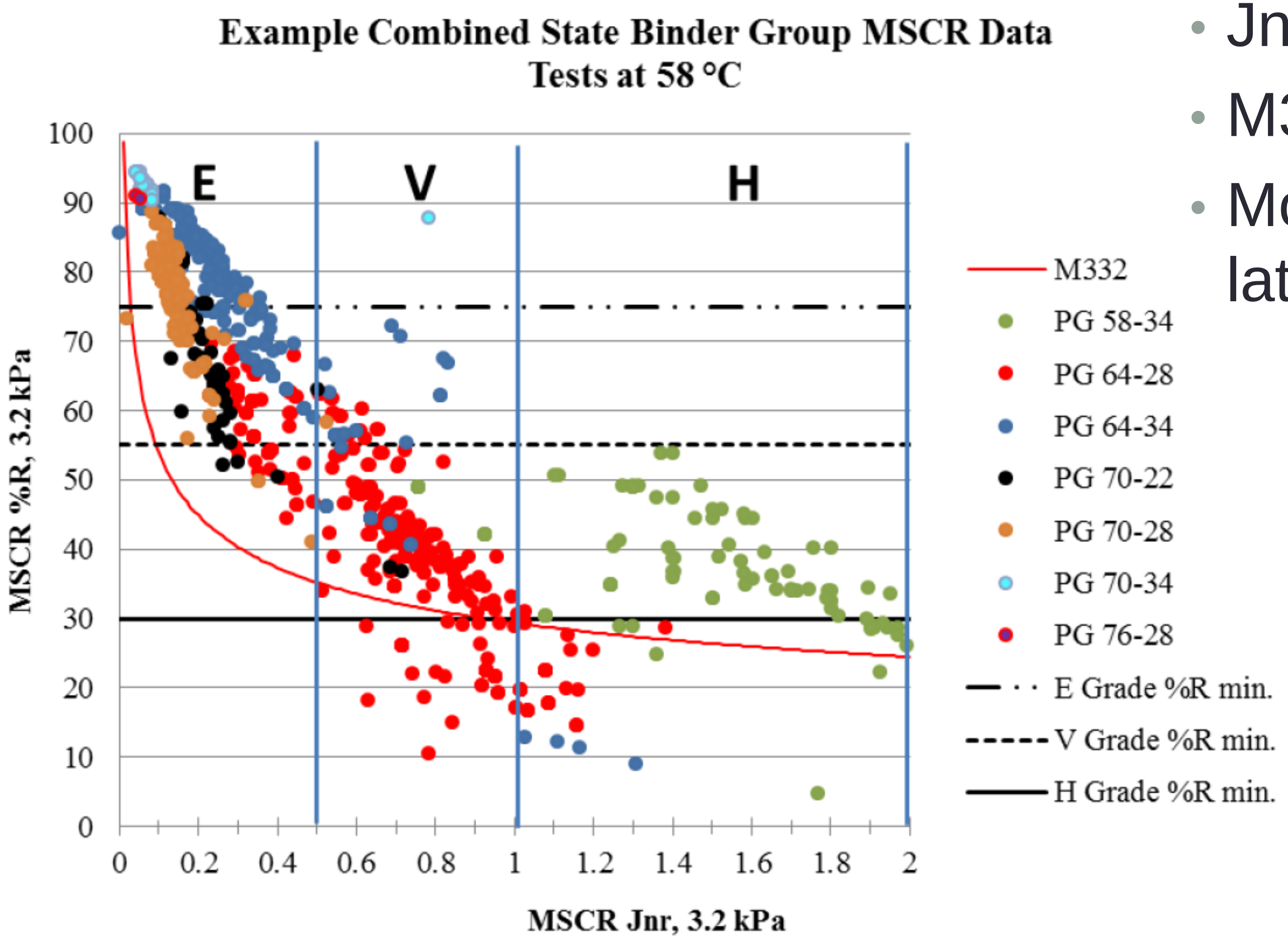
- Grade bumping was (and is) used to account for slow traffic speeds (recall loading rate dependency) and volume:

Traffic Volume ESALs	*Traffic Speed*		
	Standing	Slow	Standard
<0.3	**PG 76-22**	PG 64-22	PG 64-22
0.3 to < 3	**PG 76-22**	**PG70–22**	PG 64-22
3 to <10	**PG 76-22**	**PG70–22**	PG 64-22
10 to < 30	**PG 82-22**	**PG 76-22**	**PG 70-22**
> 30	**PG 82-22**	**PG 76-22**	**PG 70-22**

- "Rule of 90": if the HT+LT is > 90, some form of binder modification is "usually" required.
  - This, in part, gave rise to the "P" grades and the various "PG+" tests (T301 ER, Ductility, etc.)

