DEVELOPMENT OF A SIMPLE METHOD FOR DETERMINING MIXING AND COMPACTION TEMPERATURES FOR HOT-MIX ASPHALT

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Recommendations from NCHRP 9-39

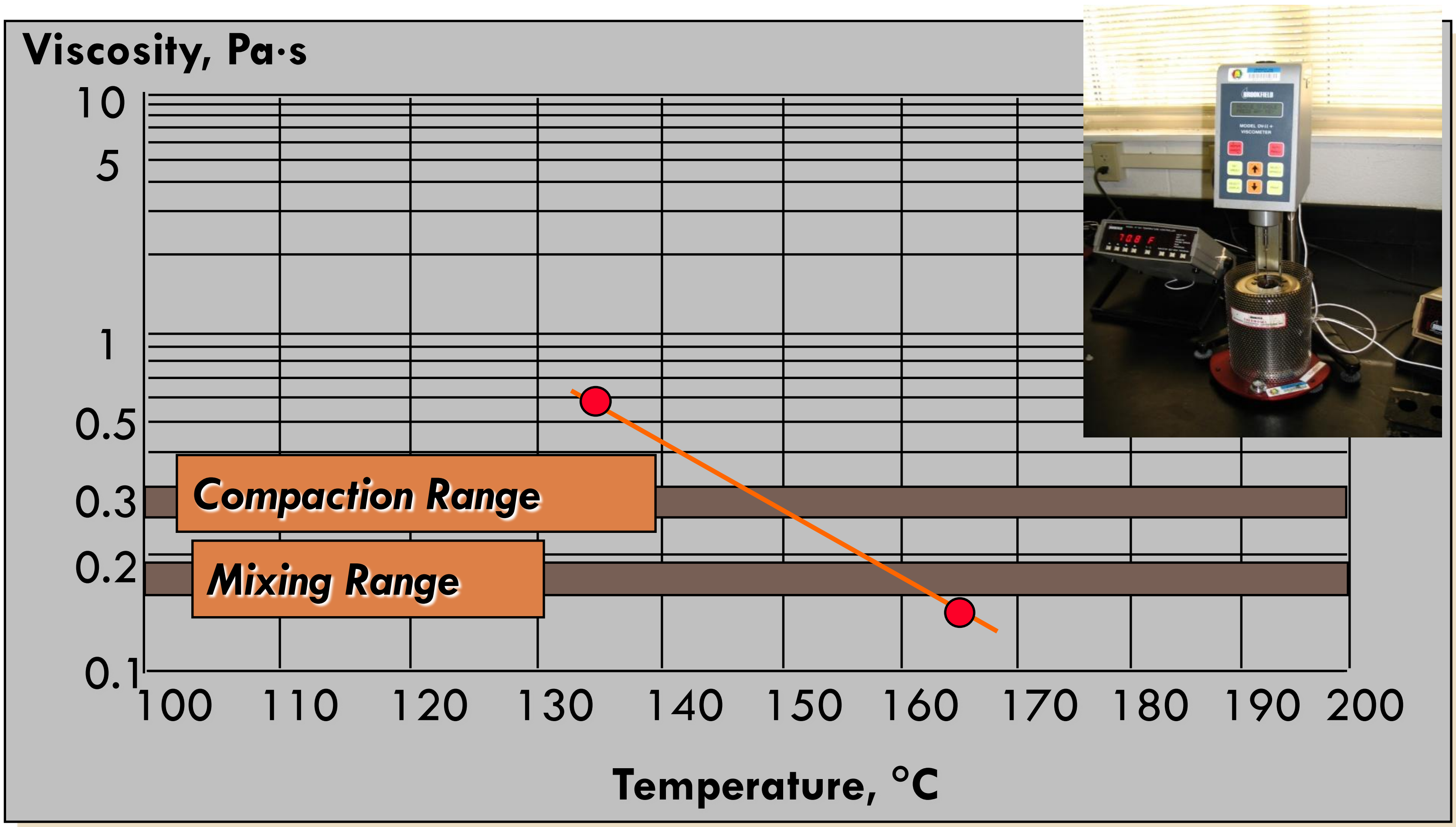
Outline

- Background
  - Problem statement
  - Project objectives
- Research plan
  - Binder tests: Candidate methods
  - Mixture tests
  - Materials

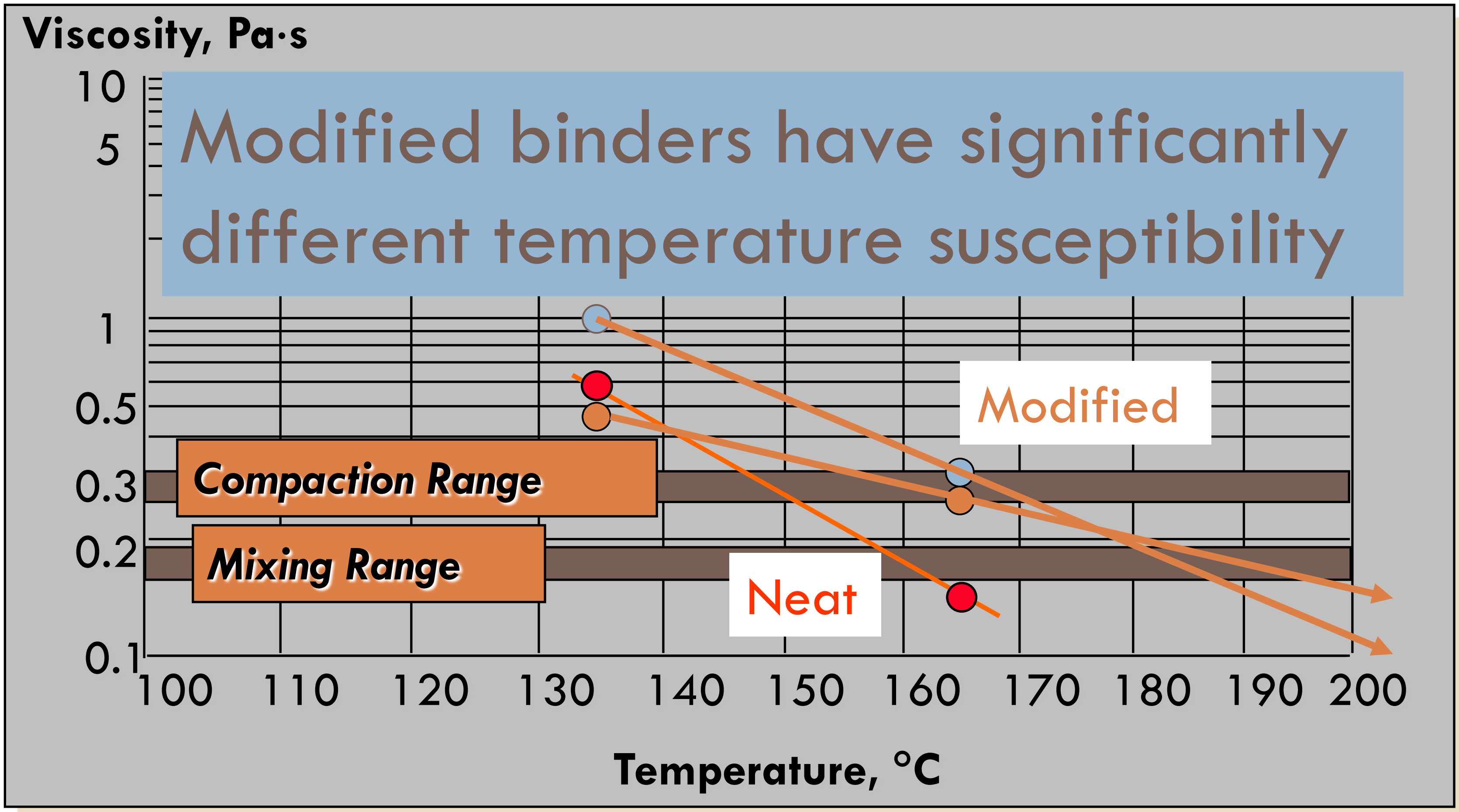
Outline

- The Steady Shear Flow Method
- The Phase Angle Method (AKA the Casola Method)
- Correlations with Mixture Test Results
- Correlation of SSF and Casola Results
- Recommendations
- Limitations of the methods

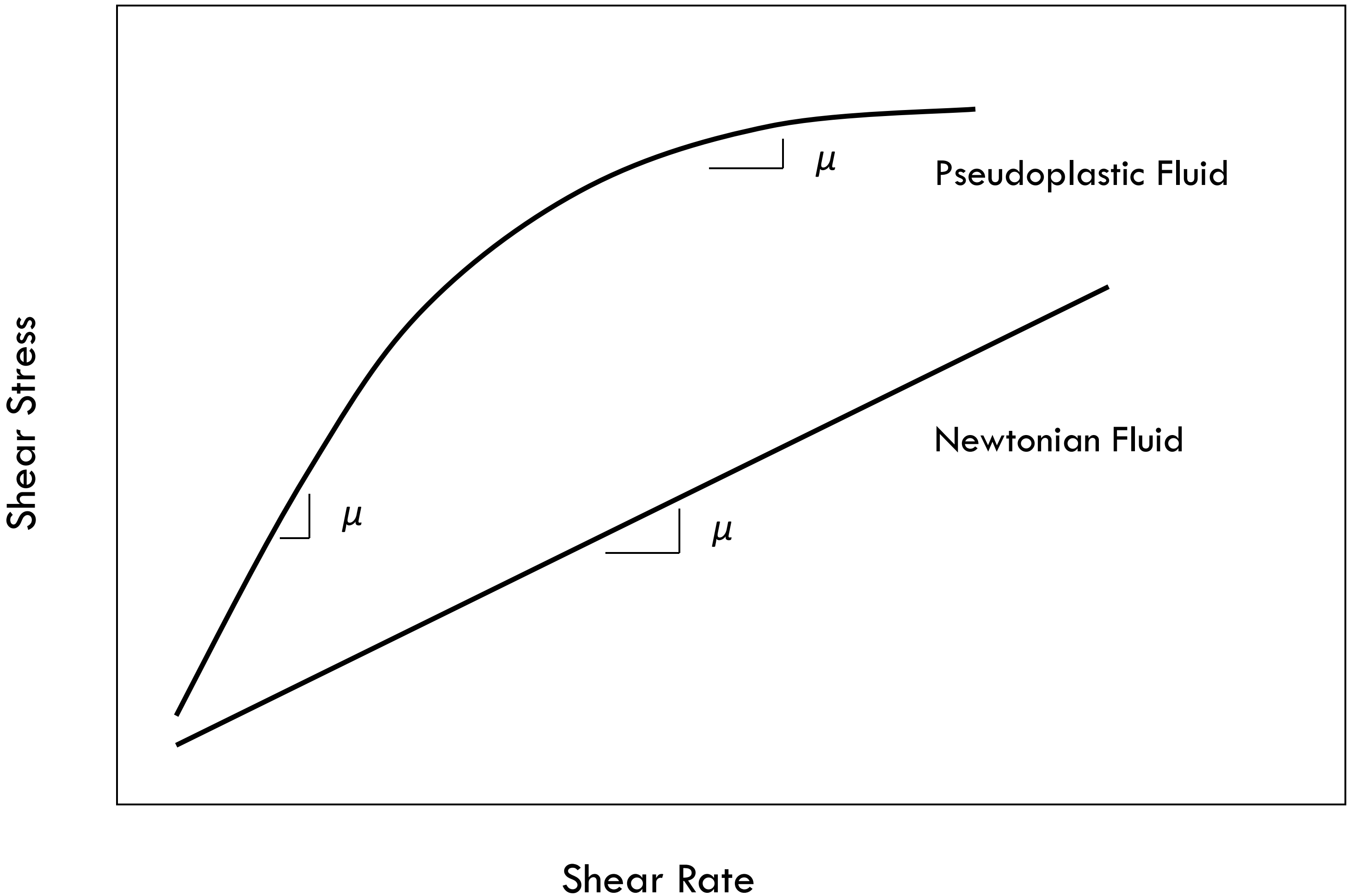
The Asphalt Institute Equi-Viscous Method



The Asphalt Institute Equi-Viscous Method

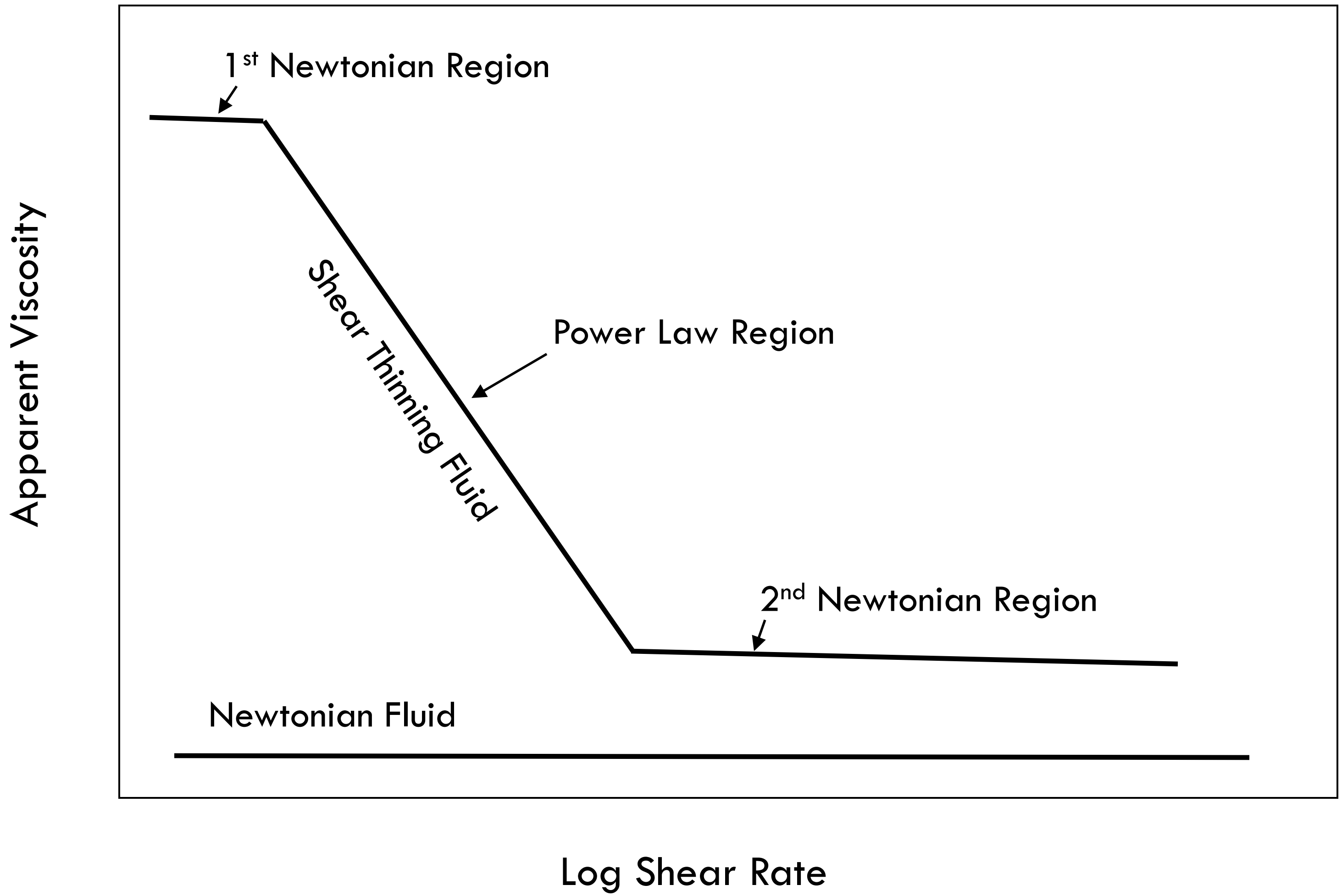


Viscosity



Shear Stress
μ
Pseudoplastic Fluid
Newtonian Fluid
μ
μ
Shear Rate

Viscosity



1st Newtonian Region
Shear Thinning Fluid
Power Law Region
2nd Newtonian Region
Newtonian Fluid
Apparent Viscosity
Log Shear Rate

Background

- The Asphalt Institute equiviscous concept works well for unmodified, unfilled binders.
- For most modified binders, the equiviscous concept results in excessive mixing and compaction temperatures:
  - Emission concerns
  - Binder degradation concerns
- Most specifying agencies have relied on binder suppliers to recommend appropriate temperatures. However, no consensus exists on how that should be done.

Does Compaction Temperature matter?

