Impact of Recycled Asphalt Shingles (RAS), Extracted Shingle Binder & Additives on Properties of Mixtures and Recovered Binders from Those Mixtures

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MTE SERVICES, INC.

Presentation Prepared for

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NASHVILLE, TN

WHY?

1. Rising cost of liquid asphalt has motivated agencies to approve, contractors to utilize, HMA plant manufacturers to develop equipment to handle, additive suppliers to market "rejuvenators" resulting in
   - Increasing the amount of RAP and RAS materials in paving mixes
2. Previous levels were pegged at 15-20% binder replacement of reclaimed binder ***(Typically RAP)***
   - This usage level generally required no change to the PG grade of the binder used in the mix

WHY?

3. Some entities (contractors, additive vendors, state DOT's) are advocating that 50% or more binder replacement can be used of which a significant amount (20-25%) can be RAS binder
   - Softening of binder grade is recommended
     - Through reduction in PG grade or use of additives
   - Marketing rejuvenators to handle these increased reclaimed binder materials has grown
   - I have some reservations as to whether that will solve the problem

WHY?

- ✓ Our concerns—mainly center around RAS
  - RAS can contain upwards of 30% bitumen (20-27% more typical)
  - Material is highly oxidized
    - Poor m-values, wide variation between S & m-value
      - BUR tear off low temp grade S=-27.8, m= +11.9 (4 mm DSR)
    - Softening points 223°F to 270°F
    - High temp PG grades 118-150
    - Very flat relaxation modulus mastercurves
- ✓ Mixes made with 20% RAS binder replacement look OK initially, but based on our data reported here, fatigue and low temperature properties seem to deteriorate rapidly
- ✓ Fatigue of these mixes is a significant concern

GOALS

- INVESTIGATE IMPACT OF RAS & RAP CONTENT and MIX AGING ON PROJECTED MIX PERFORMANCE
- INVESTIGATE IMPACT OF RAS & RAP CONTENT and MIX AGING ON PROPERTIES OF BINDER
- INVESTIGATE IMPACT OF REDUCED BINDER STIFFNESS (SOFT PG GRADES) AND DIFFERING CHEMISTRY ADDITIVES ON PERFORMANCE OF RAS & RAP CONTAINING MIXES AT HIGH ASPHALT BINDER REPLACEMENT (ABR) LEVELS

SOME PRELIMINARY INFORMATION ON TESTS THAT ARE USED TO GENERATE DATA SHOWN IN THIS PRESENTATION

4 mm DSR BINDER TEST

- ✓ Developed by Western Research Institute.
- ✓ TRB talks in 2011 and 2012 by Sui and Farrar, et al
- ✓ AASHTO & ASTM methods under development

TORSION BAR TESTING OF MIXES for G*

- ✓ Developed at MTE, now ASTM D7522


4 mm DSR test heads. Today all major DSR manufacturers have these test fixtures available. Picture on right shows sample ready to test. Upper geometry should be lock while trimming to prevent material being pulled out from between plates.

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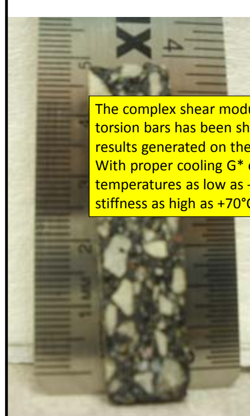
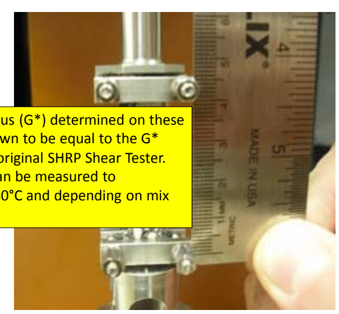

The complex shear modulus (G*) determined on these torsion bars has been shown to be equal to the G* results generated on the original SHRP Shear Tester. With proper cooling G* can be measured to temperatures as low as -40°C and depending on mix stiffness as high as +70°C

MIX TORSION BAR TEST
≈50 mm X 12 mm X 7 mm
TESTED AT -40°C TO +40-80° DEPENDING ON MIX STIFFNESS

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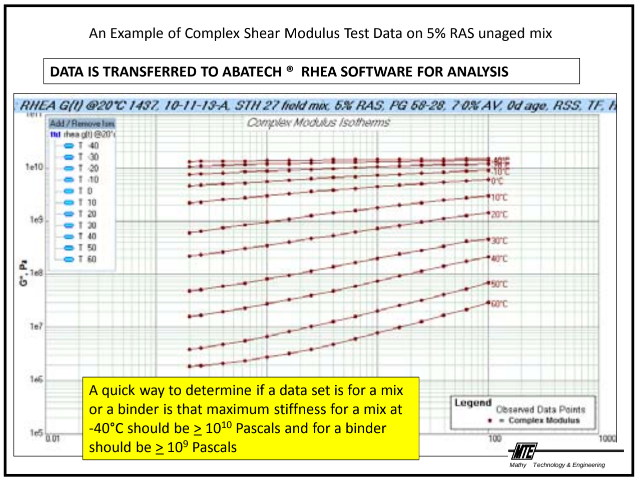
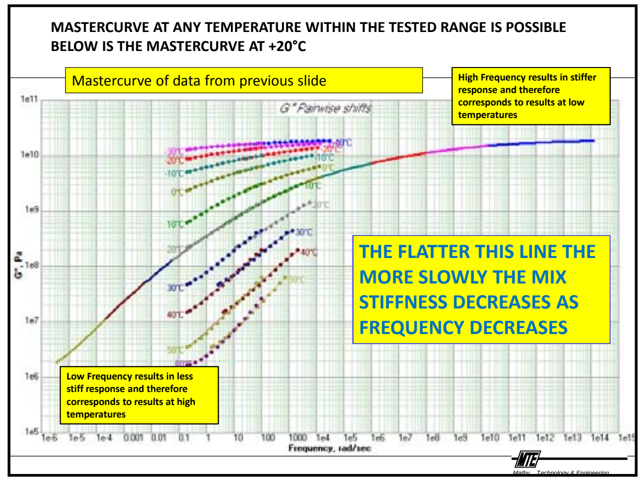
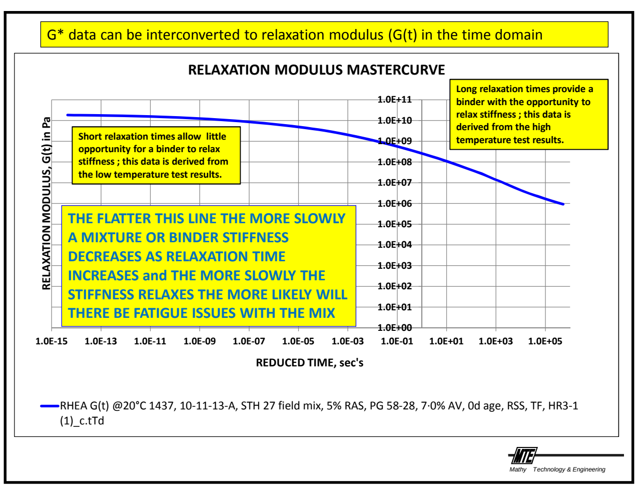
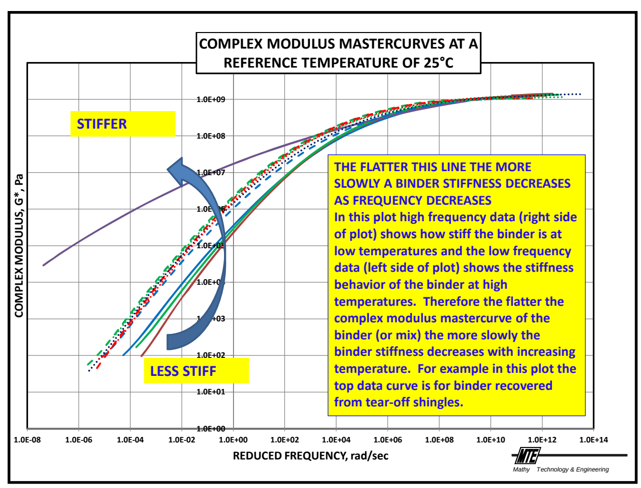
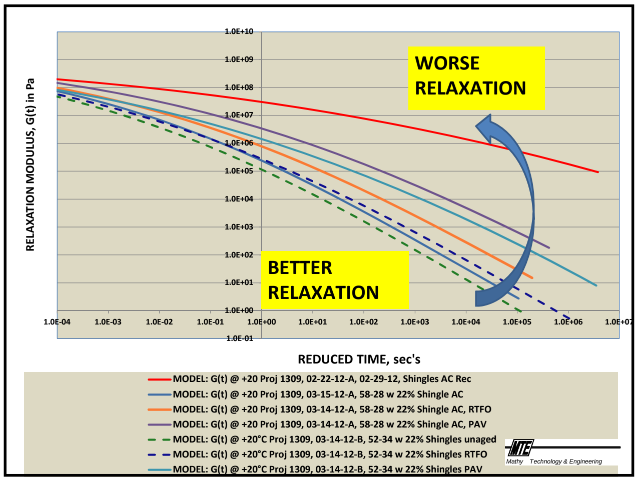