Interpretation of MSCR

- Remember, we now test ALL binder in Wisconsin at 58 °C for the MSCR. What does this look like:



- Jnr vs. %R
- M320 vs. M332
- More on this later.

Data adapted from: A. Hanz, MSCR Implementation and Impacts on Asphalt Binder Grading, Minneapolis, Minnesota, 2015.

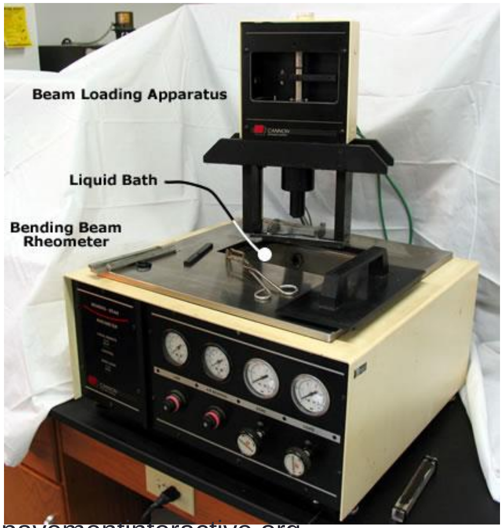
In-Service Temperature Ranges

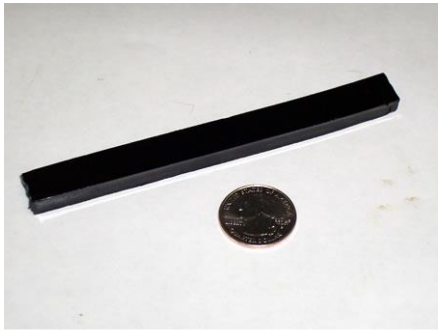
- Intermediate Service Temperature (spring/fall)
  - We again focus on stiffness (G*) and elasticity (δ), but for different reasons:
  - Failure at intermediate temps is by fatigue, which is strain controlled (for thin pavement):
    - A lower stiffness is preferred - less stress per unit strain
    - More elasticity is preferred – no hysteresis (no work done)
  - Test using a DSR (like HT), but at intermediate temperatures and using a slightly different geometry.

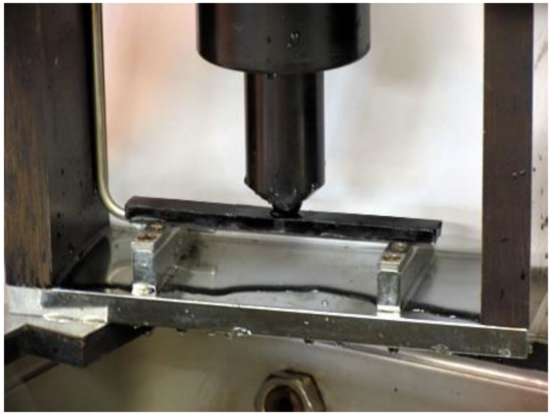
The parameter is G*sin(δ) is a representation of energy dissipation through strain controlled cracking; a lower G*sin(δ) lowers the dissipated energy (a good thing).

In-Service Temperature Ranges

- Low Service Temperatures (Winter):
  - We focus on creep stiffness and stress relaxation
  - Failure is climate-related, NOT load related
  - We want a material that is:
    - Low stiffness – less stress per unit strain (as material inevitably shrinks in cold weather)
    - High relaxation rate – stresses that build up are relaxed
  - Test using a Bending Beam Rheometer "BBR" – able to measure creep at sub-zero temperatures