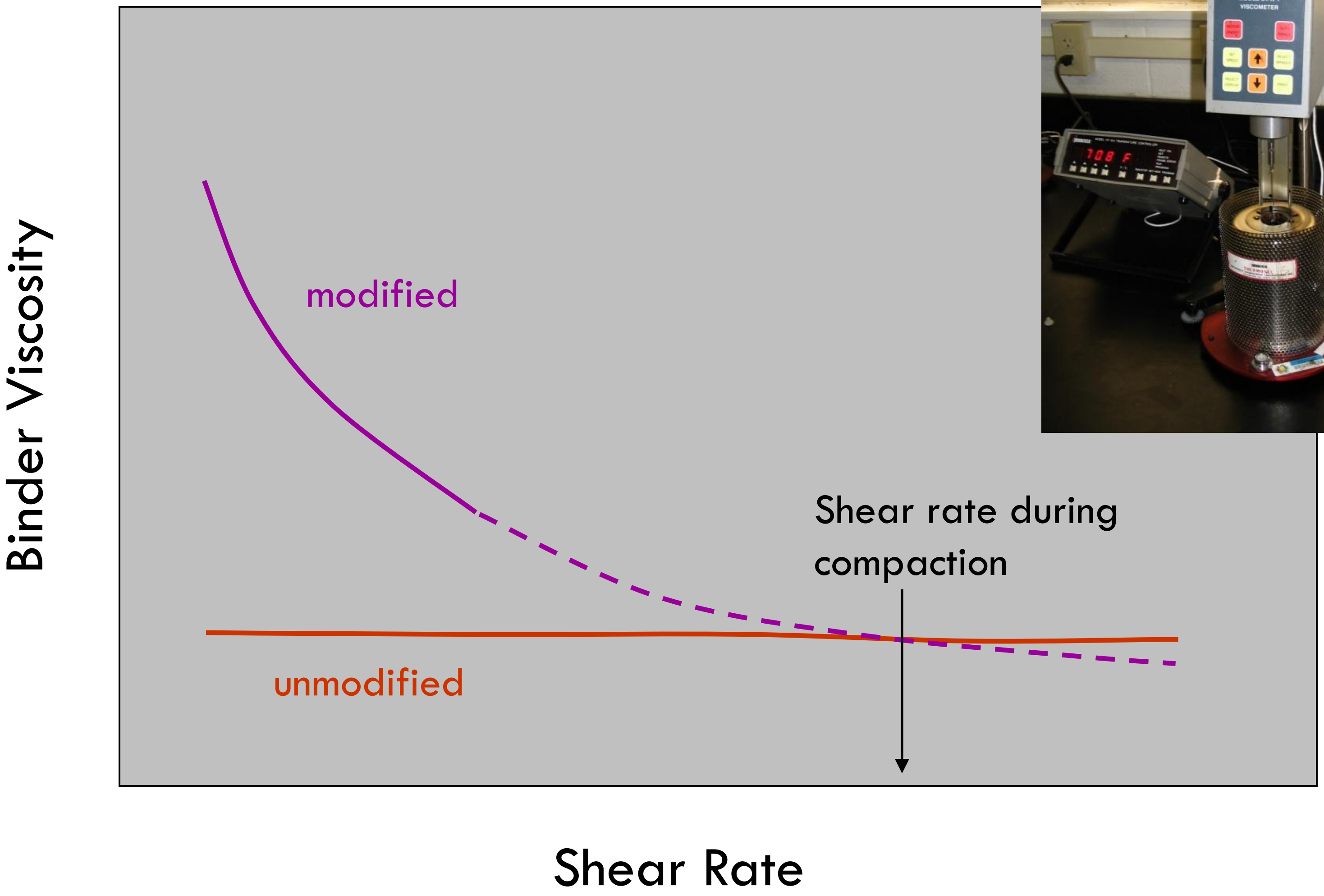
- The SGC compaction process is insensitive to binder stiffness because the compactor operates in a constant strain mode.
  - Temperature has almost negligible effect on volumetric properties.
  - However, mechanical tests on HMA are affected by mixing and compaction temperatures.

Candidate Methods for Determining Mixing & Compaction Temperatures

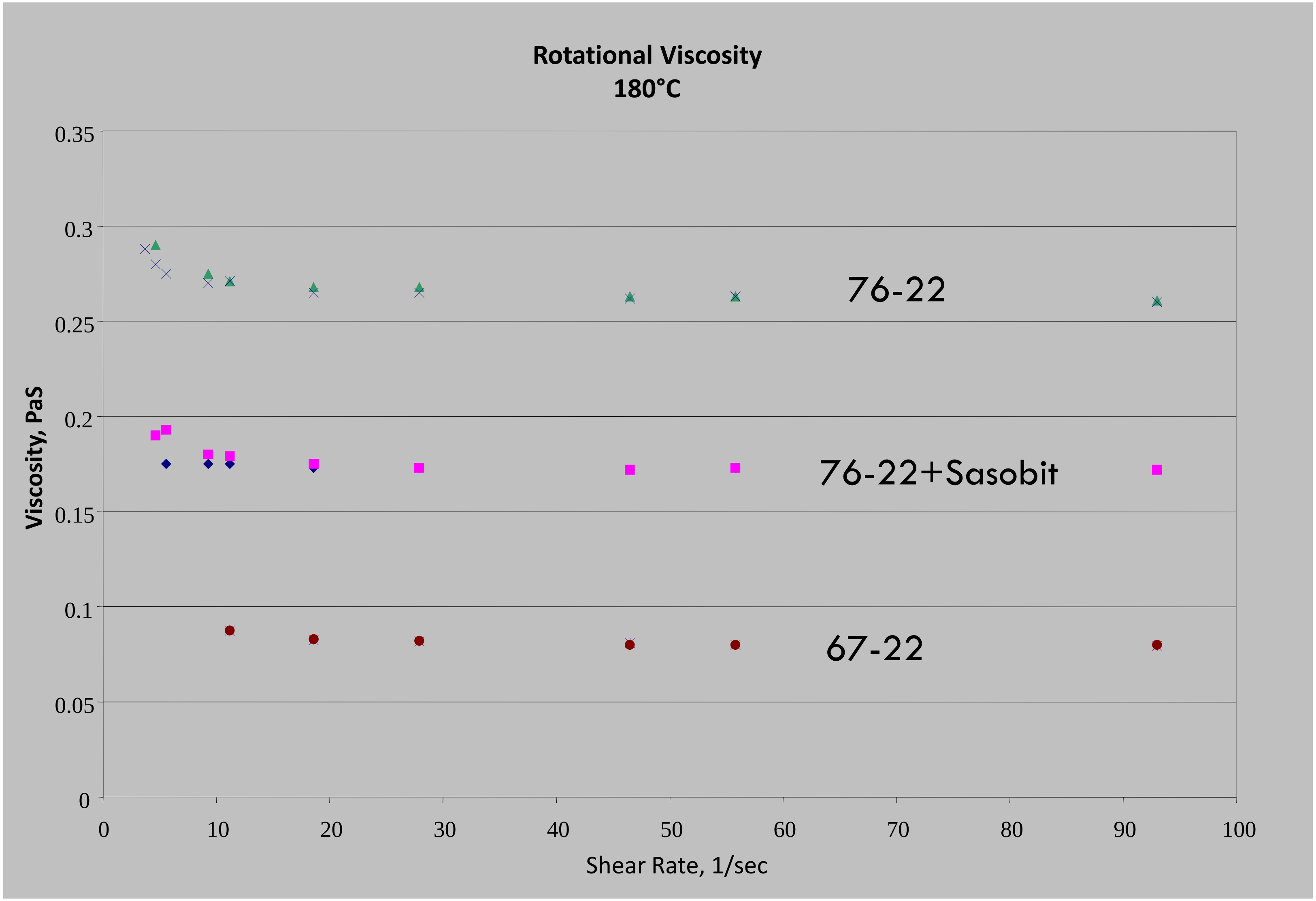
- Keep it Simple (binder test)
- Use Existing Equipment
- Work for Modified and Unmodified Binders
  - High Shear Rate Viscosity (Yildirim)
  - Steady Shear Flow (Reinke)
  - Dynamic Shear Rheology (Casola)

High Shear Rate Viscosity Method

High Shear Viscosity

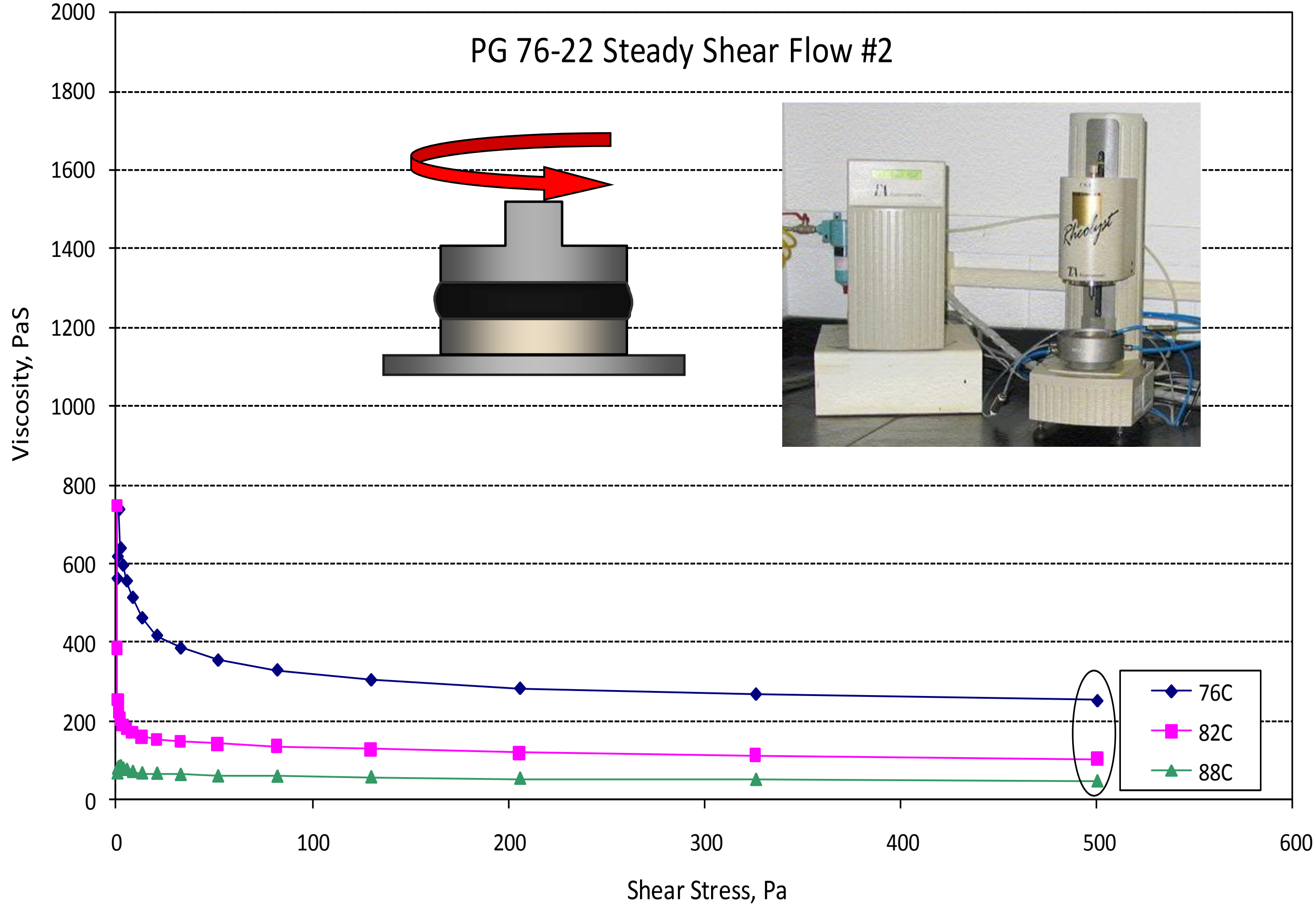


High Shear Viscosity

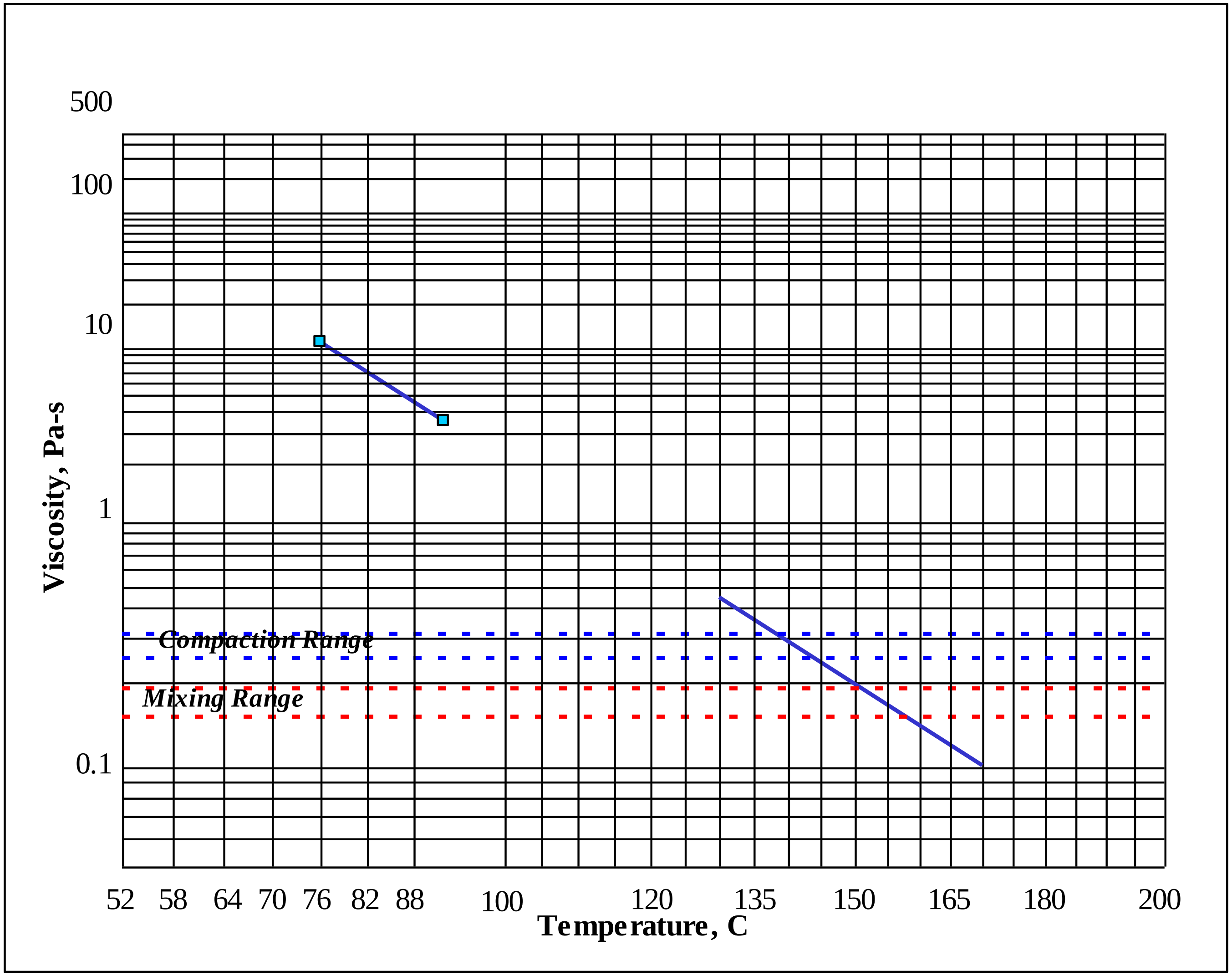


Steady Shear Flow Method

Steady Shear Flow Test



Extrapolation of SSF Viscosity



Steady Shear Flow Method

- Mixing Temperature (°F)

  Tm → 0.17±0.02 Pa·s

- Compaction Temperature (°F)