An Example of Complex Shear Modulus Test Data on 5% RAS unaged mix
DATA IS TRANSFERRED TO ABATECH ® RHEA SOFTWARE FOR ANALYSIS
RHEA G(t) @20°C 1437, 10-11-13-A, STH 27 field mix, 5% RAS, PG 58-28, 7.0% AV, 0d age, RSS, TF,
Complex Modulus Isotherms
G*, Pa
Legend
Observed Data Points
Complex Modulus
A quick way to determine if a data set is for a mix or a binder is that maximum stiffness for a mix at -40°C should be ≥ 10^10 Pascals and for a binder should be ≥ 10^9 Pascals

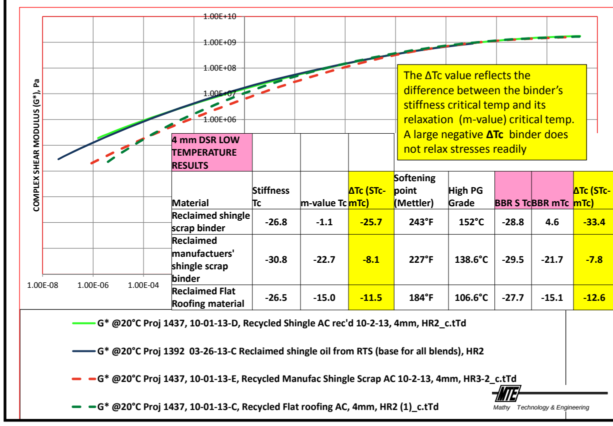

MASTERCURVE AT ANY TEMPERATURE WITHIN THE TESTED RANGE IS POSSIBLE
BELOW IS THE MASTERCURVE AT +20°C
Mastercurve of data from previous slide
High Frequency results in stiffer response and therefore corresponds to results at low temperatures
G* Pairwise shifts
THE FLATTER THIS LINE THE MORE SLOWLY THE MIX STIFFNESS DECREASES AS FREQUENCY DECREASES
Low Frequency results in less stiff response and therefore corresponds to results at high temperatures
G*, Pa
Frequency, rad/sec


G* data can be interconverted to relaxation modulus (G(t) in the time domain
RELAXATION MODULUS MASTERCURVE
Long relaxation times provide a binder with the opportunity to relax stiffness ; this data is derived from the high temperature test results.
Short relaxation times allow little opportunity for a binder to relax stiffness ; this data is derived from the low temperature test results.
THE FLATTER THIS LINE THE MORE SLOWLY A MIXTURE OR BINDER STIFFNESS DECREASES AS RELAXATION TIME INCREASES and THE MORE SLOWLY THE STIFFNESS RELAXES THE MORE LIKELY WILL THERE BE FATIGUE ISSUES WITH THE MIX
RELAXATION MODULUS, G(t) in Pa
REDUCED TIME, sec's
RHEA G(t) @20°C 1437, 10-11-13-A, STH 27 field mix, 5% RAS, PG 58-28, 7.0% AV, 0d age, RSS, TF, HR3-1 (1)_c.tTd


COMPLEX MODULUS MASTERCURVES AT A REFERENCE TEMPERATURE OF 25°C
STIFFER
LESS STIFF
THE FLATTER THIS LINE THE MORE SLOWLY A BINDER STIFFNESS DECREASES AS FREQUENCY DECREASES
In this plot high frequency data (right side of plot) shows how stiff the binder is at low temperatures and the low frequency data (left side of plot) shows the stiffness behavior of the binder at high temperatures. Therefore the flatter the complex modulus mastercurve of the binder (or mix) the more slowly the binder stiffness decreases with increasing temperature. For example in this plot the top data curve is for binder recovered from tear-off shingles.
COMPLEX MODULUS, G*, Pa
REDUCED FREQUENCY, rad/sec



DATA ON THE PROPERTIES OF THE ADDITIVES WE ARE TALKING ABOUT



4 mm DSR LOW TEMPERATURE RESULTS								
Material	Stiffness Tc	m-value Tc	ΔTc (STc-mTc)	Softening point (Mettler)	High PG Grade	BBR S Tc	BBR mTc	ΔTc (STc-mTc)
Reclaimed shingle scrap binder	-26.8	-1.1	-25.7	243°F	152°C	-28.8	4.6	-33.4
Reclaimed manufactuers' shingle scrap binder	-30.8	-22.7	-8.1	227°F	138.6°C	-29.5	-21.7	-7.8
Reclaimed Flat Roofing material	-26.5	-15.0	-11.5	184°F	106.6°C	-27.7	-15.1	-12.6

WHICH BRINGS ME TO THE QUESTION

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Do we Rejuvenate RAS?

1. Rejuvenate- to make young again; restore to youthful vigor, appearance, etc
2. To restore to a former state; make fresh or new again

OR

Do we Resuscitate It?

Resuscitate—to revive, especially from apparent death or from unconsciousness

Based on our investigations of RAS containing mixes I would say
There is no fountain of youth for aged shingle binder

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Several Studies

1. Lab study
   a) Impact of 20% RAS Binder Replacement on Short Term & 5 Day Aged Mixture Properties
   b) Evaluation of additives to improve RAS performance
      1) Initial properties and after mix aging
2. USH 14 in Winona Cty., MN mix on shoulders
   a) Four test sections place-initial testing
   b) Follow-up testing after 1 year

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Design of Experiment

1. Shingle source chosen with ≈ 250°F softening point
2. Sufficient shingle binder (SB) extracted & recovered to make test specimens for study
3. Binder replacement was chosen at 22%
4. This afforded two mixes where we knew 100% blending of shingle binder and virgin binder had taken place

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Design of Experiment

1. Mixes produced
   1) PG 58-28 virgin control
   2) **PG 58-28 + 22% recovered shingle binder**
   3) PG 58-28 + 5% RAS (=22% binder replacement from RAS)
   4) PG 58-28 + 5% RAS + 0.5% warm mix additive
   5) PG 58-28 + 5% RAS treated with 5% oil added by wt of binder in the RAS
   6) **PG 52-34 + 22% recovered shingle binder**
   7) PG 58-28 + 5% RAS (=22% binder replacement from RAS)
   8) PG 52-34 + 5% RAS treated with 5% oil added by wt of binder in the RAS
2. Mix was Wisconsin E-3 (3 million ESAL)
3. Limestone aggregate

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Design of Experiment

1. Treatment of mixes
   1) All mixes produced at 135°C (275°F)
   2) All Short term conditioned for 2 hrs at 135°C (275°F)
   3) All Compacted at 135°C (275°F)
2. One set of specimens tested at 0 day
3. One set of specimens conditioned for 5 days at 85°C

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Testing Performed

1. y in

Hamburg results not shown in this report because rutting or stripping not an issue

2. Overlay test (triplicate) conducted at 20°C both 0 day and 5 day conditioned
3. **Torsion bars tested at -40°C to +60°C** in 10°C increments from 100 to 0.5 radians/sec for complex modulus and relaxation modulus for both 0 day and 5 day conditioned
4. **Binder recovered from 0 day and 5 day** conditioned mix (only the 22% preblend), **4 mm DSR tested at -40°C to +60°C** for determination of low temp grade and relaxation modulus at +20°C