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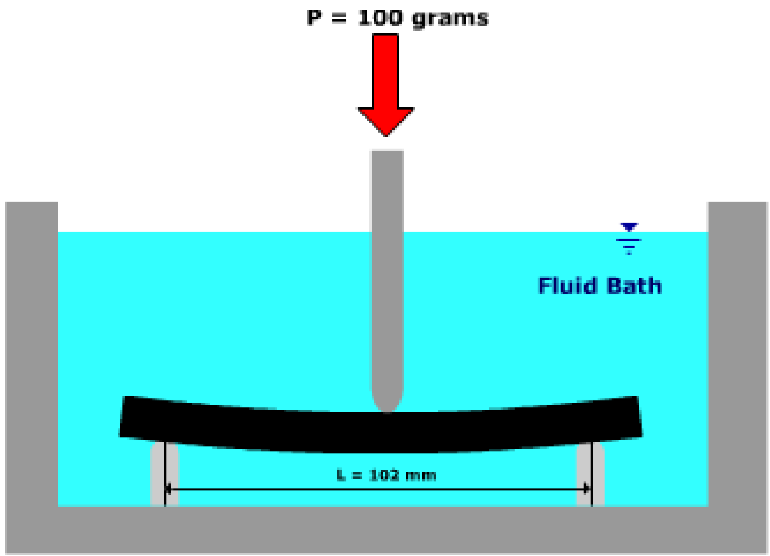
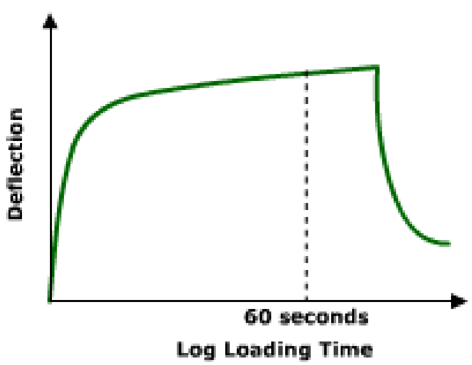
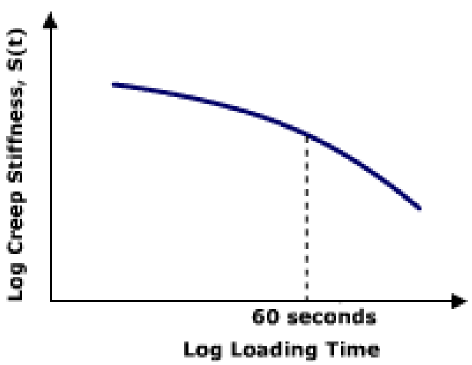
Bending Beam Rheometer



$$S(t) = \frac{PL^3}{4bh^3\delta(t)}$$

$$S(t) = A + B\log(t) + C[\log(t)]^2$$





The slope of the log stiffness-log time curve (i.e. the derivative of the above equation) is the stress-relaxation → we call it "m-value"

Parameters of interest:

Stiffness at a given time

m-value at same time

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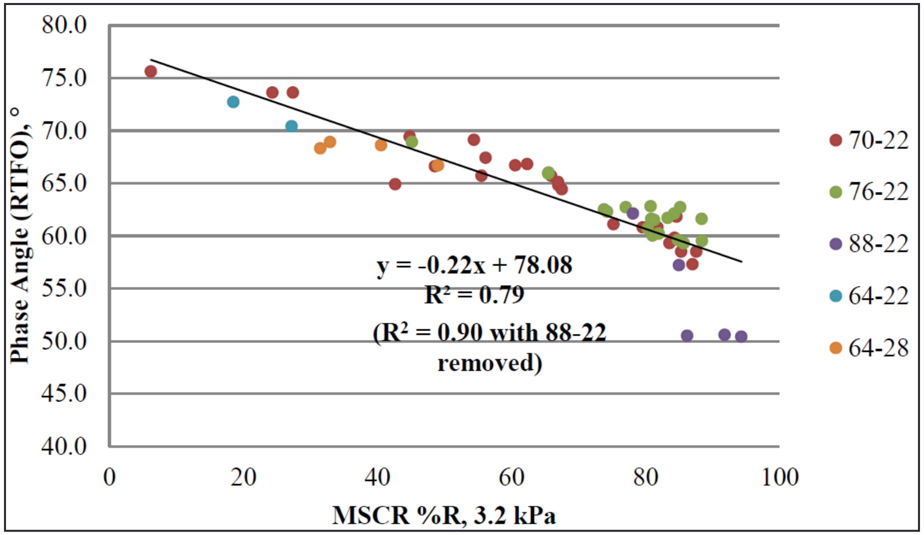
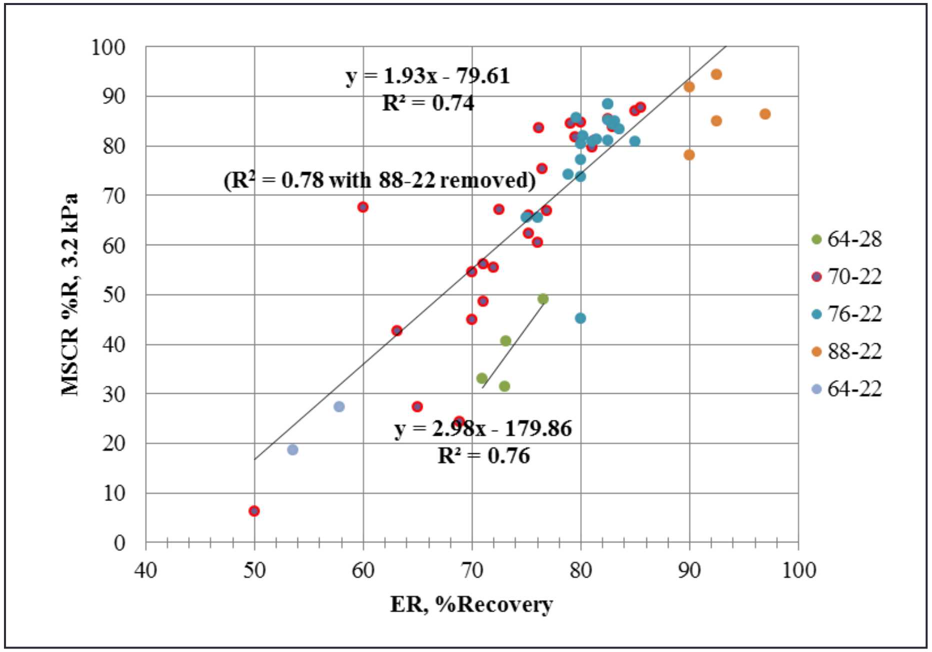
Where does my binder fit in?