  Tc → 0.35±0.03 Pa·s

Steady Shear Flow (Viscosity) Method

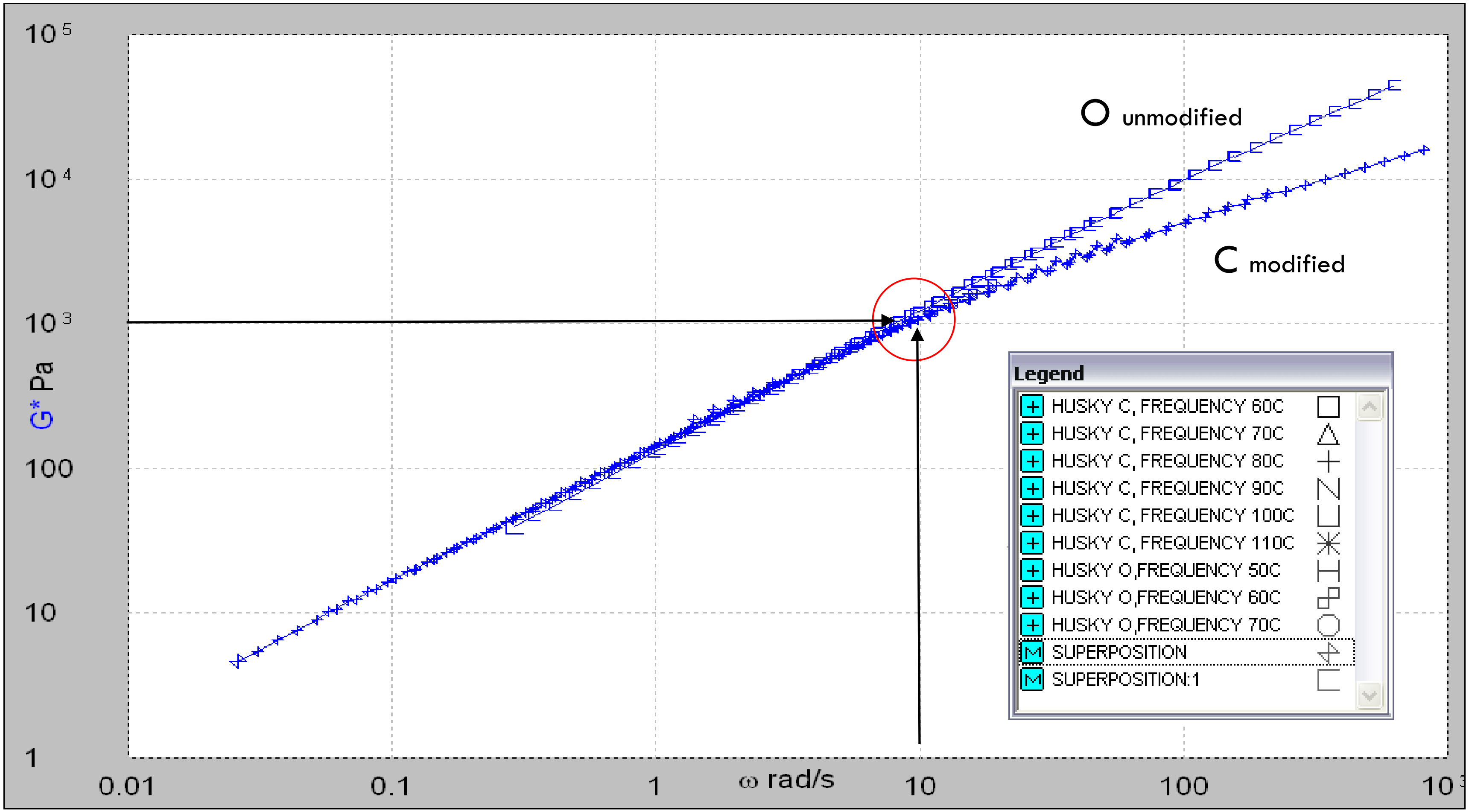
- Use standard DSR (meets requirements of AASHTO T 315)
- Most DSRs have routine for Steady Shear Flow test (application of a steady torsional shear stress)
- Sample preparation is same as T 315, unaged sample
- 0.5 mm gap
- Stress levels: 0.3, 0.5, 0.8, 1.3, 2, 3, 5, 8, 13, 20, 30, 50, 80, 130, 200, 300, and 500 Pa
- 76, 82, and 88°C (higher temperatures cause trouble with water baths)
- Binders that give trouble: heavily modified, no problem with rubber

Casola (Phase Angle) Method

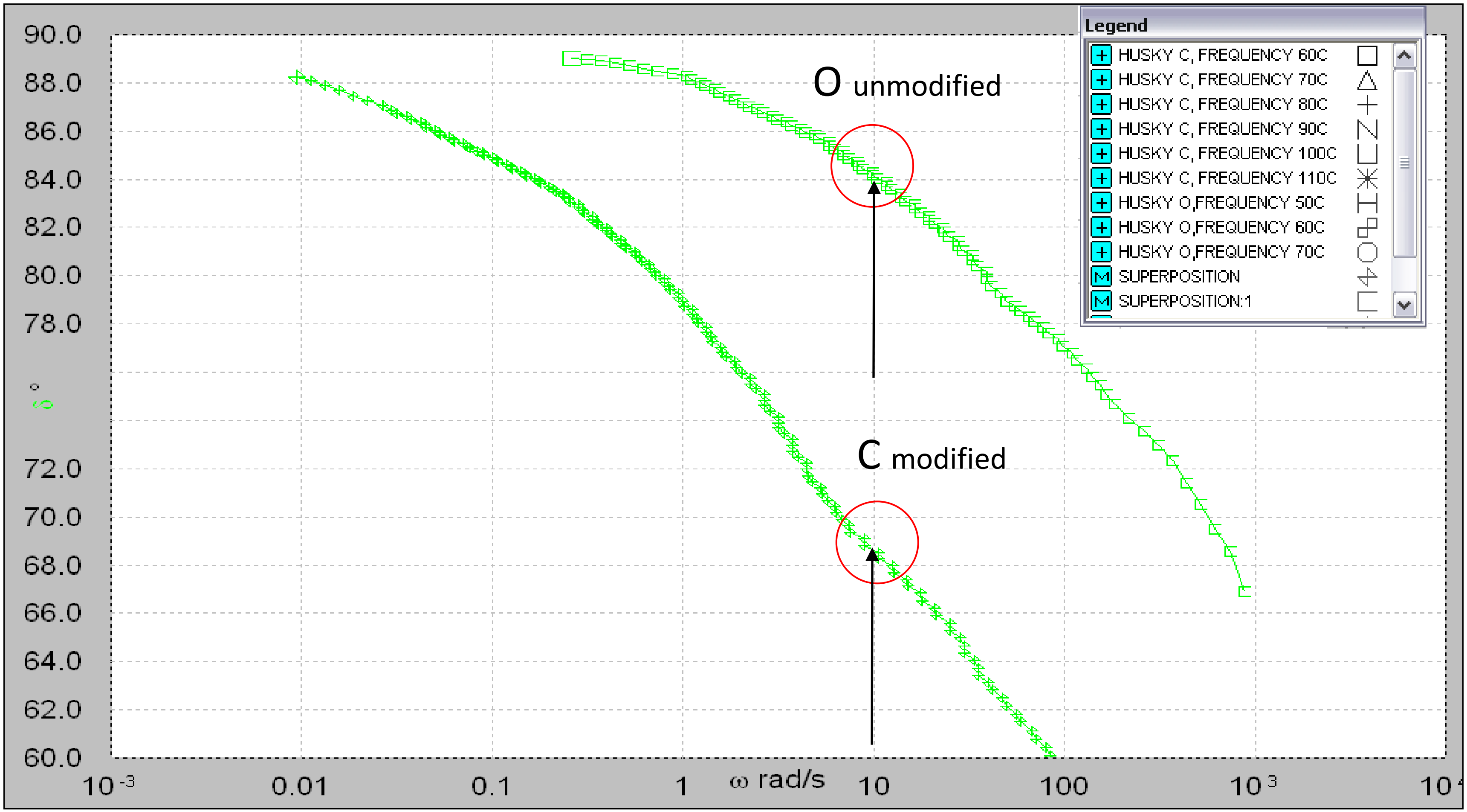
Background on the Casola Method

- Mixing stresses & shear rates are extremely complex
- The ability to coat & compact differ from ‘Neat’ to ‘Modified’ binders
- The transition from Newtonian to non-Newtonian behavior makes for an easily identifiable threshold to rank these binders

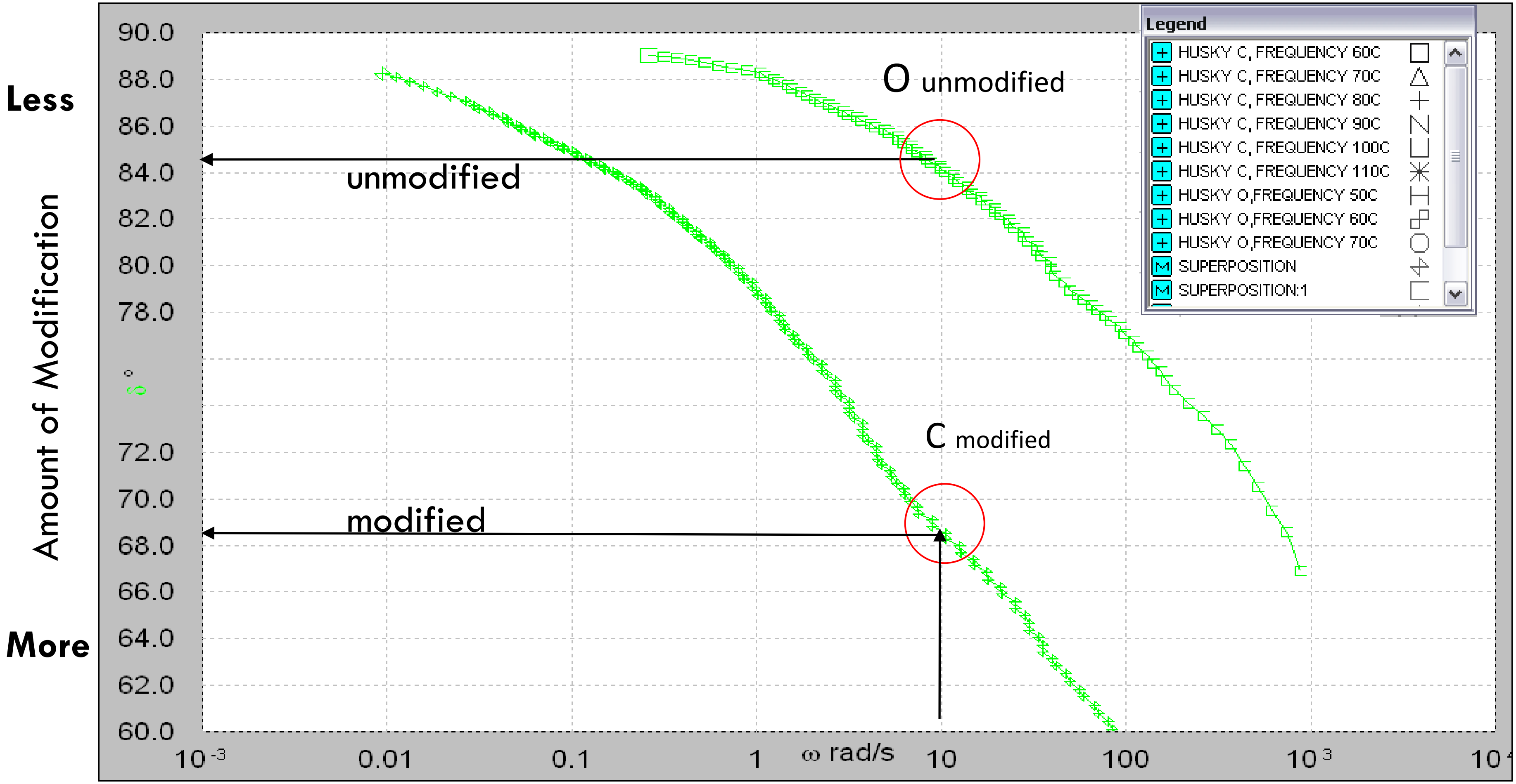
Superpave Grade Temp G* at 10rad/sec



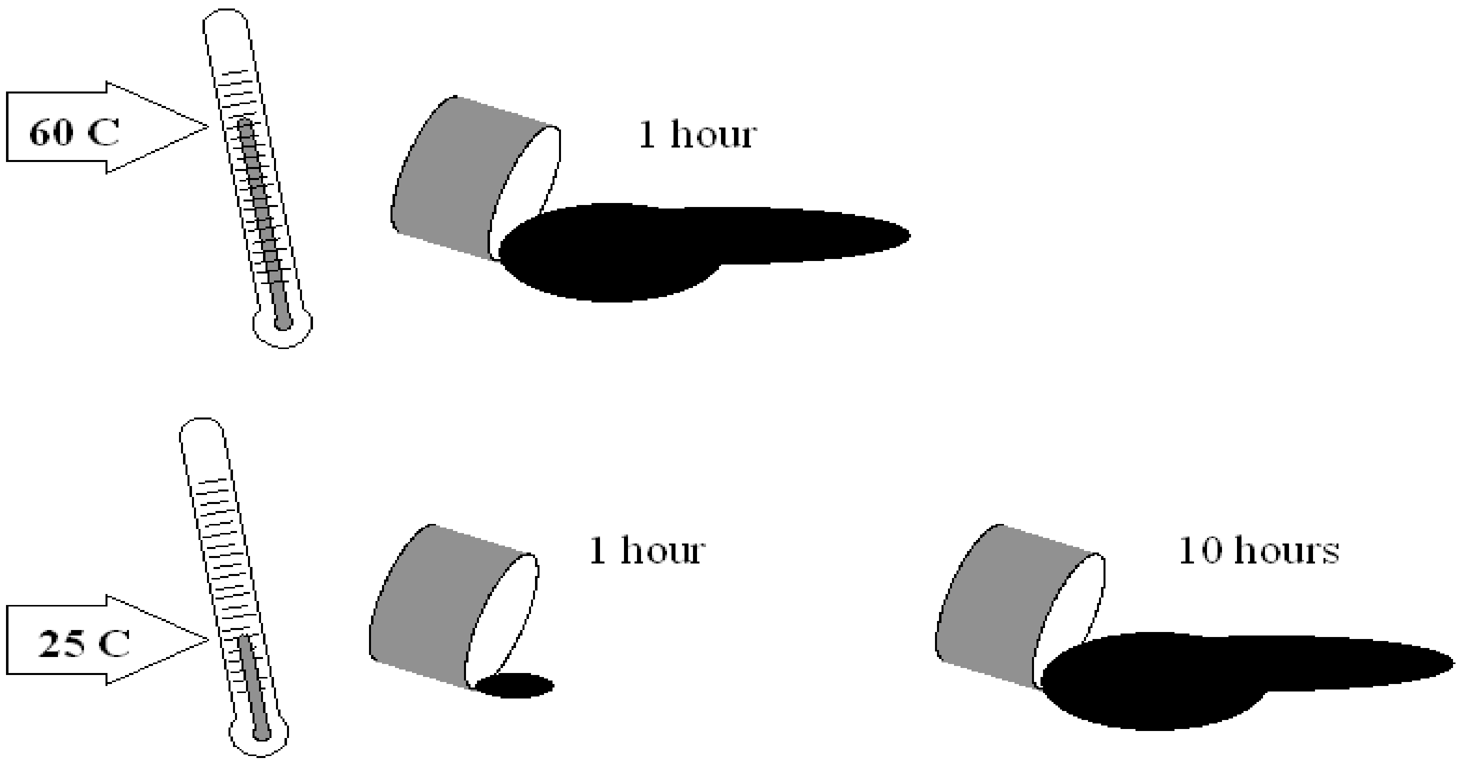
Superpave Grade Temp Phase Angle at 10rad/sec



Phase Angle Identifies the Amount of Modification



Flow Behavior of Asphalt;
Time - Temperature Dependence

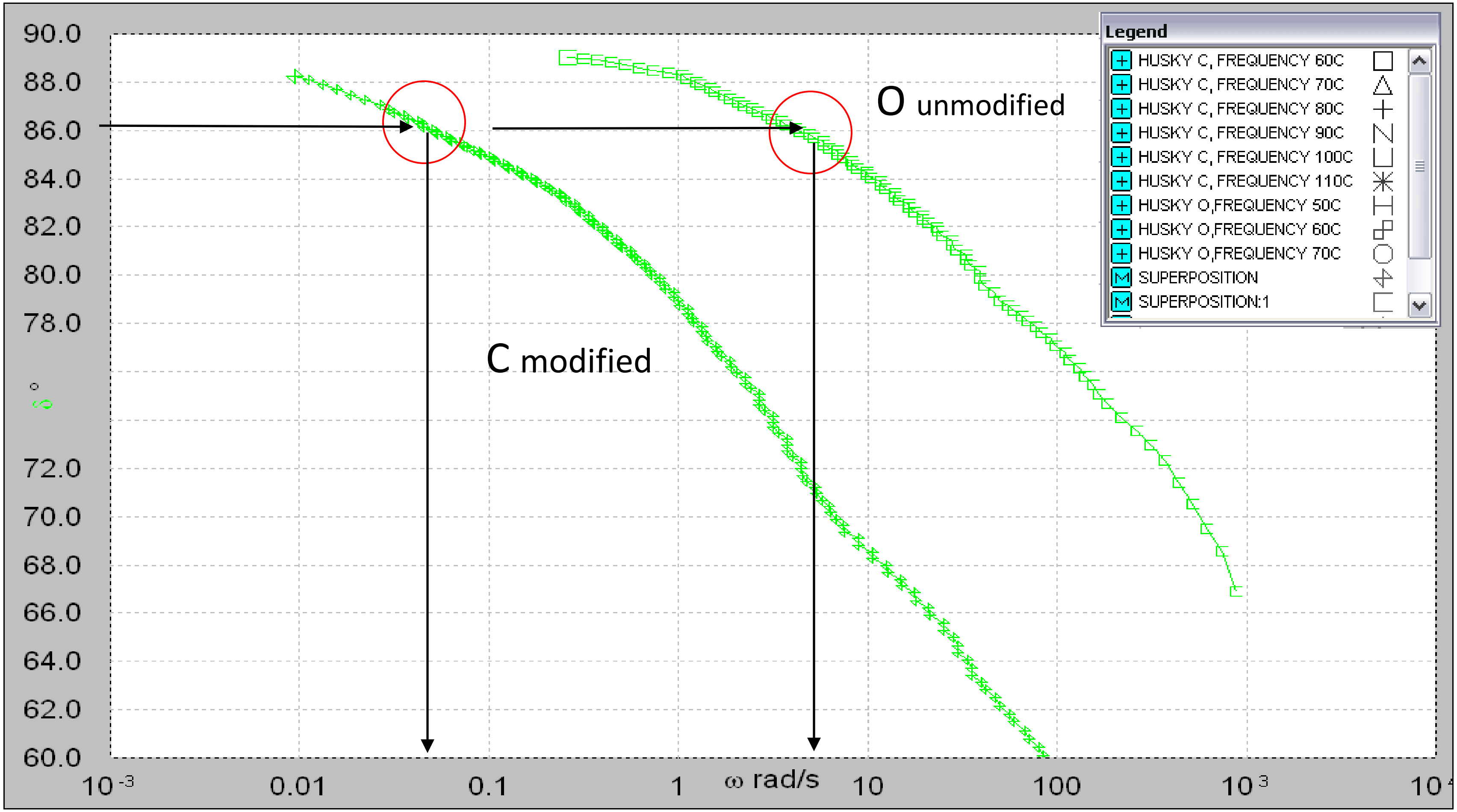


From the Asphalt Institute
Superpave
Binder Testing Manual

Background on the Casola Method

- Phase angle of 86° is an easily identifiable transition point of the material exhibiting Visco-Elastic behavior for comparison
- To see this transition over a reasonable range of frequency, the procedure investigates these samples at a reference temperature of 80°C
- The procedure uses higher temps for modified & lower temps for unmodified asphalt binders