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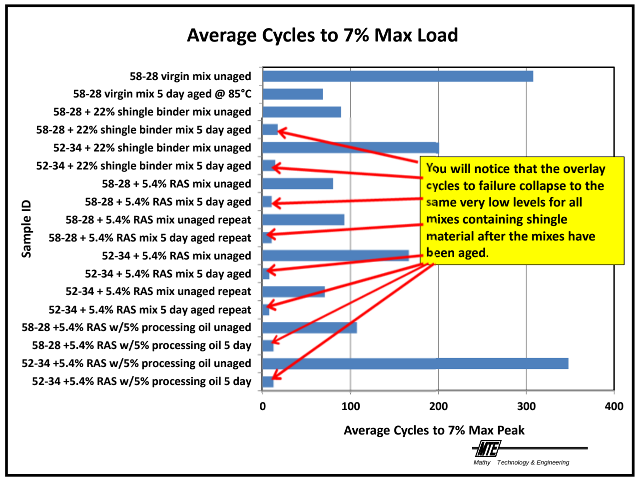

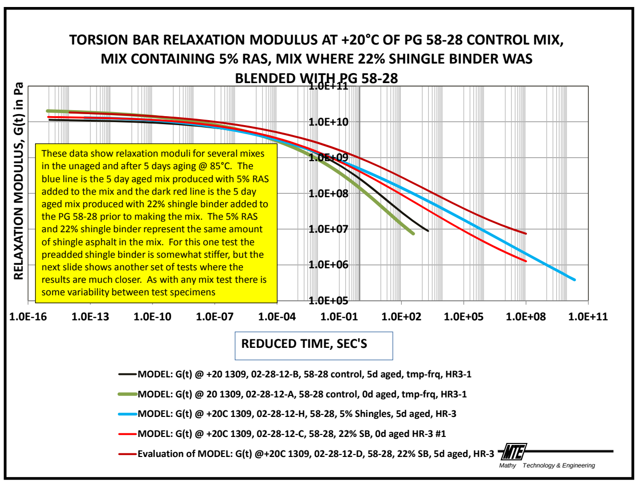

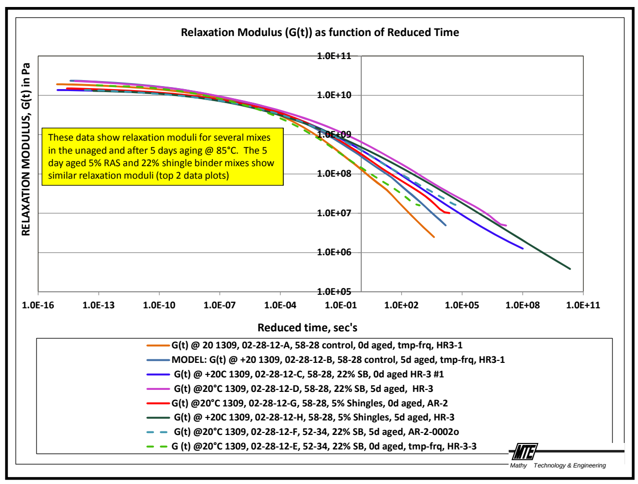

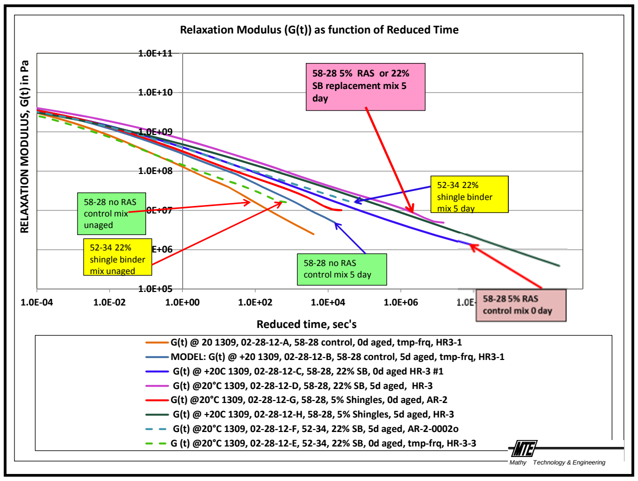

Several Studies

1. Lab study
   a) Impact of 20% RAS Binder Replacement on Short Term & 5 Day Aged Mixture Properties
   b) Evaluation of additives to improve RAS performance
      1) Initial properties and after mix aging
2. USH 14 in Winona Cty., MN mix on shoulders
   a) Four test sections place-initial testing
   b) Follow-up testing after 1 year

Several Studies-US Hwy 14

1. Field study US Hwy 14 in Winona County, MN mixes place on shoulders
   a) PG 58-28, 6% RAS (22% binder replacement) , 11% RAP (12% binder replacement)
   b) PG 52-34, 6% RAS (22% binder replacement) , 11% RAP (12% binder replacement)
   c) PG 58-28, 0% RAS, 31% RAP (32% binder replacement)
   d) PG 58-28, 0% RAS, 20% RAP (21% binder replacement-this was the original job mix

Several Studies-US Hwy 14

1. **Mix was place in September 2012**
2. FHWA trailer was on project to collect mix and obtain samples to characterize mix as placed.
3. **November 2012 three cores taken from each test section**
   a) 1 unaged core cut into **torsion bars** for mix modulus testing @ -40°C(-35°C) to +60°C
   b) After this testing binder extracted for **4 mm DSR** testing @ -40°C(-35°C) to +60°C

Several Studies—US Hwy 14

a) Additional field cores aged 5 & 10 days @ 85°C

1) Torsion bars for mix modulus testing @ -40°C(-35°C) to +60°C
2) After this testing binder extracted for 4 mm DSR testing @ -40°C(-35°C) to +60°C
3) **Iatroscan data collected on all recovered binders (asphaltenes + 3 other fractions determined)**

b) New Cores taken 1 year (2013) <u>& 2 years (Oct. 2014)</u> after placement

1) Top 12 mm and 2nd 12 mm layers of each mix were tested for
2) Mix stiffness using torsion bars
3) Recovered binder properties using 4 mm DSR

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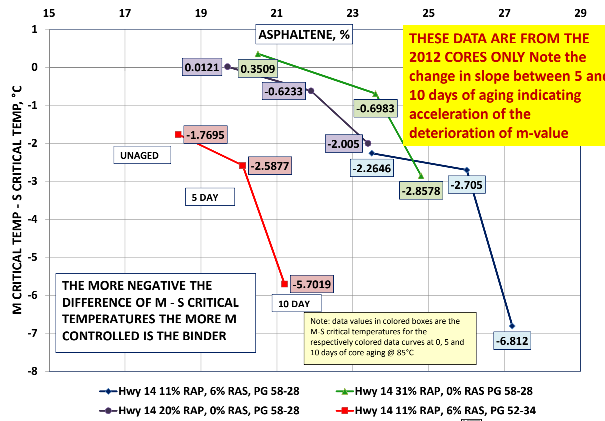

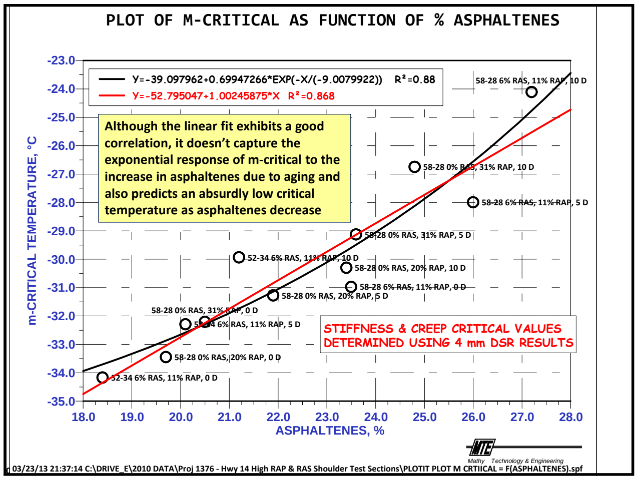

IMPACT AFTER 1 YEAR OF FIELD AGING

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Mix type	Days of 85°C core aging (or as noted in Table)	Asphaltenes	m-critical Temp, °C (mcT)	S-critical Temp, °C (ScT)	ΔTc (S-Critical - m-critical)
Sec 1 52-34	0	18.4	-34.2	-35.9	-1.8
6%RAS	5	20.1	-32.3	-34.9	-2.6
11% RAP	10	21.2	-29.9	-35.6	-5.7
Top 12 mm	11 months field	19.3	-32.9	-35.7	-2.8
2nd 12 mm	11 months field	18.6	-34.3	-35.9	-1.6
Sec 2 58-28	0	23.5	-31.0	-33.2	-2.3
6%RAS	5	26	-28.0	-30.7	-2.7
11% RAP	10	27.2	-24.1	-30.9	-6.8
Top 12 mm	11 months field	25.8	-28.2	-30.8	-2.6
2nd 12 mm	11 months field	25.1	-29.4	-31.3	-1.9
Sec 3 58-28	0	20.5	-32.2	-31.9	0.4
0%RAS	5	23.6	-29.1	-29.8	-0.7
31% RAP	10	24.8	-26.7	-29.6	-2.9
Top 12 mm	11 months field	23.2	-30.2	-31.3	-1.1
2nd 12 mm	11 months field	21.9	-31.6	-31.4	+0.2
Sec 4 58-28	0	19.7	-33.4	-33.4	0.0
0%RAS	5	21.9	-31.3	-31.9	-0.6
21% RAP	10	23.4	-30.3	-32.3	-2.0
Top 12 mm	11 months field	22.7	-32.0	-32.2	-0.2
2nd 12 mm	11 months field	22.1	-32.3	-31.9	+0.4