- The MSCR %R is intended to replace our Phase Angle and ER requirements (PG+).
  - Are we missing something?





- Keep in mind Specification drives Formulation
  - Regional test adaptations will change the modification technology used in that region.

Data adapted from: Swiertz et al;. Implementation Considerations for the Multiple Stress Creep and Recovery Test, 2017

Where does my binder fit in?
Additives, Additives, Additives

- Dr. Rowe's presentation from WAPA 2016 is a good reference.
  - http://www.wispave.org/wp-content/uploads/dlm_uploads/i-Breakout-2016-Modification-Rowe-Abatech.pdf
- Goal: Produce a 58-34 H
- Concept:
  - Start with a base asphalt that meets the low temperature grade (52-34), OR
  - Soften an existing asphalt with "oil"; Asphalt flux is not created equal
    - Bio-Oils, etc.
    - Do you homework: check mass loss, delta Tc, extended BBR, mix design?
  - Modify High Temperature with polymers and/or acids
    - Can start with PMA concentrate and blend down as well.
    - Strategy changes based on spec: Specification drives Formulation:

MSCR %R Note: Elastomer to establish %R, Stiffening to efficiently increase %R relative to Elastomer % (See Slide 21)

What about RAP & RAS?

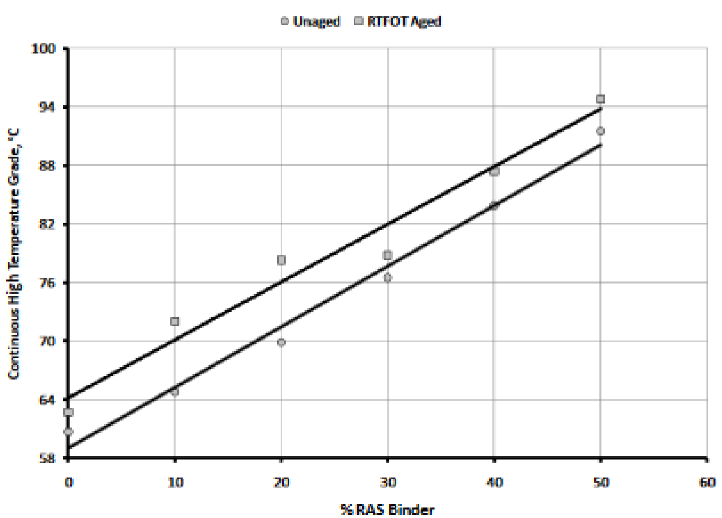
- What you put in is not (exactly) what you get out:
  - "Some" blending occurs between the recycled binder and the added binder:
    - Recycled Binder = Aged Binder; ΔTc Concept (next slide)
    - Recall what we expect as asphalt ages…