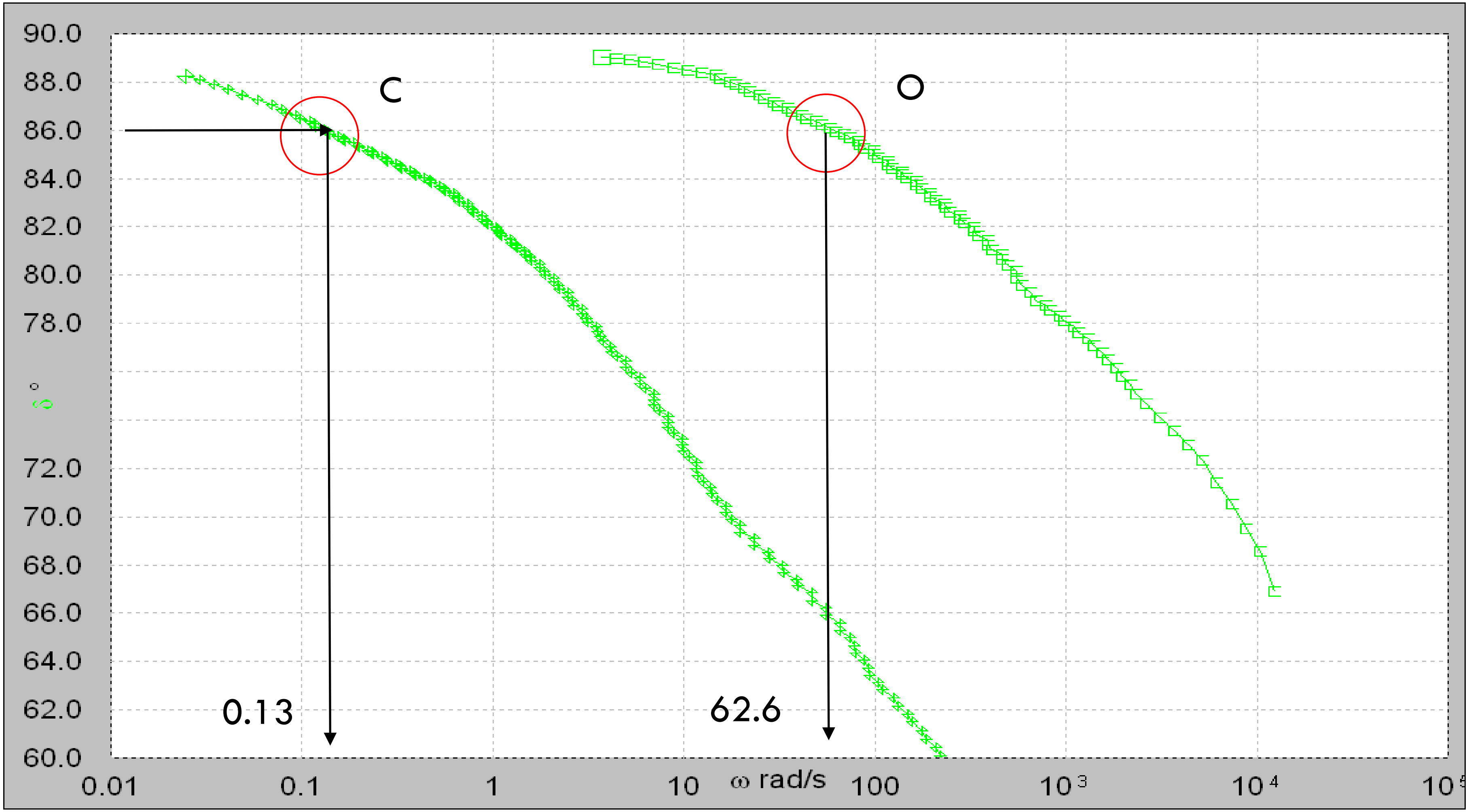
Low freq relates to high temps & High freq low temps



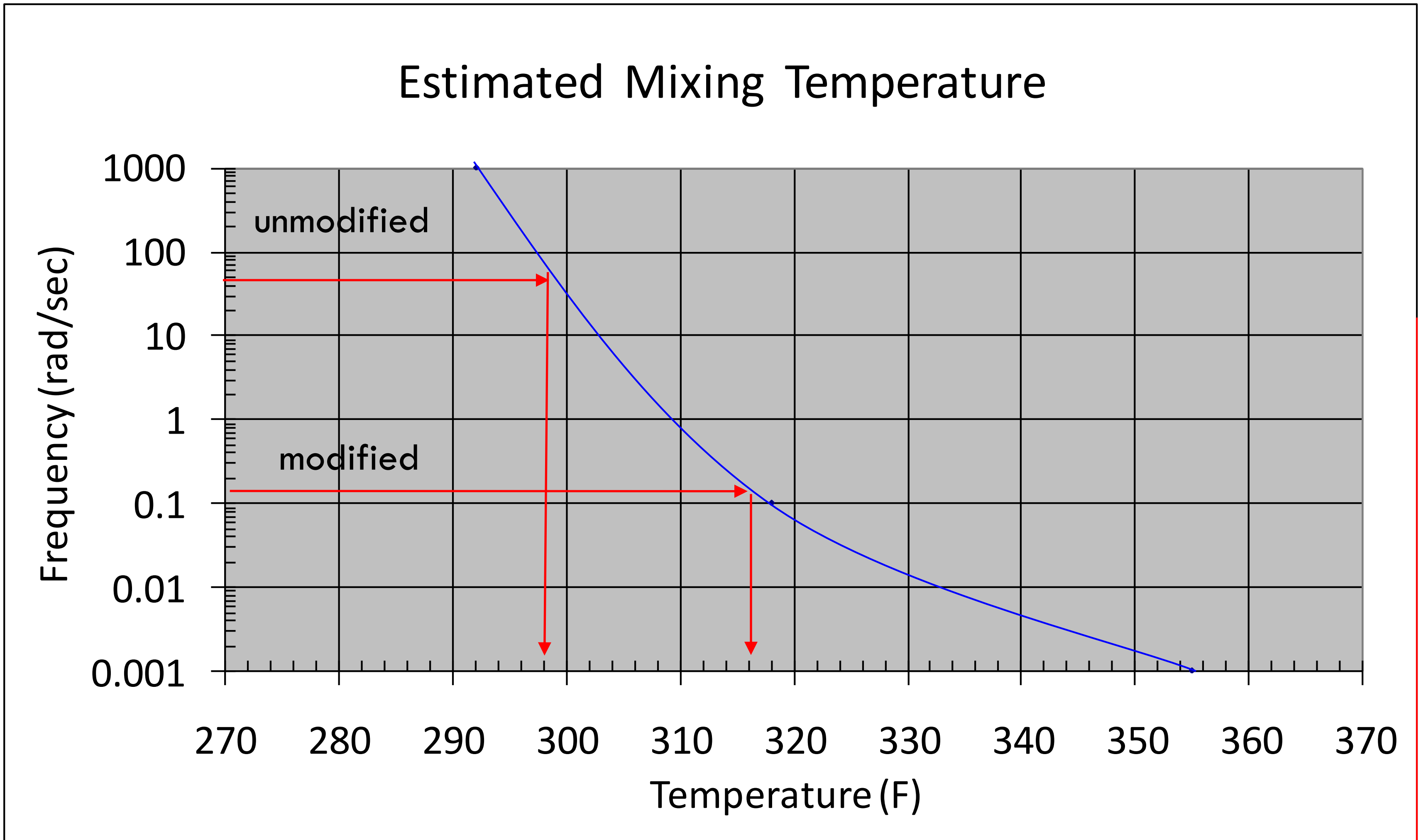
Frequency inversely relates to Temperature:

High Temperatures **Low Temperatures**

The Casola Method; 86° Phase Angle Data at 80°C



Concept of the Mixing Temperature Chart



Casola Method Equations

- *Mixing Temperature (°F) =* $325\omega^{-0.0135}$
- *Compaction Temperature (°F) =* $300\omega^{-0.012}$

Calculations

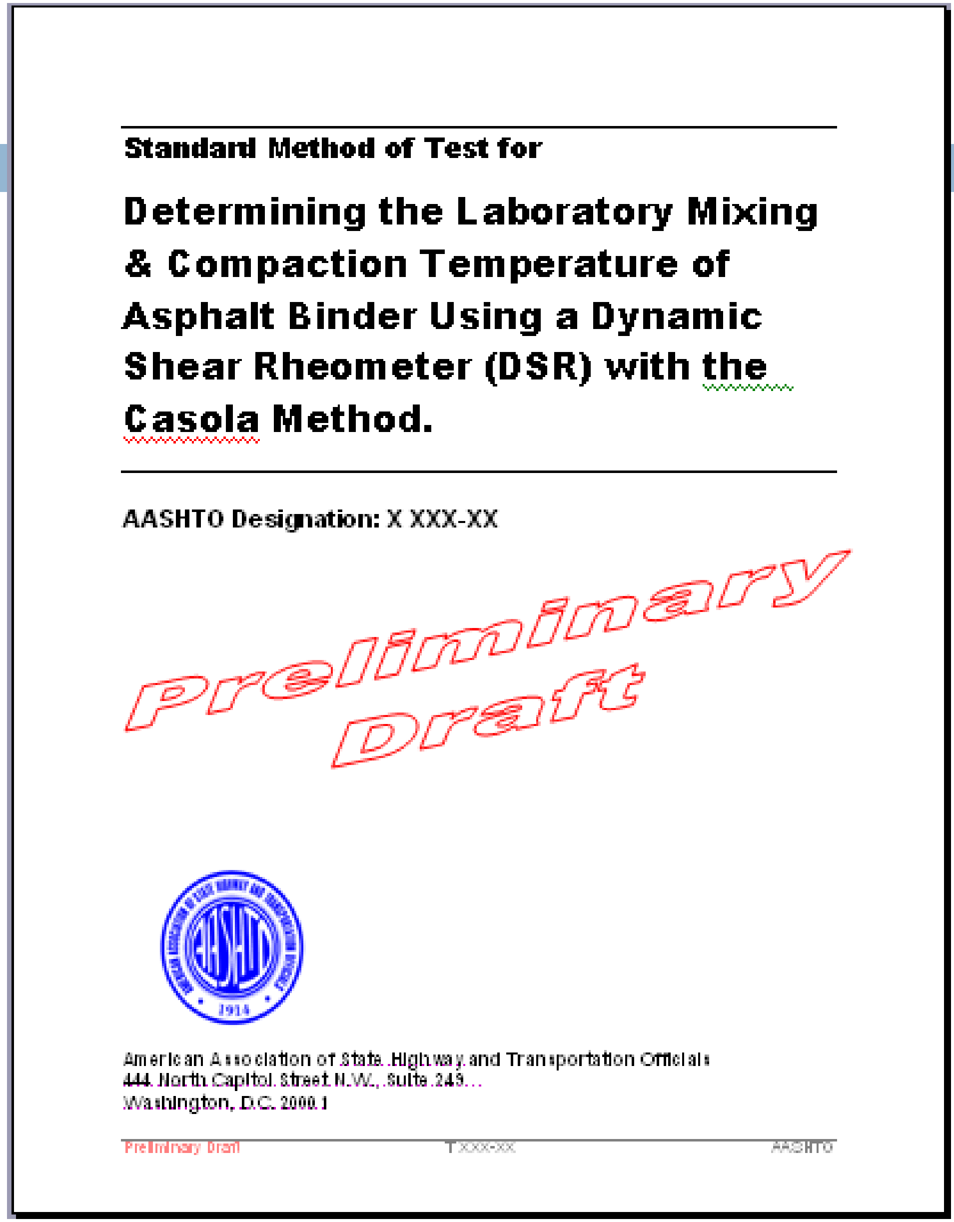
Asphalt Binder Mix & Compaction Temperature Using the CASOLA Method					Temperature (°F)		Temperature (°C)	
					mix	compaction	mix	compaction
Sample #	Modification Type	DSR Data Collected			325 -0.0135	300 -0.012	F to C	F to C
		temp (°C)	phase (°)	freq (rad/sec)				
C	SBS	80	85.96	0.13	334	307	168	153
O	None	80	86.06	62.6	307	285	153	141

$325(freq)^{-0.0135}$

$300(freq)^{-0.012}$

The Procedure…

- Test asphalt binders using existing DSRs



Standard Method of Test for

Determining the Laboratory Mixing & Compaction Temperature of Asphalt Binder Using a Dynamic Shear Rheometer (DSR) with the Casola Method.

AASHTO Designation: X XXX-XX

Preliminary Draft

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249…
Washington, D.C. 20001

Preliminary Draft | T XXX-XX | AASHTO

Data is collected at several temperatures

4.4 The required temperatures to test the sample will depend on the Performance Grade (PG) of the binder. Lower PG binders will be tested at lower temperatures while higher PG binders will be tested at higher temperatures. All grades will be tested at 80°C. The chart in Table 1. below provides a guide to temperature selection.

Table 1—Temperature testing schedule

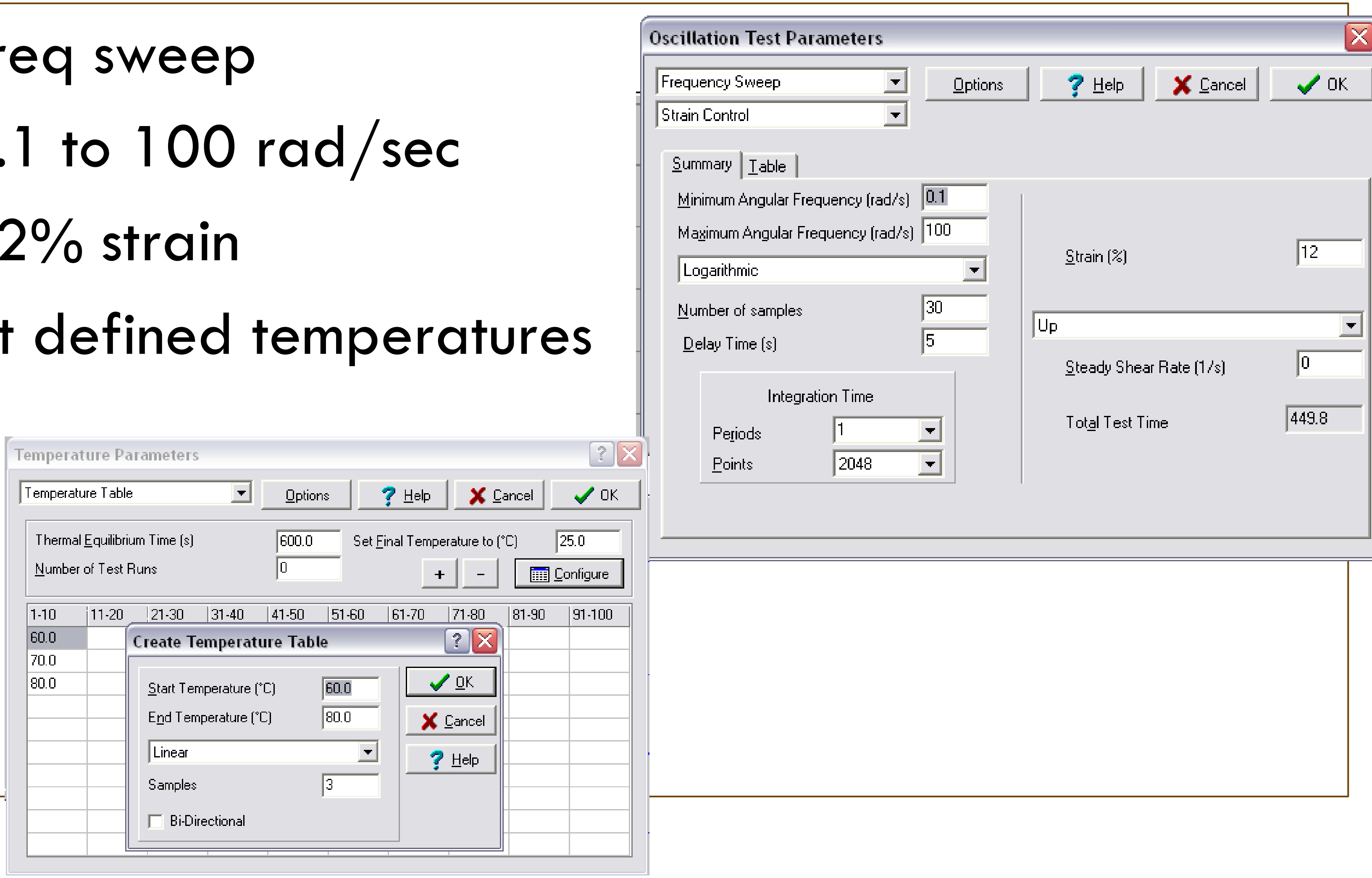
Temperature °C	Nominal PG value 46	52	58	64	70	76	82	88	94
40	xx	xx	xx						
50	X	X	X	xx	xx				
60	X	X	xx	X	xx	xx			
70	xxx	xxx	X	X	X	xx	xx		
80	X	X	X	X	X	X	xx	xx	xx
90			xxx	xxx	X	X	X	xx	xx
100					xxx	X	X	X	X
110					xxx	xxx	X	X	
120						xxx	xxx	X	X
130						xxx	xxx	xxx	xxx
140							xxx	xxx	X
									xxx

xx	May be required to achieve a phase angle of 75 degrees
xxx	May be required to achieve a phase angle of 88 degrees