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Mix type	Days of 85°C core aging (or as noted in Table)	Asphaltenes	m-critical Temp, °C (mcT)	S-critical Temp, °C (ScT)	ΔTc (S-Critical - m-critical)	CI (Colloidal Index)
Sec 1 52-34	0	18.4	-34.2	-35.9	-1.8	2.5966
6%RAS	5	20.1	-32.3	-34.9	-2.6	2.61
11% RAP	10	21.2	-29.9	-35.6	-5.7	2.5037
Top 12 mm	11 months field	19.3	-32.9	-35.7	-2.8	2.69
Top 12 mm	**2 year field core**	**20.9**	**-33.2**	**-33.1**	**0.1**	**2.45**
~~Top 12 mm~~	~~2 year field core~~	~~24.1~~	~~-28.9~~	~~-29.2~~	~~-0.3~~	~~2.226~~
Sec 2 58-28	0		-31	-33.2	-2.3	2.2266
6%RAS	5	26	-28	-30.7	-2.7	2.006
11% RAP	10	27.2	-24.1	-30.9	-6.8	1.9326
Top 12 mm	11 months field	25.8	-28.2	-30.8	-2.6	1.99
Top 12 mm	**2 year field core**	**24.9**	**-28.1**	**-30.5**	**-2.4**	**2.06**
Sec 3 58-28	0	20.5	-32.2	-31.9	0.4	2.595
0%RAS	5	23.6	-29.1	-29.8	-0.7	2.2967
31% RAP	10	24.8	-26.7	-29.6	-2.9	2.1607
Top 12 mm	11 months field	23.2	-30.2	-31.3	-1.1	2.39
Top 12 mm	**2 year field core**	**24.1**	**-28.7**	**-29.8**	**-1.1**	**2.19**
Sec 4 58-28	0	19.7	-33.4	-33.4	0	2.6446
0%RAS	5	21.9	-31.3	-31.9	-0.6	2.4588
21% RAP	10	23.4	-30.3	-32.3	-2	2.3687
Top 12 mm	11 months field	22.7	-32.0	-32.2	-0.2	2.5
Top 12 mm	**2 year field core**	**22.8**	**-30.5**	**-31.0**	**-0.51**	**2.41**

IATROSCAN TEST RESULTS PG 58-28, 6% RAS, 11% RAP

	Asphaltenes	Resins	Cyclics	Saturates	CI
unaged(11-15-12-E)	23.5	33.2	35.8	7.5	2.2258
5 day aged(01-23-13-A)	26	31.6	35.2	7.3	2.0060
10 day aged(11-15-12-O)	27.2	33.7	32.2	6.9	1.9326
Section 2, 1 year field cores, top 1/2 inch	25.8	32.5	34.1	7.6	1.9940
Section 2, 1 year field cores, 2nd 1/2 inch	25.1	32.6	35.8	6.5	2.1646
Section 2, 2 year field cores, top 1/2 inch	24.9	36.8	30.4	7.8	2.0550

COLLOIDAL INDEX = (Resins + Cyclics)/(Asphaltenes + Saturates)

As a binder ages the Colloidal Index decreases due mainly to the increase in asphaltenes, although there can also be increases in the resin fraction

Bitumen in colloid science: a chemical, structural and rheological approach
By L. Loeber, et al *Fuel* Vol. 77, No. 13, pp. 1443-1450, 1998

CI **= $\frac{\text{dispersed constituents}}{\text{flocculated constituents}} = \frac{\text{aromatics + resins}}{\text{saturates + asphaltenes}}$**

A higher colloidal index means that the asphaltenes are more peptized by the resins in the oil based medium.
As the binder ages the asphaltenes tend to agglomerate and increase and aromatics decrease. The result is the colloidal index decreases as binder ages.

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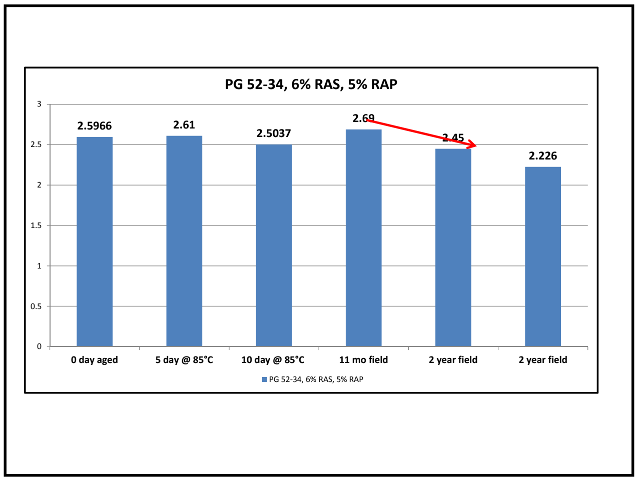
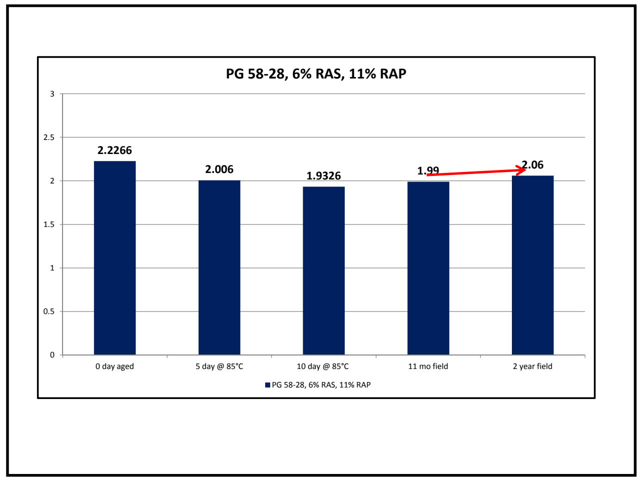

PG 52-34, 6% RAS, 5% RAP
2.5966
2.61
2.5037
2.69
2.45
2.226
0 day aged
5 day @ 85°C
10 day @ 85°C
11 mo field
2 year field
2 year field
PG 52-34, 6% RAS, 5% RAP