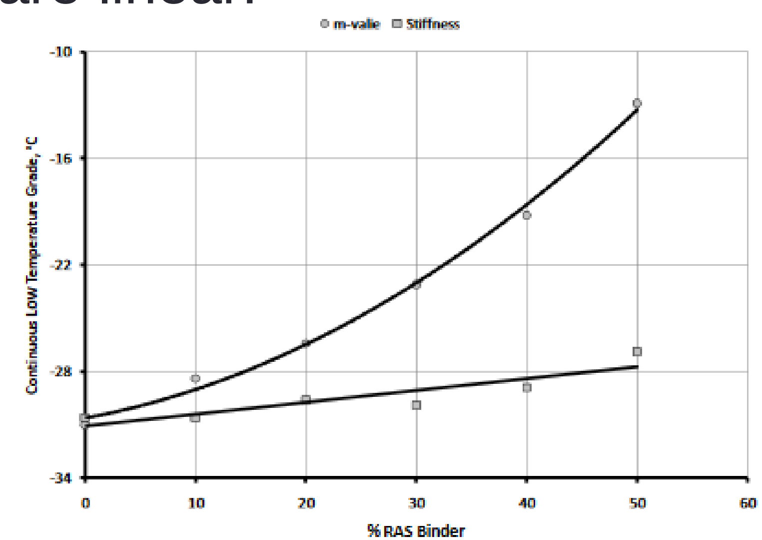
MAXIMUM ALLOWABLE PERCENT BINDER REPLACEMENT

RECYCLED ASPHALTIC MATERIAL	LOWER LAYERS	UPPER LAYER
RAS if used alone	25	20
RAP and FRAP in any combination	40	25
RAS, RAP, and FRAP in combination[1]	35	25

[1] When used in combination the RAS component cannot exceed 5 percent of the total weight of the aggregate blend.

- Keep in mind, **<u>not</u>** all relationships are linear:

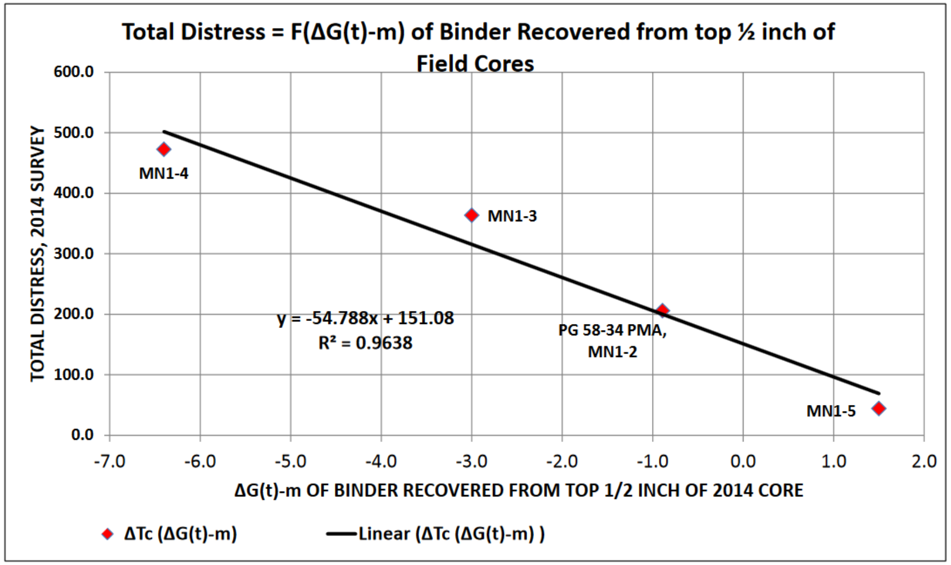




Data adapted from: Bonaquist, Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG, 2011

Things to look for…

- Binder Testing:
  - Low Temperature: ΔTc Concept
  - Intermediate Temperature: Fatigue Estimation
- Mixture Testing:
  - Binder is only a component of mixture, i.e., we should not expect to be able to fully predict performance based on binder data alone.
  - HWT: High Temperature/Moisture
  - SCB: Int. Temperature
  - DCT/SCB: Low Temperature



Data adapted from: Reinke et al. Asphalt Binder ETG, 2015

Thank You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