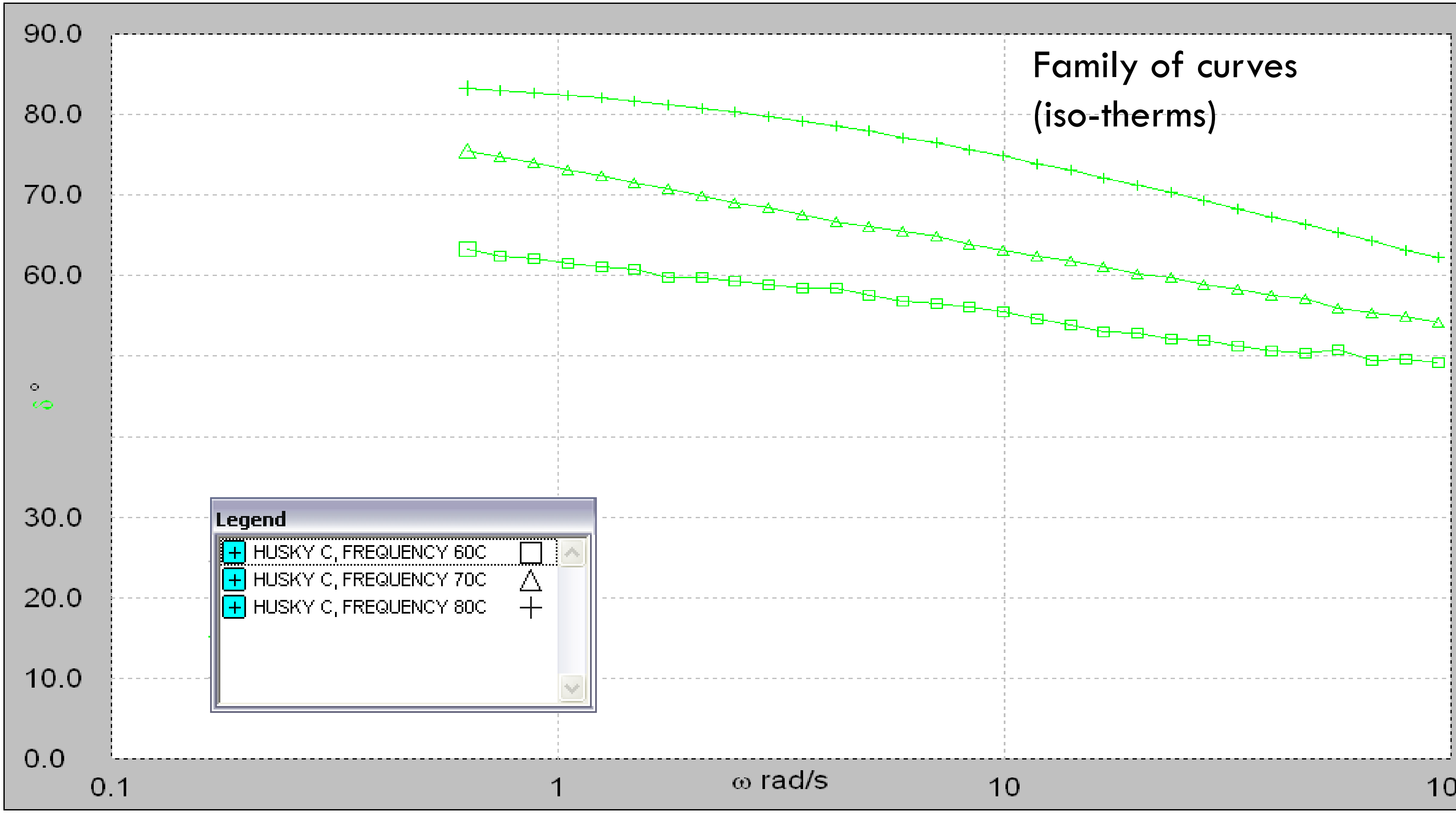
4.5 Test specimens 1 mm thick by 25 mm in diameter are formed between parallel metal plates. During testing, one of the parallel plates is oscillated with respect to the other at pre-selected frequencies and rotational deformation amplitudes (strain control) (or torque amplitudes (stress control)). The required stress or strain amplitude depends upon the value of the complex shear modulus of the asphalt binder being tested. The required amplitudes have been selected to ensure that the measurements are within the region of linear behavior.

Test set up

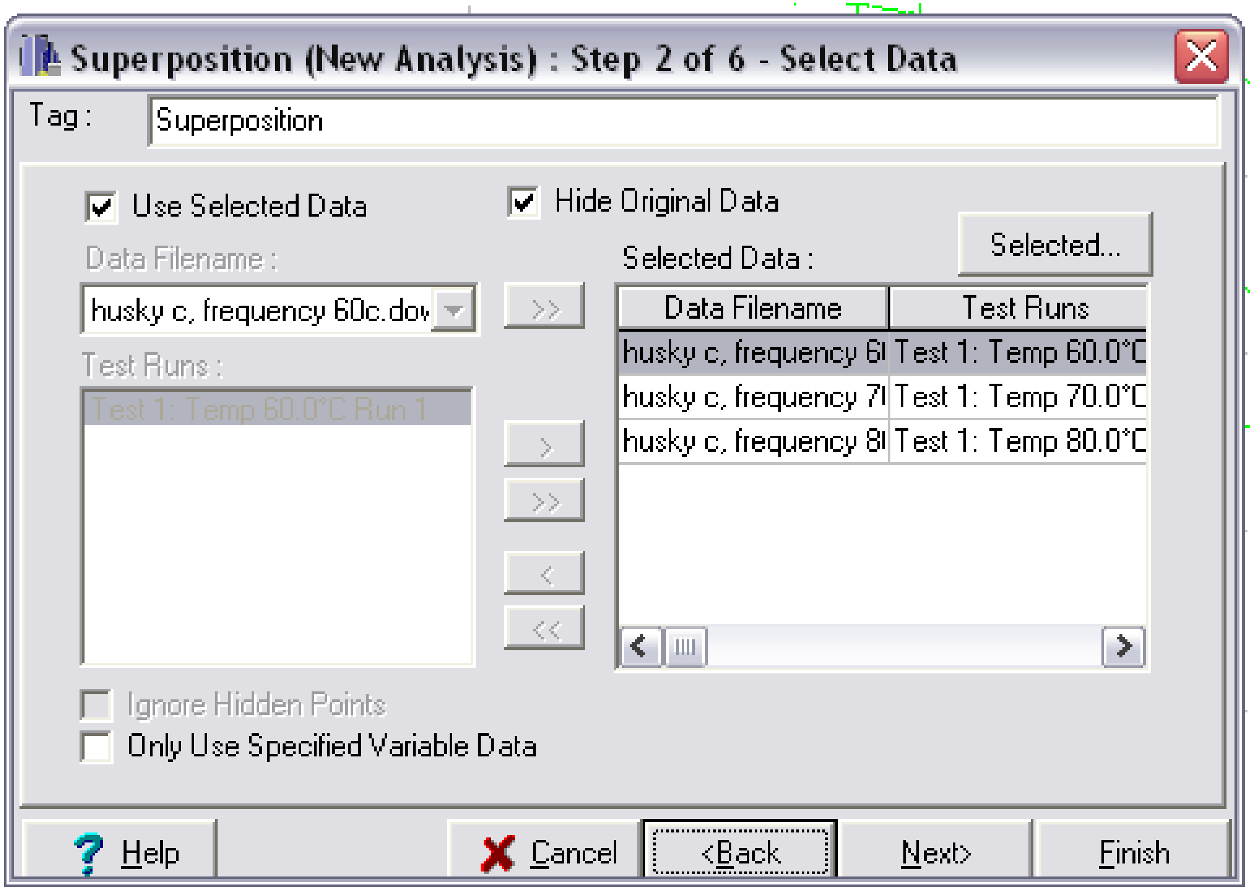
- Freq sweep
- 0.1 to 100 rad/sec
- 12% strain
- At defined temperatures



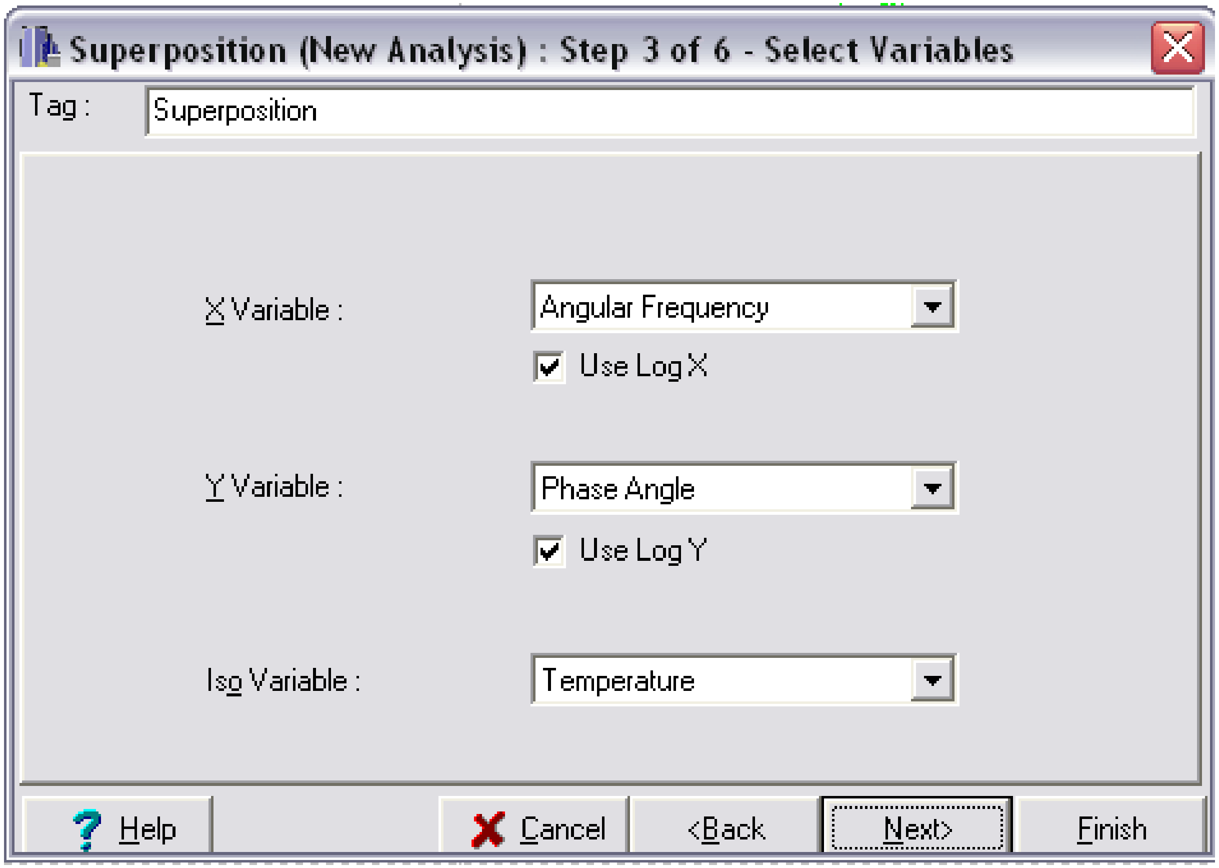
Analysis requires the creation of a master curve