PG 58-28, 6% RAS, 11% RAP
2.2266
2.006
1.9326
1.99
2.06
0 day aged
5 day @ 85°C
10 day @ 85°C
11 mo field
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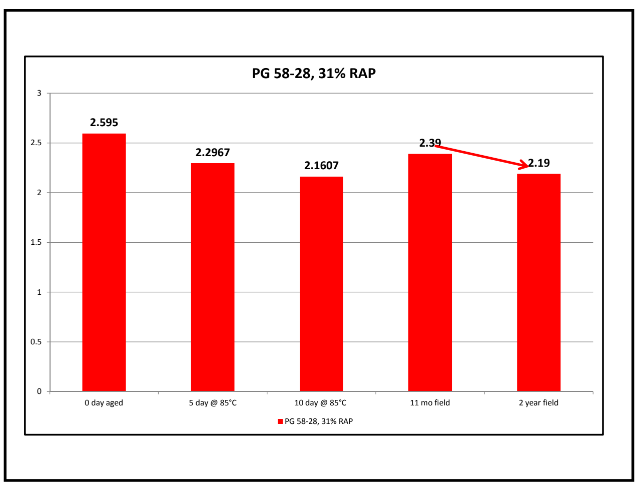
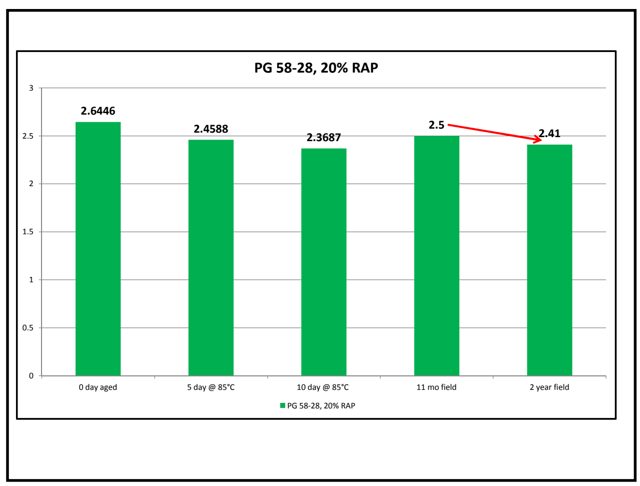
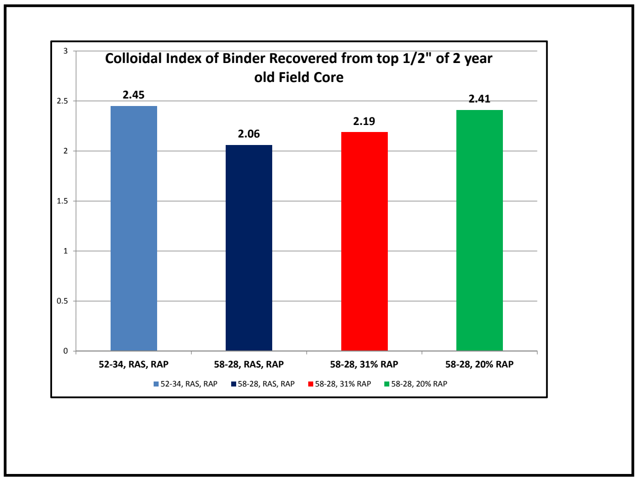
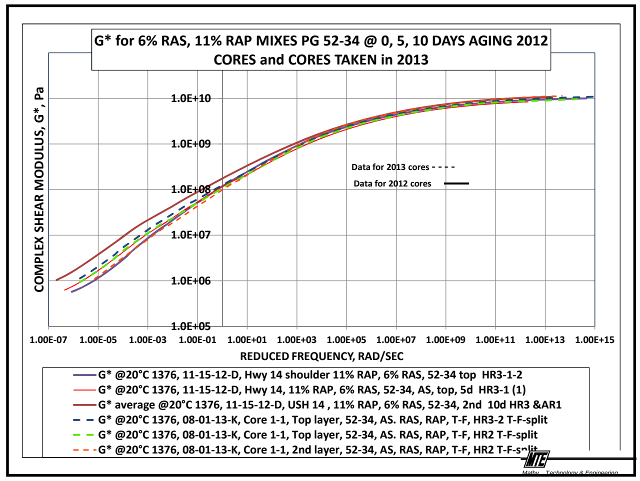
PG 58-28, 6% RAS, 11% RAP


PG 58-28, 31% RAP
2.595
2.2967
2.1607
2.39
2.19
0 day aged
5 day @ 85°C
10 day @ 85°C
11 mo field
2 year field
PG 58-28, 31% RAP

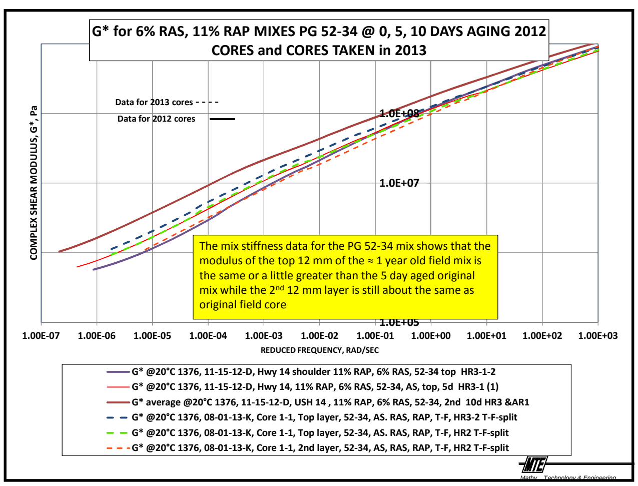

PG 58-28, 20% RAP
2.6446
2.4588
2.3687
2.5
2.41
0 day aged
5 day @ 85°C
10 day @ 85°C
11 mo field
2 year field
PG 58-28, 20% RAP



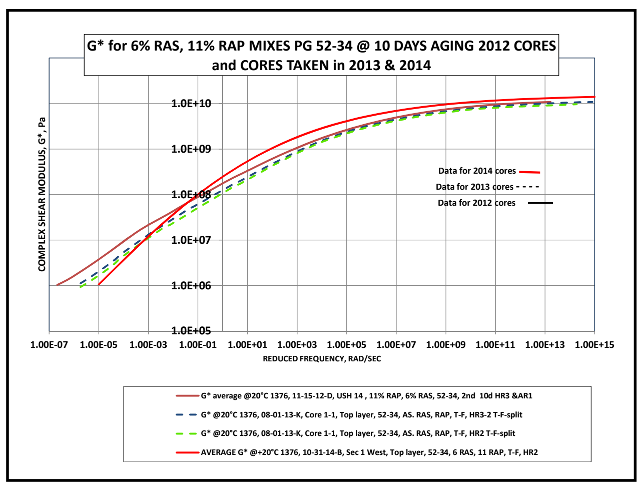
Colloidal Index of Binder Recovered from top 1/2" of 2 year old Field Core
2.45
2.06
2.19
2.41
3
2.5
2
1.5
1
0.5
0
52-34, RAS, RAP
58-28, RAS, RAP
58-28, 31% RAP
58-28, 20% RAP



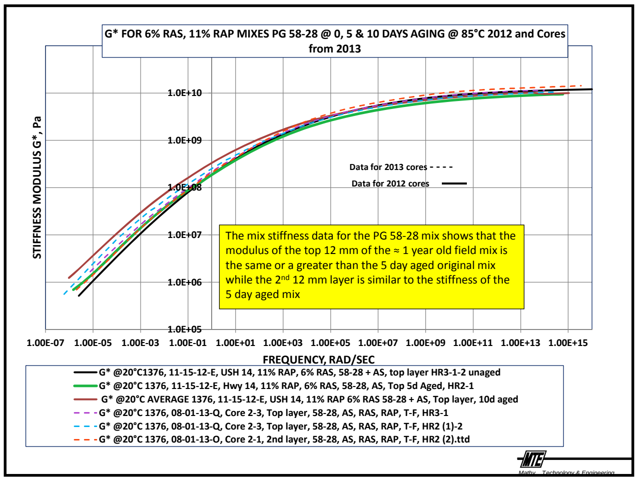
G* for 6% RAS, 11% RAP MIXES PG 52-34 @ 0, 5, 10 DAYS AGING 2012 CORES and CORES TAKEN in 2013
COMPLEX SHEAR MODULUS, G*, Pa
Data for 2013 cores - - - -
Data for 2012 cores
REDUCED FREQUENCY, RAD/SEC
G* @20°C 1376, 11-15-12-D, Hwy 14 shoulder 11% RAP, 6% RAS, 52-34 top HR3-1-2
G* @20°C 1376, 11-15-12-D, Hwy 14, 11% RAP, 6% RAS, 52-34, AS, top, 5d HR3-1 (1)
G* average @20°C 1376, 11-15-12-D, USH 14 , 11% RAP, 6% RAS, 52-34, 2nd 10d HR3 &AR1
G* @20°C 1376, 08-01-13-K, Core 1-1, Top layer, 52-34, AS. RAS, RAP, T-F, HR3-2 T-F-split
G* @20°C 1376, 08-01-13-K, Core 1-1, Top layer, 52-34, AS. RAS, RAP, T-F, HR2 T-F-split
G* @20°C 1376, 08-01-13-K, Core 1-1, 2nd layer, 52-34, AS, RAS, RAP, T-F, HR2 T-F-split