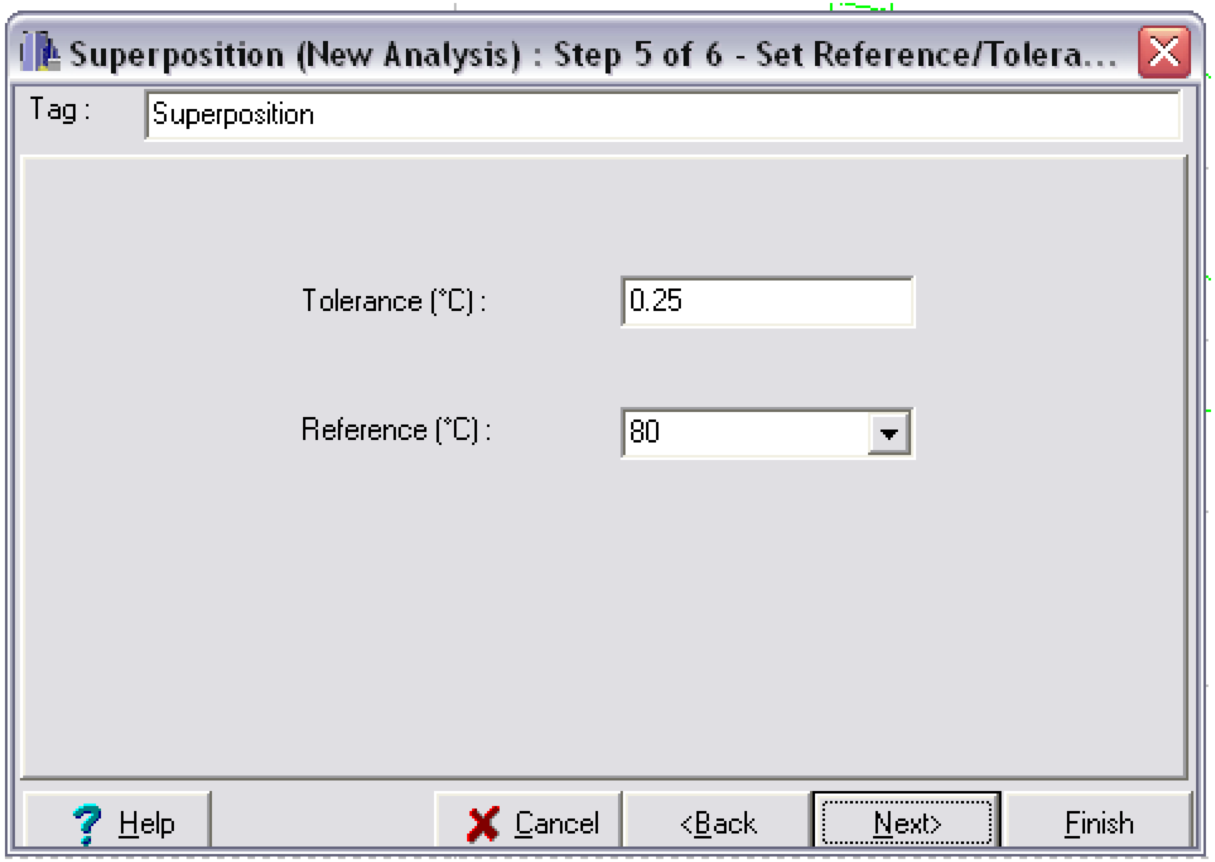
Superposition helps in the analysis



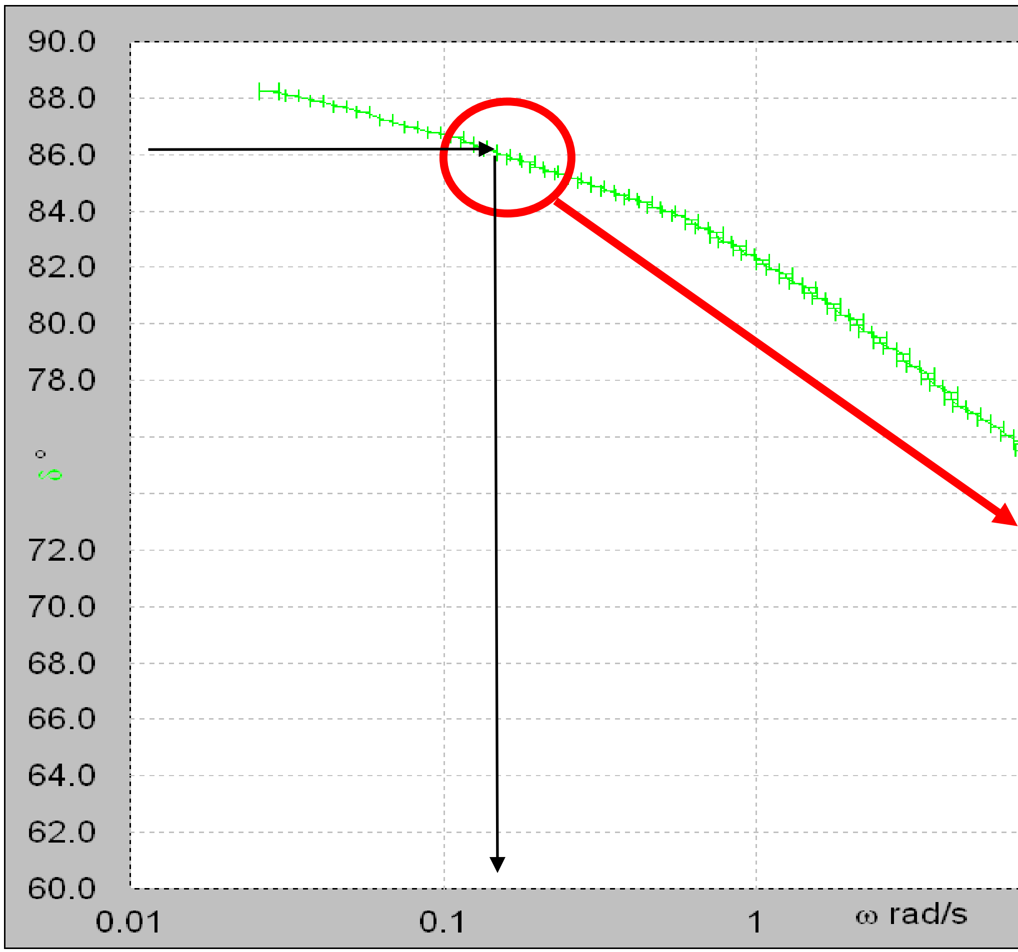
Superposition Variables



Reference Temperature at 80°C



Master Curve Results

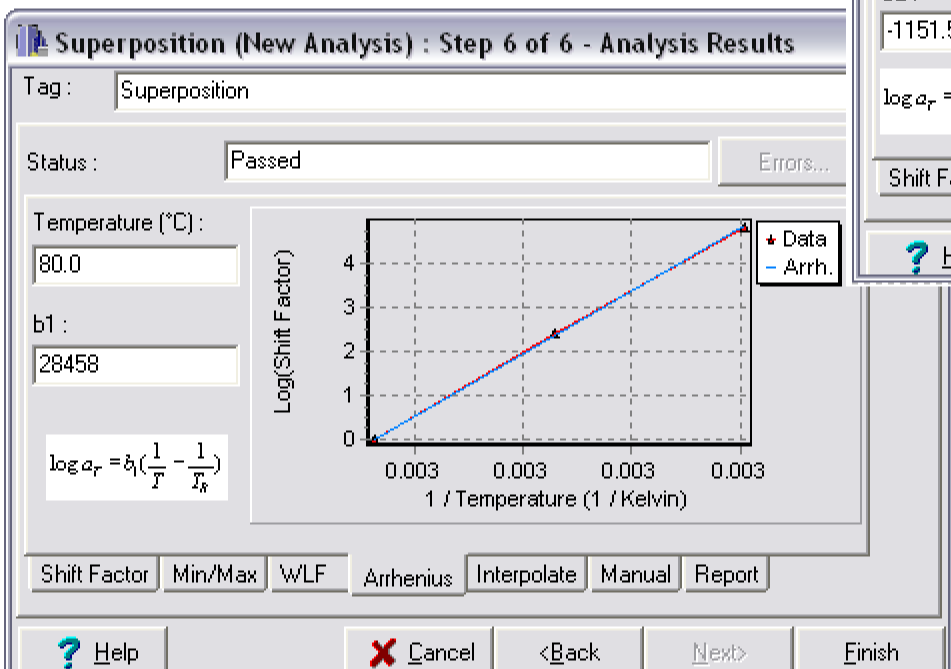


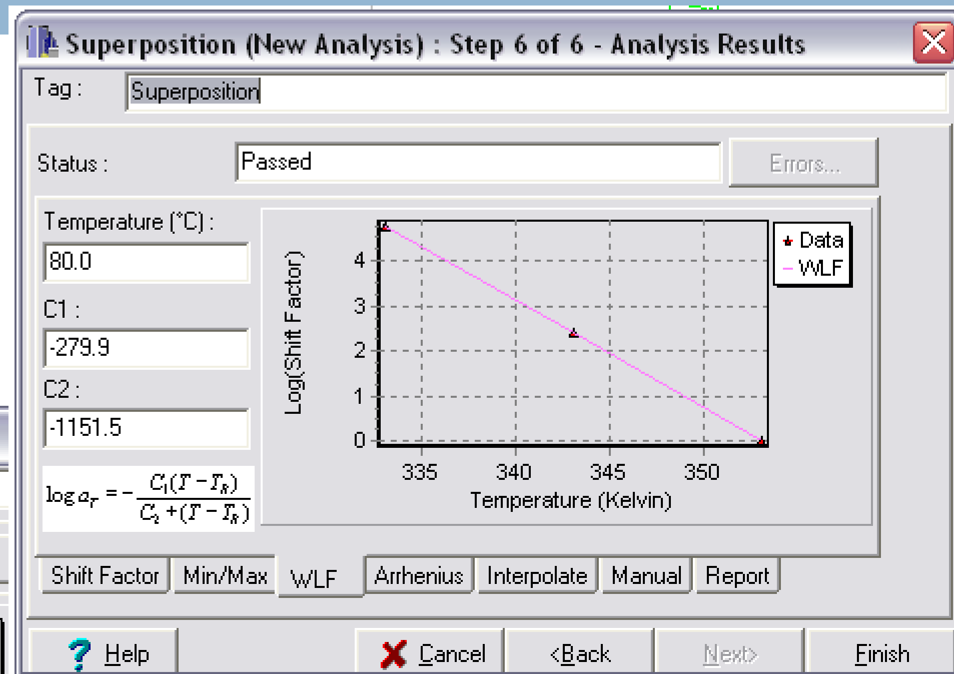
Superposition

Select Data | Export | Templates | Close | Help

Temperature T °C	Phase Angle δ °	Angular Freque ω rad/s	Complex Modul G* Pa
80.0	88.21	0.0279734	4.6621
80.0	88.17	0.0332492	5.4115
80.0	87.87	0.0395209	6.4225
80.0	87.66	0.046973	7.5856
80.0	87.47	0.055835	8.9063
80.0	87.27	0.0663642	10.482
80.0	87.06	0.0788795	12.35
80.0	86.84	0.0937586	14.528
80.0	86.65	0.111441	17.049
[illegible]	85.40	0.119279	19.7[illegible]
80.0	86.40	0.13246	20.043
80.0	85.21	0.141775	23.298
80.0	86.18	0.157443	23.608
80.0	85.05	0.168517	27.329
80.0	85.95	0.187137	27.823
80.0	84.86	0.200293	32.063
80.0	85.74	0.222431	32.795
80.0	84.66	0.238081	37.651
80.0	85.47	0.264383	38.518
80.0	84.44	0.282977	44.161
80.0	85.22	0.314254	45.41
80.0	84.26	0.336343	51.759
80.0	84.90	0.373529	53.523

Shift Factors are used to check data quality





Procedure discusses data quality

X15. VERIFICATION OF MASTER CURVE WORKING DATA BY USING BLACK SPACE DIAGRAM

X15.1. A good example of a Black Space diagram where there is shown a continuous curve exhibited in the results (Figure X15.1). This is where there are not obvious discontinuities.

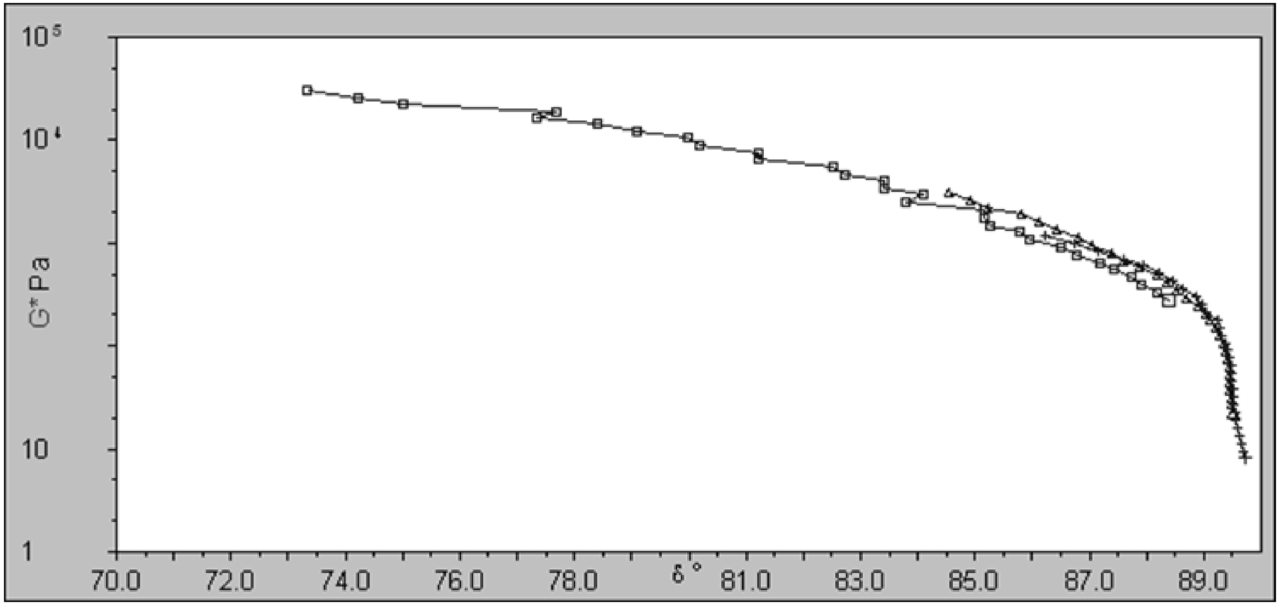


FIGURE X15.1- Good example of Black Space diagram

Discontinuities are an example of poor data

X15.2. A poor example of a Black Space diagram, where there are obvious discontinuities in the results (Figure X15.2). In the case of a poor Black Space, the data should be retested with particular attention to ensuring all the data are collected in the linear visco-elastic region by ensuring the correct strains are applied properly to all frequencies and that the temperatures are correct for each frequency tested. (Figure X15.2)

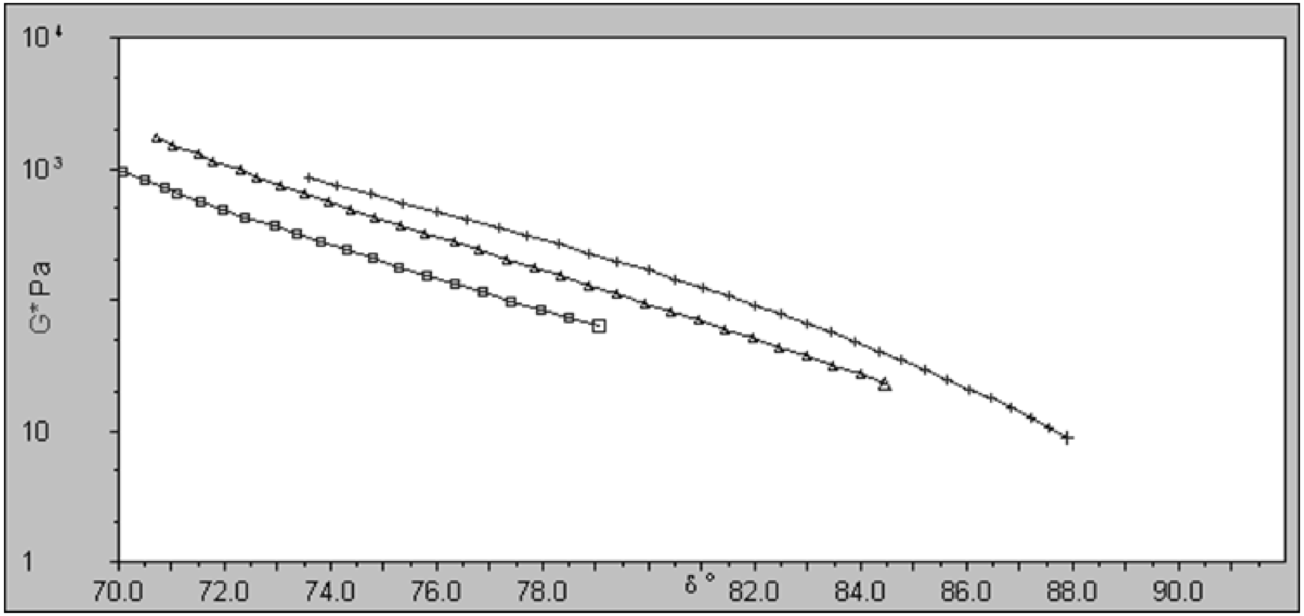


FIGURE X15.2- Poor example of Black Space diagram

Summary Review

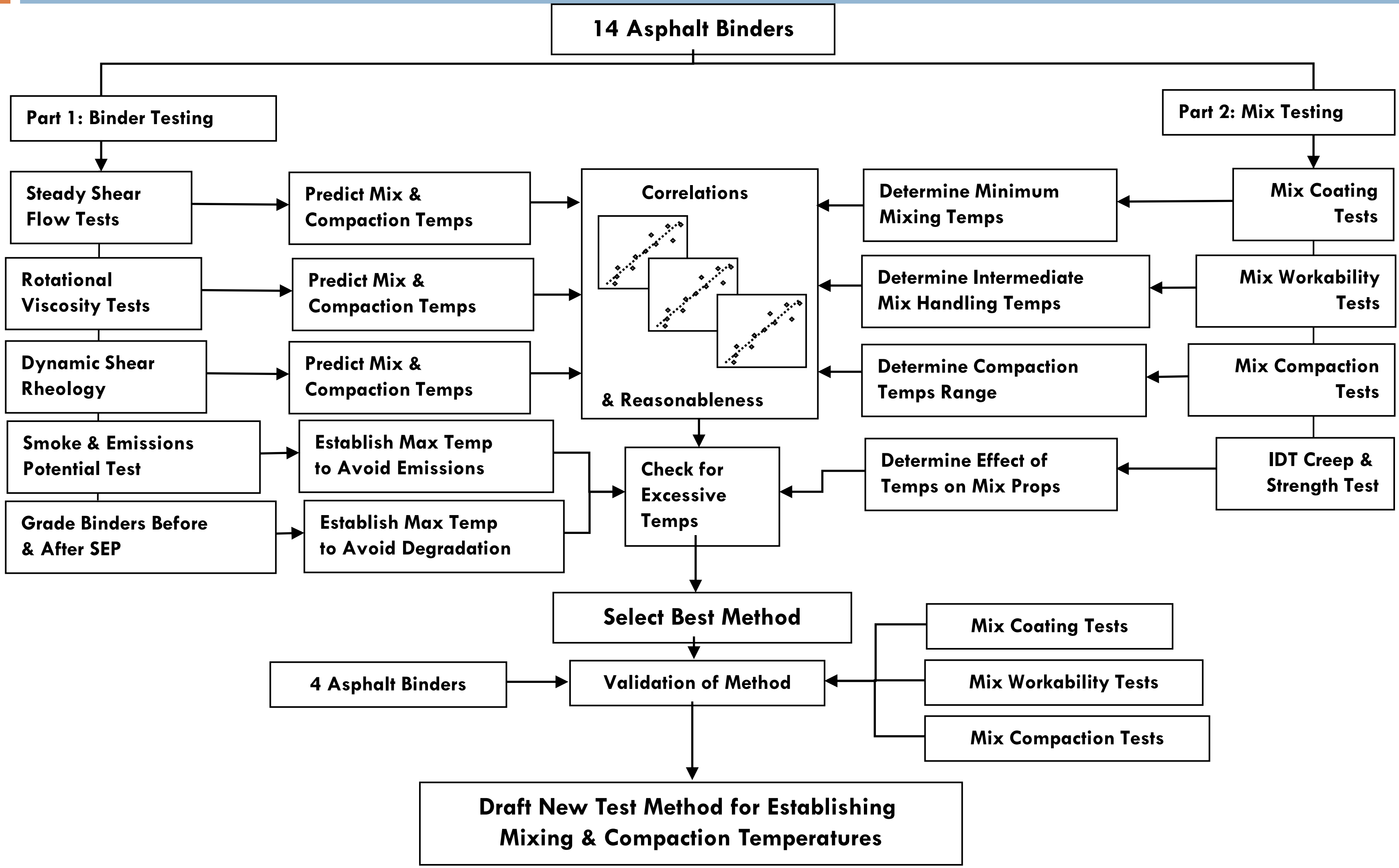
- Collect family of Freq Sweep at various temps as needed to collect phase angle data crossing 86°
- Perform WLF time-temp superposition master curve for results shifted to 80°C
- Check shift factors and/or Blacks curves to verify data quality
- Identify the Frequency where the phase angle equals 86° within +/-0.1° phase angle
- Calculate mixing temp using $325(\text{freq})^{-0.0135}$
- Calculate compaction temp using $300(\text{freq})^{-0.012}$

RESEARCH PLAN

Research Approach

- Use candidate methods to predict mixing and compaction temperatures
- Check reasonableness
- Use mix tests to validate mixing and compaction temperatures
- Use correlation analyses between predicted mix and compaction temps with mix test results
- Determine temperature limits that cause binder degradation and emissions problems