G* for 6% RAS, 11% RAP MIXES PG 52-34 @ 0, 5, 10 DAYS AGING 2012 CORES and CORES TAKEN in 2013
COMPLEX SHEAR MODULUS, G*, Pa
Data for 2013 cores - - - -
Data for 2012 cores
The mix stiffness data for the PG 52-34 mix shows that the modulus of the top 12 mm of the ≈ 1 year old field mix is the same or a little greater than the 5 day aged original mix while the 2nd 12 mm layer is still about the same as original field core
REDUCED FREQUENCY, RAD/SEC
G* @20°C 1376, 11-15-12-D, Hwy 14 shoulder 11% RAP, 6% RAS, 52-34 top HR3-1-2
G* @20°C 1376, 11-15-12-D, Hwy 14, 11% RAP, 6% RAS, 52-34, AS, top, 5d HR3-1 (1)
G* average @20°C 1376, 11-15-12-D, USH 14 , 11% RAP, 6% RAS, 52-34, 2nd 10d HR3 &AR1
G* @20°C 1376, 08-01-13-K, Core 1-1, Top layer, 52-34, AS. RAS, RAP, T-F, HR3-2 T-F-split
G* @20°C 1376, 08-01-13-K, Core 1-1, Top layer, 52-34, AS. RAS, RAP, T-F, HR2 T-F-split
G* @20°C 1376, 08-01-13-K, Core 1-1, 2nd layer, 52-34, AS, RAS, RAP, T-F, HR2 T-F-split



G* for 6% RAS, 11% RAP MIXES PG 52-34 @ 10 DAYS AGING 2012 CORES and CORES TAKEN in 2013 & 2014
COMPLEX SHEAR MODULUS, G*, Pa
Data for 2014 cores
Data for 2013 cores - - - -
Data for 2012 cores
REDUCED FREQUENCY, RAD/SEC
G* average @20°C 1376, 11-15-12-D, USH 14 , 11% RAP, 6% RAS, 52-34, 2nd 10d HR3 &AR1
G* @20°C 1376, 08-01-13-K, Core 1-1, Top layer, 52-34, AS. RAS, RAP, T-F, HR3-2 T-F-split
G* @20°C 1376, 08-01-13-K, Core 1-1, Top layer, 52-34, AS. RAS, RAP, T-F, HR2 T-F-split
AVERAGE G* @+20°C 1376, 10-31-14-B, Sec 1 West, Top layer, 52-34, 6 RAS, 11 RAP, T-F, HR2


G* FOR 6% RAS, 11% RAP MIXES PG 58-28 @ 0, 5 & 10 DAYS AGING @ 85°C 2012 and Cores from 2013
STIFFNESS MODULUS G*, Pa
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
Data for 2013 cores - - - -
Data for 2012 cores
The mix stiffness data for the PG 58-28 mix shows that the modulus of the top 12 mm of the ≈ 1 year old field mix is the same or a greater than the 5 day aged original mix while the 2nd 12 mm layer is similar to the stiffness of the 5 day aged mix
1.00E-07 1.00E-05 1.00E-03 1.00E-01 1.00E+01 1.00E+03 1.00E+05 1.00E+07 1.00E+09 1.00E+11 1.00E+13 1.00E+15
FREQUENCY, RAD/SEC
G* @20°C1376, 11-15-12-E, USH 14, 11% RAP, 6% RAS, 58-28 + AS, top layer HR3-1-2 unaged
G* @20°C 1376, 11-15-12-E, Hwy 14, 11% RAP, 6% RAS, 58-28, AS, Top 5d Aged, HR2-1
G* @20°C AVERAGE 1376, 11-15-12-E, USH 14, 11% RAP 6% RAS 58-28 + AS, Top layer, 10d aged
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR3-1
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR2 (1)-2
G* @20°C 1376, 08-01-13-O, Core 2-1, 2nd layer, 58-28, AS, RAS, RAP, T-F, HR2 (2).ttd
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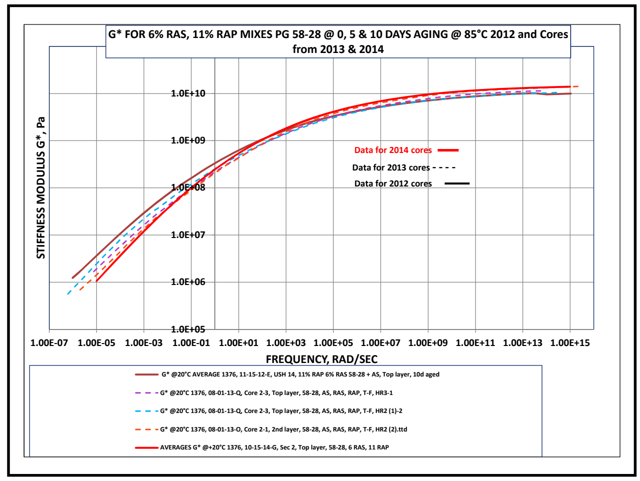
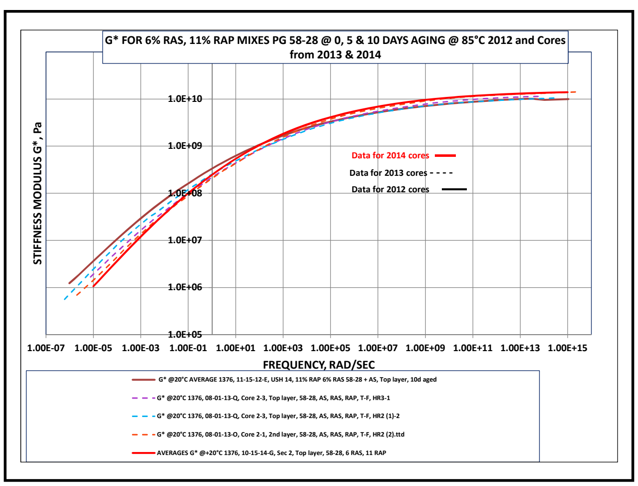
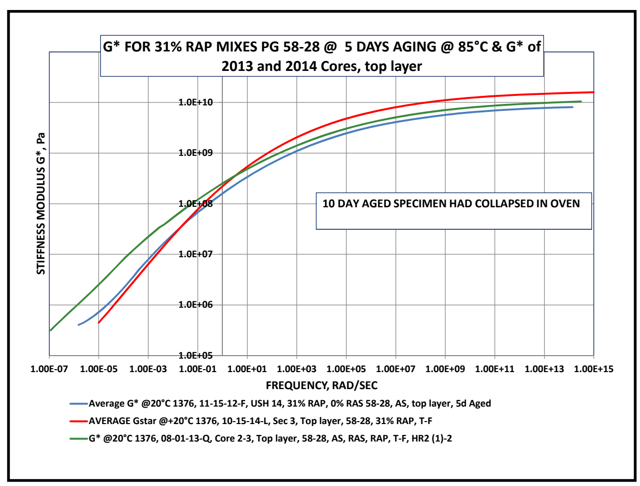

G* FOR 6% RAS, 11% RAP MIXES PG 58-28 @ 0, 5 & 10 DAYS AGING @ 85°C 2012 and Cores from 2013 & 2014
STIFFNESS MODULUS G*, Pa
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
Data for 2014 cores
Data for 2013 cores - - - -
Data for 2012 cores
1.00E-07 1.00E-05 1.00E-03 1.00E-01 1.00E+01 1.00E+03 1.00E+05 1.00E+07 1.00E+09 1.00E+11 1.00E+13 1.00E+15
FREQUENCY, RAD/SEC
G* @20°C AVERAGE 1376, 11-15-12-E, USH 14, 11% RAP 6% RAS 58-28 + AS, Top layer, 10d aged
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR3-1
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR2 (1)-2
G* @20°C 1376, 08-01-13-O, Core 2-1, 2nd layer, 58-28, AS, RAS, RAP, T-F, HR2 (2).ttd
AVERAGES G* @+20°C 1376, 10-15-14-G, Sec 2, Top layer, 58-28, 6 RAS, 11 RAP


G* FOR 6% RAS, 11% RAP MIXES PG 58-28 @ 0, 5 & 10 DAYS AGING @ 85°C 2012 and Cores from 2013 & 2014
STIFFNESS MODULUS G*, Pa
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
Data for 2014 cores
Data for 2013 cores - - - -
Data for 2012 cores
1.00E-07 1.00E-05 1.00E-03 1.00E-01 1.00E+01 1.00E+03 1.00E+05 1.00E+07 1.00E+09 1.00E+11 1.00E+13 1.00E+15
FREQUENCY, RAD/SEC
G* @20°C AVERAGE 1376, 11-15-12-E, USH 14, 11% RAP 6% RAS 58-28 + AS, Top layer, 10d aged
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR3-1
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR2 (1)-2
G* @20°C 1376, 08-01-13-O, Core 2-1, 2nd layer, 58-28, AS, RAS, RAP, T-F, HR2 (2).ttd
AVERAGES G* @+20°C 1376, 10-15-14-G, Sec 2, Top layer, 58-28, 6 RAS, 11 RAP