Work Plan Flow Chart



High Shear Viscosity method results

Binder ID	True Grade	Mixing Temperature F (C)		Compaction Temperature F (C)	
		Equiviscous Method	High Shear Viscosity	Equiviscous Method	High Shear Viscosity
M	85.5 -19.5	372 (189)	363 (184)	343 (173)	336 (169)
N	84.3 -25.5	433 (223)	433 (223)	401 (205)	401 (205)
G	82.5 -24.2	379 (193)	372 (189)	352 (178)	349 (176)
H	78.3 -26.1	365 (185)	363 (184)	338 (170)	338 (170)
C	75.1 -38.7	388 (198)	385 (196)	355 (179)	352 (178)
I	71.8 -29.2	333 (167)	333 (167)	311 (155)	311 (155)
B	69.3 -37.3	354 (179)	352 (178)	325 (163)	325 (163)
F	67.8 -21.3	320 (160)	318 (159)	298 (148)	297 (147)
O	65.6 -29.7	318 (159)	318 (159)	293 (145)	297 (147)
K	65.3 -13.0	295 (146)	295 (146)	271 (132)	275 (135)
J	64.3 -20.7	295 (146)	295 (146)	275 (135)	273 (134)
E	60.9 -33.1	293 (145)	293 (145)	298 (148)	297 (147)
D	60.3 -31.7	295 (146)	297 (147)	275 (135)	297 (137)

SSF method results

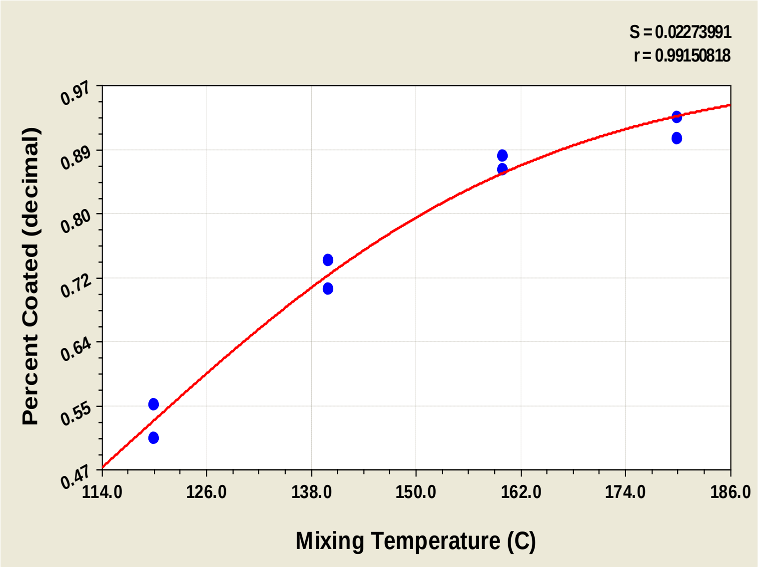
Binder ID	True Grade	Mixing Temperature F (C)		Compaction Temperature F (C)	
		Equiviscous Method	Steady Shear Flow Viscosity	Equiviscous Method	Steady Shear Flow Viscosity
M	85.5 -19.5	372 (189)	296 (147)	343 (173)	275 (135)
N	84.3 -25.5	433 (223)	337 (169)	401 (205)	311 (155)
G	82.5 -24.2	379 (193)	340 (171)	352 (178)	312 (156)
H	78.3 -26.1	365 (185)	333 (167)	338 (170)	304 (151)
C	75.1 -38.7	388 (198)	320 (160)	355 (179)	291 (144)
I	71.8 -29.2	333 (167)	316 (158)	311 (155)	289 (143)
B	69.3 -37.3	354 (179)	325 (163)	325 (163)	295 (146)
F	67.8 -21.3	320 (160)	309 (154)	298 (148)	281 (138)
O	65.6 -29.7	318 (159)	309 (154)	293 (145)	280 (138)
K	65.3 -13.0	295 (146)	280 (138)	271 (132)	257 (125)
J	64.3 -20.7	295 (146)	289 (143)	275 (135)	263 (128)
E	60.9 -33.1	293 (145)	293 (145)	298 (148)	269 (132)
D	60.3 -31.7	295 (146)	289 (143)	275 (135)	262 (128)

Casola method results

Binder ID	True Grade	Freq. at δ=86 T=80 C	Mixing Temp. F (C)		Compaction Temp. F (C)	
			Equiviscous Method	Phase Angle Method	Equiviscous Method	Phase Angle Method
M	85.5 -19.5	0.07	372 (189)	337 (169)	343 (173)	310 (154)
N	84.3 -25.5	0.03	433 (223)	341 (172)	401 (205)	313 (156)
G	82.5 -24.2	0.03	379 (193)	341 (172)	352 (178)	313 (156)
H	78.3 -26.1	0.22	365 (185)	332 (167)	338 (170)	305 (152)
C	75.1 -38.7	0.21	388 (198)	332 (167)	355 (179)	306 (152)
I	71.8 -29.2	2.98	333 (167)	320 (160)	311 (155)	296 (147)
B	69.3 -37.3	1.10	354 (179)	325 (163)	325 (163)	300 (149)
F	67.8 -21.3	75.00	320 (160)	307 (153)	298 (148)	285 (141)
O	65.6 -29.7	21.12	318 (159)	312 (156)	293 (145)	289 (143)
K	65.3 -13.0	800	295 (146)	297 (147)	271 (132)	277 (136)
J	64.3 -20.7	580	295 (146)	298 (148)	275 (135)	278 (137)
E	60.9 -33.1	37.85	293 (145)	309 (154)	298 (148)	287 (142)
D	60.3 -31.7	122.56	295 (146)	305 (152)	275 (135)	283 (139)

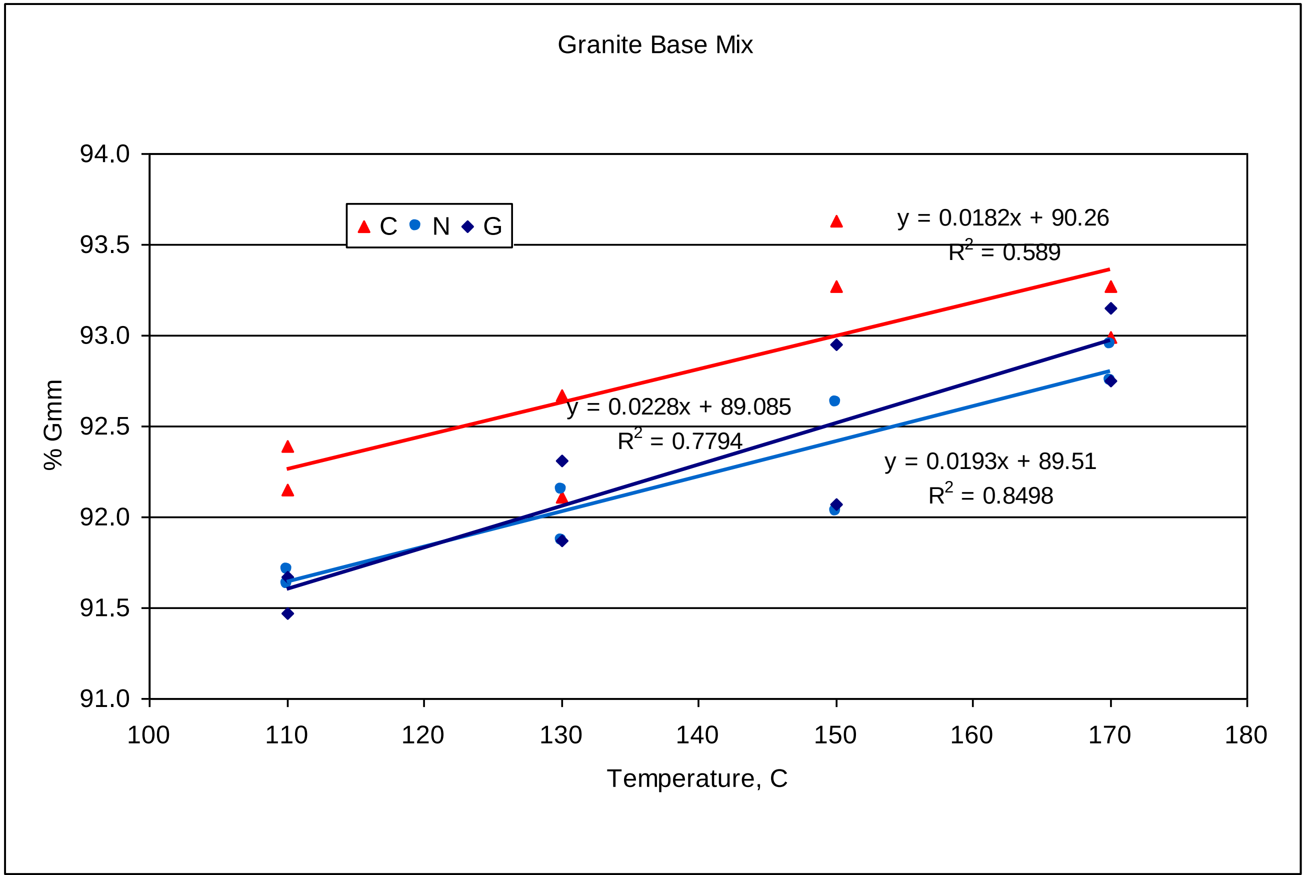
Mix Coating Tests

- Lab Pugmill Mixer and Bucket Mixer to simulate Batch Plant and Drum Plant Mixing
- Mix binders with a standard aggregate blend at four temperatures for a set time
- Rate aggregate coating percentage using Ross count

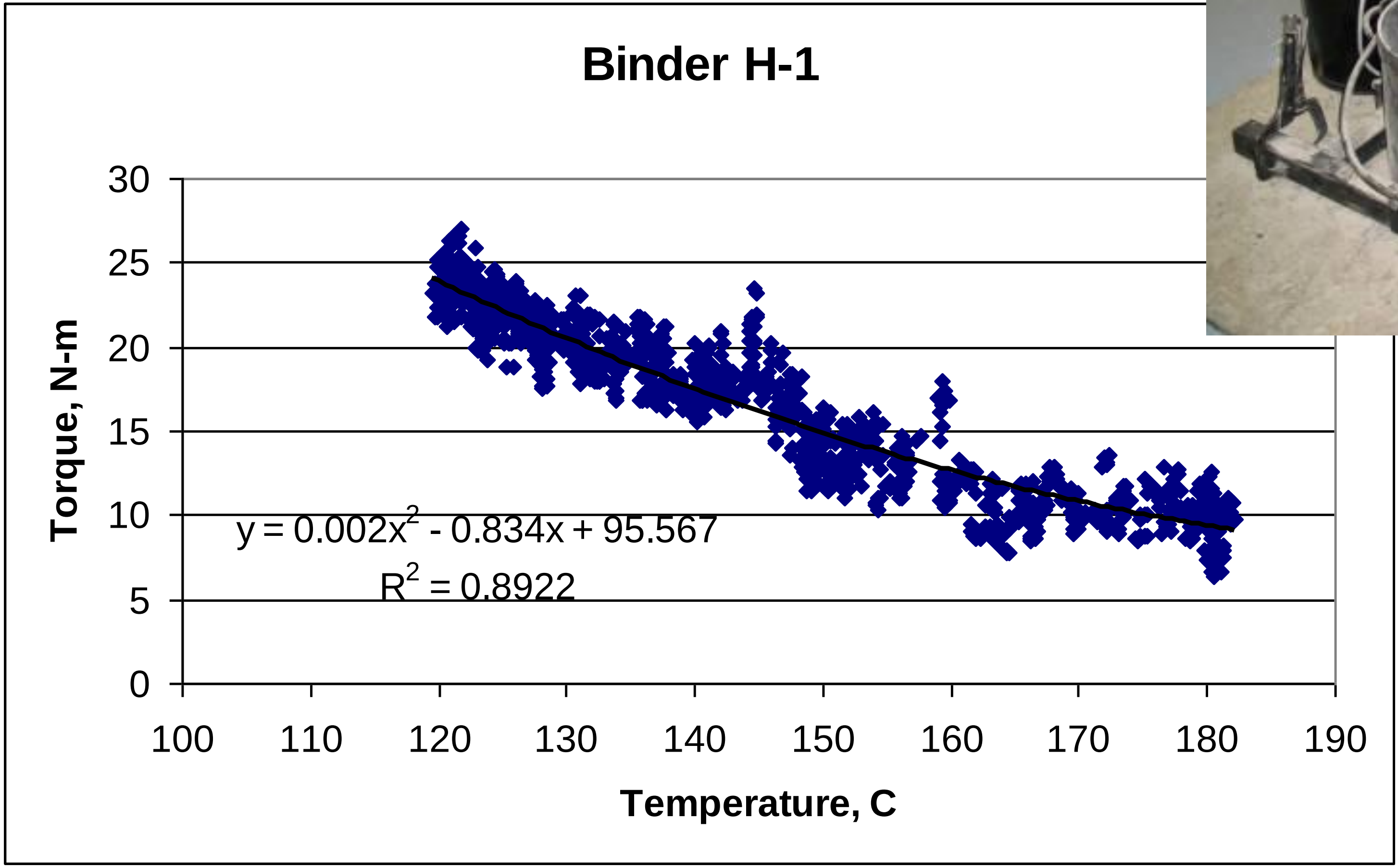


Mix Compactability

- Four compaction temperatures
- Used 25 gyrations to amplify effect of binder stiffness



Mix Workability

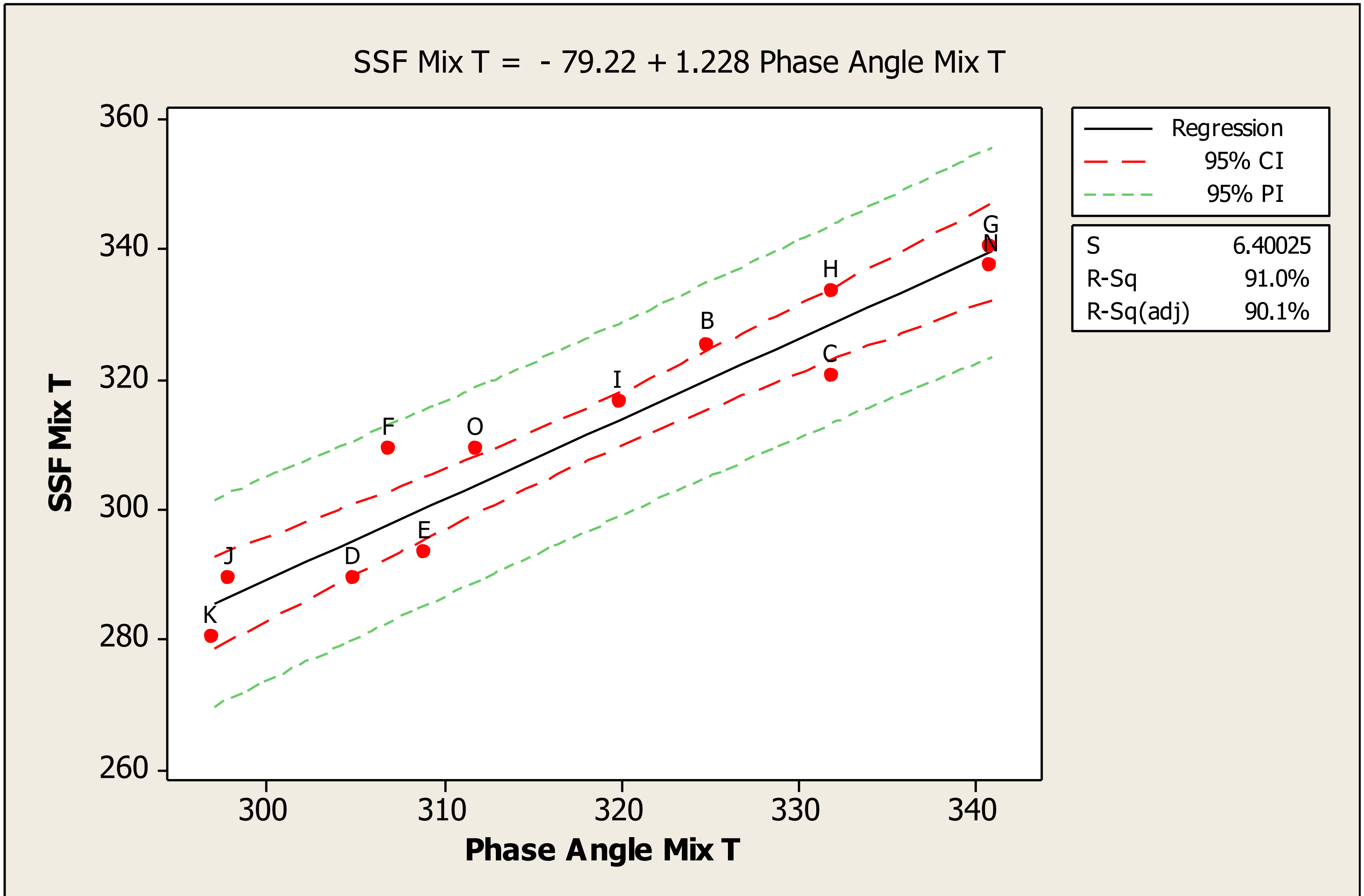


CORRELATION ANALYSES: REGRESSIONS BETWEEN RESULTS OF CANDIDATE METHODS TO MIXTURE TESTS

Statistical Comparison of Results

	Steady Shear Flow			Casola		
Mix Test	Std. Error	R^2	*p*-value	Std. Error	R^2	*p*-value
Coating: Bucket	22.1	40.8	0.025	25.3	22.4	0.121
Coating: Pugmill	27.3	34.6	0.044	25.7	41.9	0.023
Workability	34.0	30.6	0.050	30.5	44.3	0.013
Compaction	18.7	68.4	0.002	16.7	74.8	0.001