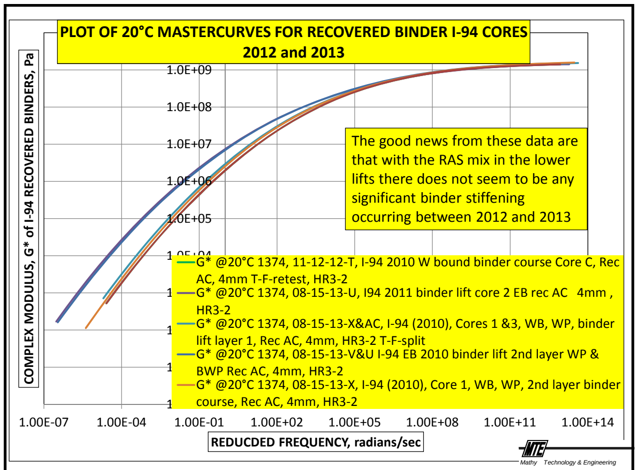

G* FOR 31% RAP MIXES PG 58-28 @ 5 DAYS AGING @ 85°C & G* of 2013 and 2014 Cores, top layer
STIFFNESS MODULUS G*, Pa
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
10 DAY AGED SPECIMEN HAD COLLAPSED IN OVEN
1.00E-07 1.00E-05 1.00E-03 1.00E-01 1.00E+01 1.00E+03 1.00E+05 1.00E+07 1.00E+09 1.00E+11 1.00E+13 1.00E+15
FREQUENCY, RAD/SEC
Average G* @20°C 1376, 11-15-12-F, USH 14, 31% RAP, 0% RAS 58-28, AS, top layer, 5d Aged
AVERAGE Gstar @+20°C 1376, 10-15-14-L, Sec 3, Top layer, 58-28, 31% RAP, T-F
G* @20°C 1376, 08-01-13-Q, Core 2-3, Top layer, 58-28, AS, RAS, RAP, T-F, HR2 (1)-2

Comments relevant to the next 4 slides

- In 2010 and 2011 we paved two lower lifts of a 3 lift overlay on Interstate 94 in Wisconsin using a combination of RAS and RAP
- Sections of 2010 paving happened to be low in RAS content due to problems feeding the ground shingle stock.
  - Therefore the mix stiffness and recovered binder stiffness of the 2010 sections were lower than for the 2011 mixes where those issues were not present
  - The data on the next shows that recovered binder from the 2010 paved mix had lower failure temperatures than the recovered binder from the 2011 paved mix

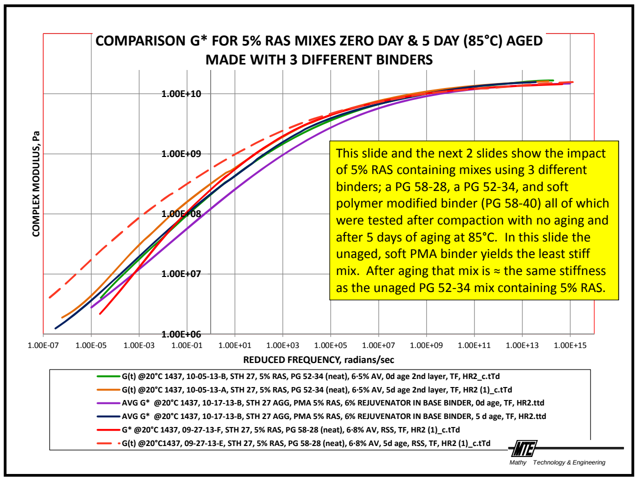
Recovered binder properties of 2010 & 2011 mixes

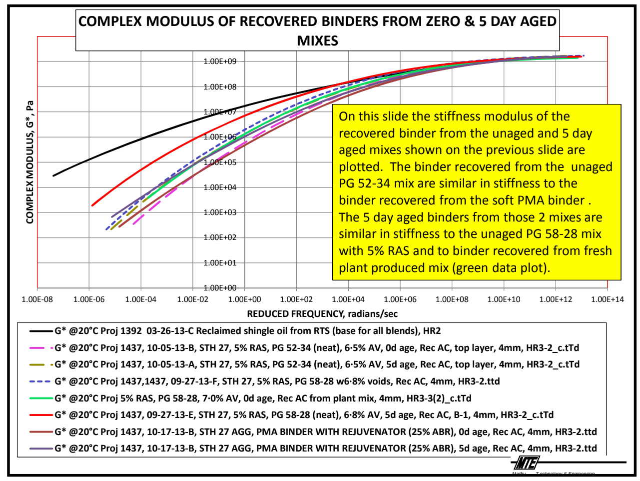
Year of coring	West Bound Low temp stiffness grade paved 2010	West Bound low temp m-value grade paved 2010	East Bound Low temp stiffness grade paved 2011	East Bound low temp m-value grade paved 2011
2012 (top binder lift layer)			-27.6	-22.0
2013 (lower binder lift layer)			-25.6	-21.9
2012 (top binder lift layer)	-29.8	-29.0		
2013 (lower binder lift layer)	-28.8	-28.2		

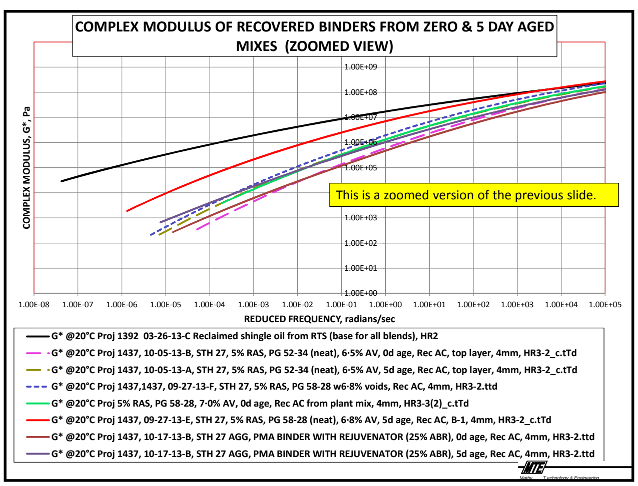


The next five slides show mixture and recovered binder stiffness properties of laboratory prepared mixtures containing RAS produced using 3 different binders

1. **A PG 58-28 used to make the mix**
2. **A PG 52-34 used to make the mix**
3. **A PG 52-34 plus an oil that is supposed to provide rejuvenating properties to the reclaimed binder in the mix**







A comparison of the impact of 3 different additives on shingle asphalt blends with aging

RHEA G(t) @-20°C 1437, 11-06-13-E, 90% 58-28 (Tk 5), 10% ADDITIVE #H1, 25% RTS Shingle AC ADDED TO 75% OF 90/10 BLEND, Unaged, 4mm, HR3-3 (1).ttd			RHEA G(t) @-30°C 1437, 11-06-13-D, 90% 58-28 (Tk 5), 10% ADDITIVE #W2, 25% RTS Shingle AC ADDED TO 75% OF 90/10 BLEND, unaged, 4mm, HR2.ttd			RHEA G(t) @-20°C 1437, 11-06-13-F, 90% 58-28 (Tk 5), 10% ADDITVE #H3, 25% RTS Shingle AC ADDED TO 75% OF 90/10 BLEND, [illegible]		
AROMATIC PROCESS OIL			BIO DERIVED PROCESS OIL			AROMATIC PROCESS OIL		
PG oil only	51.0	Δ=11.0	PG oil only	40.1	Δ=14.8	PG oil only	53.3	Δ=11.4
PG + SB	62.0		PG + SB	54.9		PG + SB	64.7	
UNAGED		delta(G(t)-m)	UNAGED		delta(G(t)-m)	UNAGED		delta(G(t)-m)
G(t) critical	-38.5	1.36	G(t) critical	-45.8	0.80	G(t) critical	-37.4	0.70
m critical	-39.9		m critical	-46.6		m critical	-38.1	
RTFO		delta(G(t)-m)	RTFO		delta(G(t)-m)	RTFO		delta(G(t)-m)
G(t) critical	-36.8	0.64	G(t) critical	-43.5	-1.49	G(t) critical	-35.6	0.14
m critical	-37.4		m critical	-42.0		m critical	-35.8	
PAV		delta(G(t)-m)	PAV		delta(G(t)-m)	PAV		delta(G(t)-m)
G(t) critical	-35.3	-1.48	G(t) critical	-38.9	-3.21	G(t) critical	-33.2	-2.44
m critical	-33.8		m critical	-35.7		m critical	-30.7	

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MATERIAL	AGING	high temp grade, ODSR	Δ G(t)-m	S critical	m critical	R-value	Asphaltenes	CI
64-22 + 5% REOB	unaged	64.3	**1.3**	-34.6	-35.6	1.669	15.600	3.673
64-22 + 5% REOB	RTFO	65.5	**0.6**	-32.9	-33.4	1.937	18.500	3.065
64-22 + 5% REOB	20 hr. PAV		**-2.7**	-30.9	-28.2	2.439	23.000	2.390
64-22 + 5% REOB	40 hr. PAV		**-5.8**	-29.8	-24	2.826	25.500	2.115
64-22 + 5% BIO DERIVED OIL	unaged	58.3	**2.2**	-37.1	-39.3	1.549	15.500	4.051
64-22 + 5% BIO DERIVED OIL	RTFO	59.9	**1.2**	-35.8	-37.1	1.783	17.600	3.525
64-22 + 5% BIO DERIVED OIL	20 hr. PAV		**-1.1**	-33.3	-32.2	2.208	23.100	2.559
64-22 + 5% BIO DERIVED OIL	40 hr. PAV		**-1.9**	-31.5	-29.6	2.501	26.000	2.219
64-22 +20% SB+ 5% REOB	unaged	69.5	**0.9**	-34.5	-35.4	2.014	19.600	2.861
64-22 +20% SB+ 5% REOB	RTFO	72.1	**0.6**	-33	-32.4	2.355	23.200	2.344
64-22 +20% SB+ 5% REOB	20 hr. PAV		**-3.3**	-31.9	-28.6	2.812	26.300	2.058
64-22 +20% SB+ 5% REOB	40 hr. PAV		**-7.1**	29.8	-22.7	3.307	28.500	1.833
64-22 + 20% SB + 5% BIO DERIVED OIL	unaged	63.5	**1.6**	-38.2	-39.8	1.881	19.600	3.054
64-22 + 20% SB + 5% BIO DERIVED OIL	RTFO	65.7	**1.8**	-35.9	-37.7	2.099	22.100	2.661
64-22 + 20% SB + 5% BIO DERIVED OIL	20 hr. PAV		**-1.5**	-33.9	-32.4	2.63[illegible]	[illegible]	[illegible]
64-22 + 20% SB + 5% BIO DERIVED OIL	40 hr. PAV		**-3.8**	-31.5	-27.7	2.948	28.900	1.933

ALL LOW TEMPERATURE PROPERTIES ARE BASED ON 4 mm DSR TESTING

RECOMMENDATION FOR EVALUATING ADDITIVES

1. BINDER EVALUATION STEP
   a) Make 5% and 10% blends of additive with base binder
   b) To this blend add 25% shingle binder (there are sources for obtaining this) May want to add more if that is your ultimate target or use a blend of shingle binder and recovered RAP AC
   c) Evaluate unaged, RTFO and PAV properties paying attention to changes in BBR (or 4mm DSR) stiffness and m-value limiting temperatures
   d) A strongly m controlled binder (5°C or more after 40 hr. PAV) is cause for concern

RECOMMENDATION FOR EVALUATING ADDITIVES #2

1. MIXTURE EVALUATION STEP
   a) Choose a additive + base binder blend from binder evaluation
   b) Make mixes at target RAS and/or RAP levels at 7% ± 0.5% air voids
      i. Evaluate mix stiffness (could be AMPT, torsion bar or ??)
      ii. Recover binder and characterize especially low temp of short term aged mix
   c) 5 day age mix samples at 85°C and repeat steps b.i and b.ii above
   d) Suggest comparing these types of data to same test properties with mixtures of good known performance
   e) I prefer to perform a 10 day aging step as well to get a clear idea of aging trend of the mixtures

RECOMMENDATION FOR EVALUATING ADDITIVES & MIXES

f) 10 days of aging is not convenient
g) We have not been aging mixes or binders severely enough to identify problems
h) ∴ We have been exploring the approach used by Bill Buttlar at U of Illinois and Phil Blankenship at the Asphalt Institute
   1. Age the loose mix at 135°C for 12 hrs.
   2. Age the loose mix at 135°C for 24 hrs.
   3. Compact the mixture specimens for testing
   4. Recover binder from mixtures for determination of low temperature S & m values
i) Alternatively binder blends of "rejuvenating" additives can be made with extracted RAP binder and/or extracted shingle binder
   1. PAV age for 20 hr. then test low temperature S & m
   2. PAV age another sample for an additional 20 hr. , test again.

COMMENTS

1. There is **probably not** complete blending of shingle binder with virgin binder in mixes initially
   1) The similarity of mix stiffness from 5% RAS PG 58-28 mixture and mixture produced with 25% shingle binder blended with PG 58-28 argues that there is sufficient interaction of the binder from the RAS with the virgin binder to provide true measure of stiffness even though that stiffness may not result from a truly homogeneous blending of binders.
   2) It does appear as though some blending (or level of interaction?) does occur ***to sufficient degree*** after aging of the mix *based on torsion bar stiffness data*

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COMMENTS

2. Low temperature grade of preblended shingle binder and virgin 58-28 appears to be acceptable, even after a single 20 hr. PAV aging
   1) I believe this give a false sense of security and likelihood for performance
   2) Aging of shingle binder blends on aggregates in much thinner films than the PAV film seems to result in greater aging of the mix and its binder and more representative of what happens in the field.
   3) The recovered binder from aged mix shows that the relaxation value of the binder deteriorates more rapidly as does the failure stiffness of the binder

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COMMENTS

3. The overlay tester cracking response shows that after 5 days of conditioning all mixes containing RAS collapse to the same unacceptable level
   - The overlay tester is “blunt instrument”, but such systematic and dramatic changes in results is a real cause for concern especially given the wide variety of mixtures that were evalutated.
4. Recovered binder relaxation modulus mastercurves at +20C show that shingle blended binders relax at a an increasingly slower rate as mix ages than do traditional mixes containing the same binder replacement using RAP

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COMMENTS

5. Fatigue of aged mixes appears to be the major concern. Mixture testing for fatigue evaluation should be considered an essential step
   - RAS or recovered shingle binder seems to accelerate the aging of mixes and the binders therein
6. I don’t believe we understand the mechanism by which aged shingle binder blends and interacts with virgin paving binders—this needs to be studied on a more fundamental level
   - Blending kinetics may change with conditioning time and amount as indicated by the behavior before and after the 216 hour thin film aging experiment.

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COMMENTS

7. Use of some oils appear to improve performance of shingles in mixes.
   - The amount of additive appears to be at least 6% and as high as 10% for a 20% shingle binder replacement. Greater amounts would be needed for higher binder replacement levels
   - The initial stiffness of these mixtures at these levels could be a concern or there could be a need for polymer modification to improve the near term high temperature performance in order to secure desired intermediate and low temperature performance.
     - ✓ Would this be cost effective?
8. There is an ever increasing array of so called rejuvenators. The ones we have evaluated appear to function as softening agents which tend to degrade as the binder is aged on aggregate.
   - These additives have varying chemical composition, each needs to be carefully evaluated on aggregate and with aging.
   - This is testing that should be done with the job aggregate and based on the proposed job mix design

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COMMENTS

- There are only a few sources of molecules to reduce binder stiffness
  - Soft asphalt (i.e. someone has to add gas oil or not take the gas oil out to start with)
  - "Process Oils"—A catch-all category that today can mean almost anything, but none are asphalt
    - Aromatic, napthenic and paraffinic oils are derived from crude; but are not asphalt
    - Bio derived oils can come from soybeans; sunflower, rapeseed, flaxseed, etc; wood pulping (i.e. tall oil fatty acids and rosin)
    - Recycled, re-refined, repurposed materials
      - Re-refined engine oil bottoms
      - Oils from tire pyrolysis, oils from plastic recycling
      - Manure and other forms waste
- The additive's source does not *a priori* make it "good" or "bad"
  - Only a thorough, rigorous evaluation of the additive can enable you to make the decision

QUESTIONS

Direct questions or comments to:
gerald.reinke@mteservices.com

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