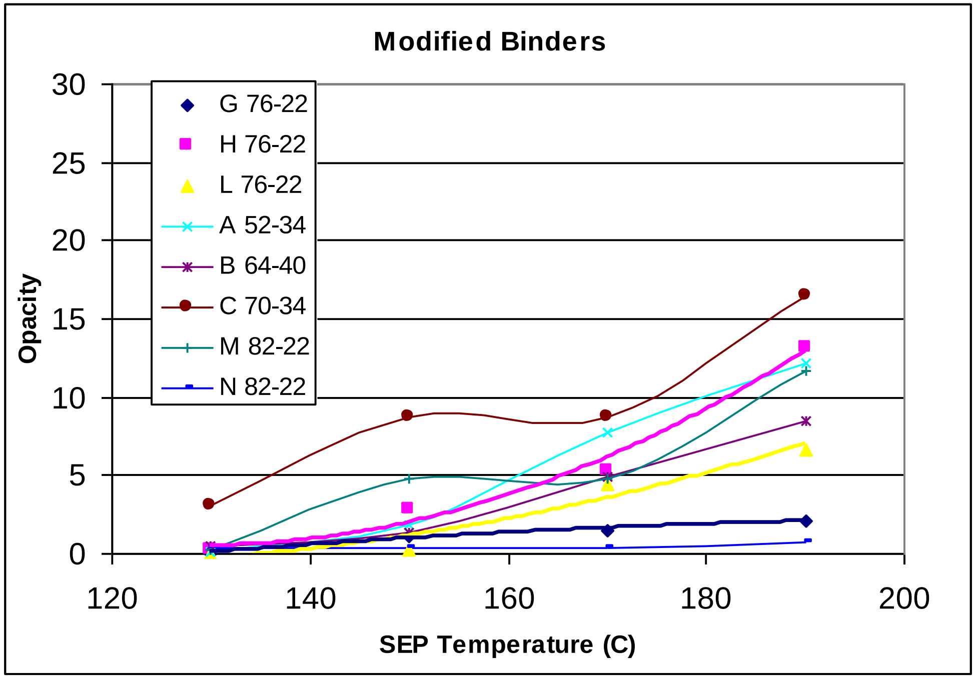
Comparison of SSF and Casola Results

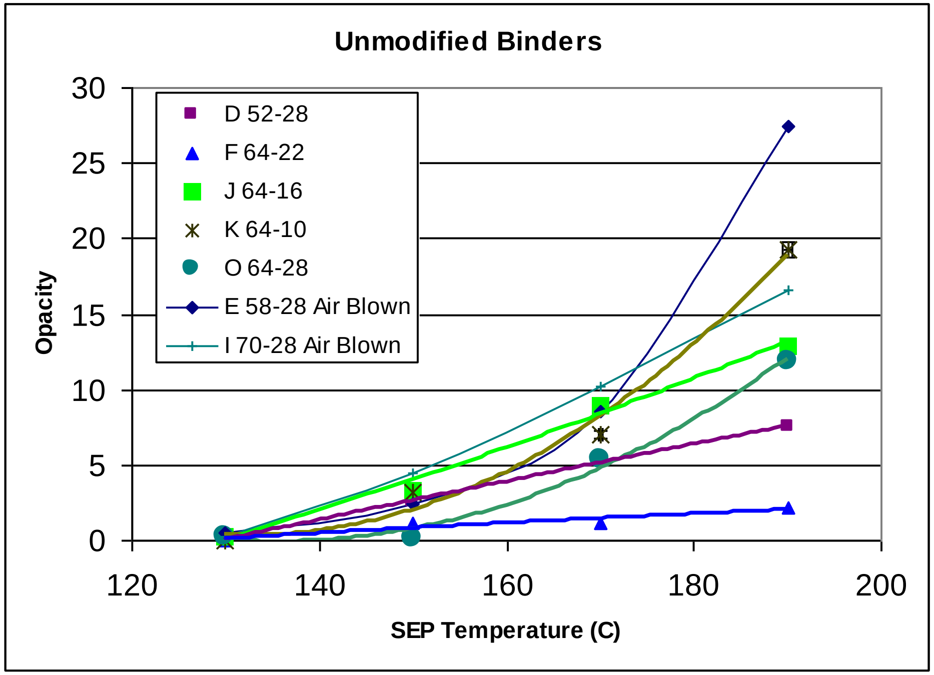


Smoke & Emissions Potential

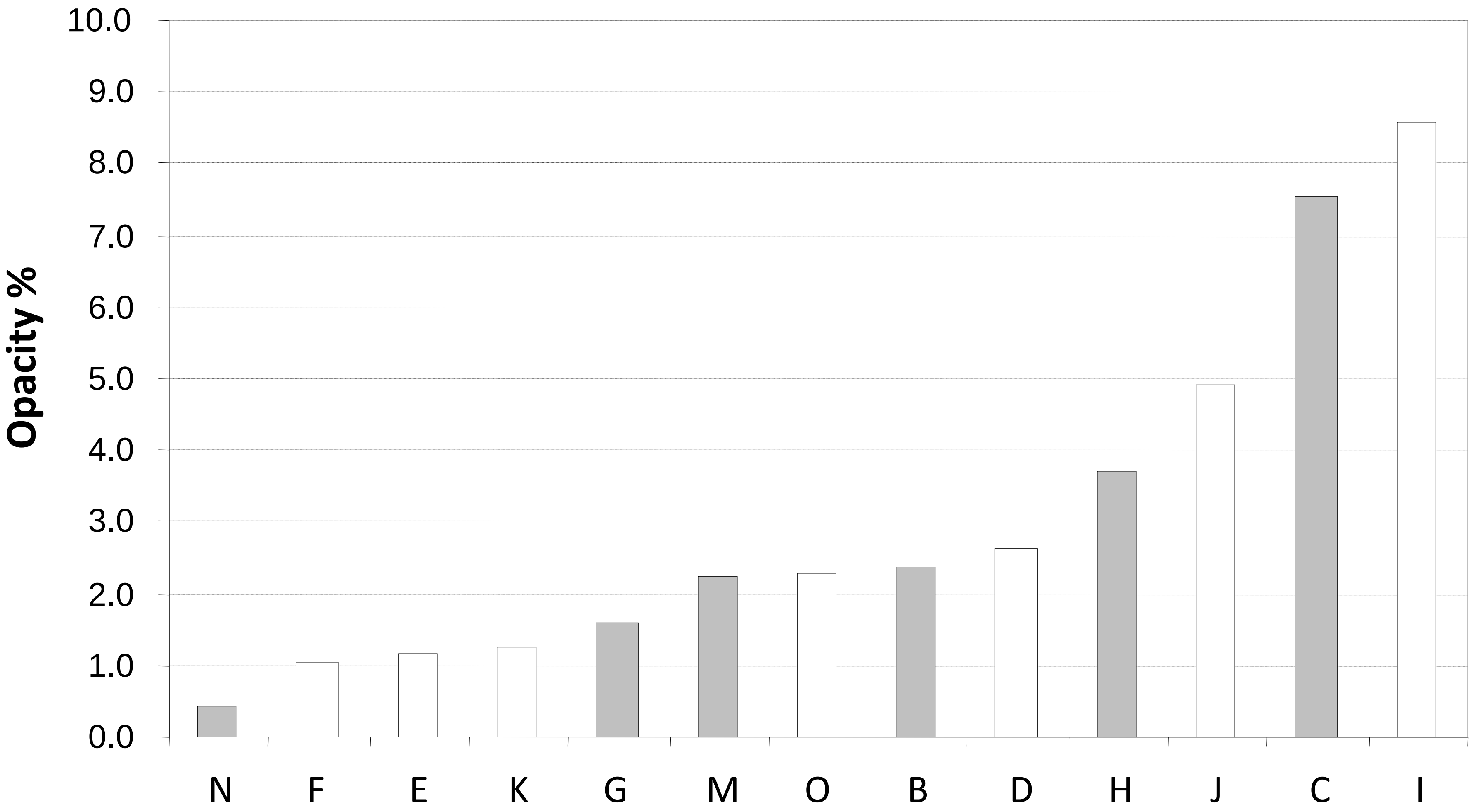
- Stroup-Gardiner and Lange
- Oven with Opacity Meter and Internal Balance
- Tests conducted at 130, 150, 170, and 190°C
- Use to evaluate maximum temperature binder can be used without degrading the binder or causing emission problems.

Opacity Results





Opacity at Producers' Recommended Mixing Temp.



Evaluation of Degradation of SEP Conditioned Binders

1. changes in the true grade critical high temperature of the binders
2. changes in the true grade critical low temperature of the binders
3. changes in the phase angle of the binders at their respective grade temperatures
4. changes in the MSCR non-recoverable creep compliance

Change in High Temp Grade

Binder ID	True Grade	SEP Temperature (C)			
		130	150	170	190
M	85.5 -19.5	3.0	4.2	5.4	6.8
N	84.3 -25.5	-1.3	1.4	4.6	6.7
G	82.5 -24.2	7.4	5.4	6.2	7.3
H	78.3 -26.1	3.2	1.4	8.0	9.7
C	75.1 -38.7	1.1	1.5	2.8	4.4
I	71.8 -29.2	5.5	4.7	8.8	12.1
B	69.3 -37.3	1.8	2.3	3.1	5.2
F	67.8 -21.3	2.4	3.3	6.5	5.8
O	65.6 -29.7	3.5	4.6	8.0	10.4
K	65.3 -13.0	1.8	2.0	3.0	4.6
J	64.3 -20.7	4.8	5.1	6.9	8.1
E	60.9 -33.1	1.9	2.5	5.0	8.6
D	60.3 -31.7	2.1	2.9	4.4	5.6
Avg. of Modified Binders		2.5	2.7	5.0	6.7
Avg. of Unmodified Binders		3.1	3.6	6.1	7.9

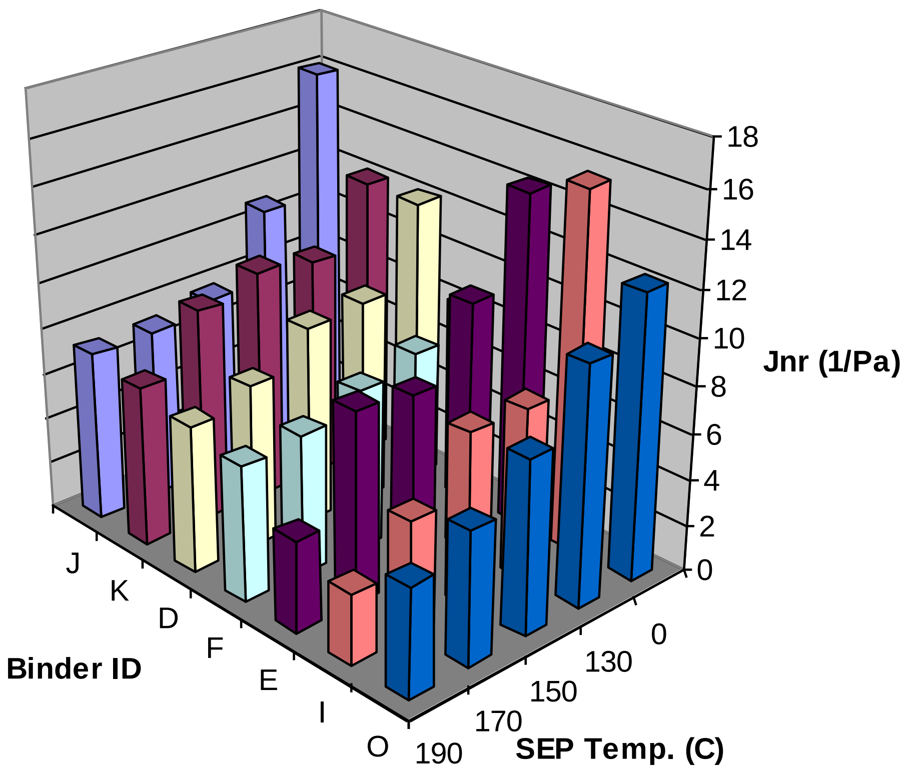
Change in Low Temp Grade

Binder ID	True Grade	SEP Temperature (C)			
		130	150	170	190
M	85.5 -19.5	1.8	3.1	2.2	2.2
N	84.3 -25.5	7.1	5.2	5.0	6.0
G	82.5 -24.2	0.3	1.9	0.7	3.0
H	78.3 -26.1	2.4	3.7	5.1	3.4
C	75.1 -38.7	2.1	2.8	1.2	0.8
I	71.8 -29.2	2.2	3.8	5.4	6.0
B	69.3 -37.3	-0.4	0.8	1.1	0.7
F	67.8 -21.3	2.6	3.1	5.4	2.8
O	65.6 -29.7	5.9	6.1	6.9	7.7
K	65.3 -13.0	5.5	2.5	3.6	3.0
J	64.3 -20.7	6.7	6.5	7.4	7.6
E	60.9 -33.1	2.5	3.7	3.1	3.9
D	60.3 -31.7	2.5	2.3	2.7	3.0
Avg. of Modified Binders		2.9	2.2	2.7	2.6
Avg. of Unmodified Binders		4.0	4.0	4.9	4.9

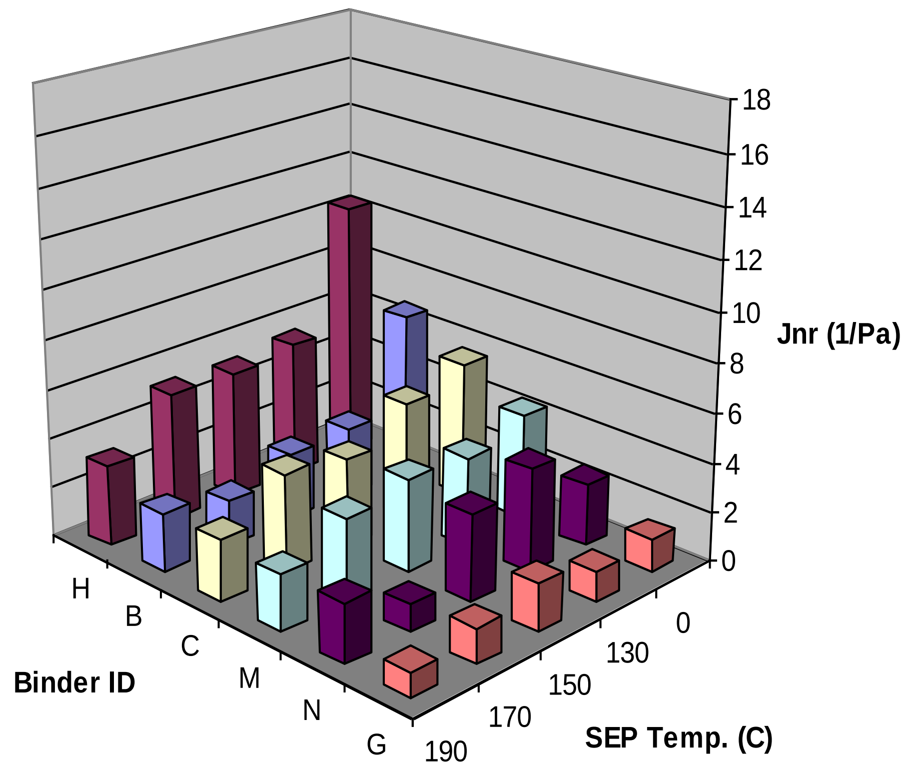
Change in Phase Angle

Binder ID	True Grade	SEP Temperature (C)			
		130	150	170	190
M	85.5 -19.5	-1.73	-0.62	0.05	-3.34
N	84.3 -25.5	-0.40	1.40	-3.50	-3.90
G	82.5 -24.2	-3.07	-3.76	-5.32	-4.02
H	78.3 -26.1	-2.10	-3.83	-4.57	-5.54
C	75.1 -38.7	1.66	1.18	0.97	-5.21
I	71.8 -29.2	-2.03	-2.44	-5.43	-6.80
B	69.3 -37.3	-3.18	-2.93	-4.73	-6.22
F	67.8 -21.3	1.89	1.70	0.12	0.13
O	65.6 -29.7	4.29	3.67	1.06	-0.42
K	65.3 -13.0	-1.06	-2.40	-1.03	-0.84
J	64.3 -20.7	-2.50	-1.00	-1.20	-2.80
E	60.9 -33.1	-0.31	-0.58	-1.96	-4.45
D	60.3 -31.7	-1.23	-2.35	-2.68	-3.57
Avg. of Modified Binders		-1.5	-1.4	-2.9	-4.7
Avg. of Unmodified Binders		-0.1	-0.5	-1.6	-2.7

MSCR Non Recoverable Compliance (Jnr)



Unmodified Binders



Modified Binders

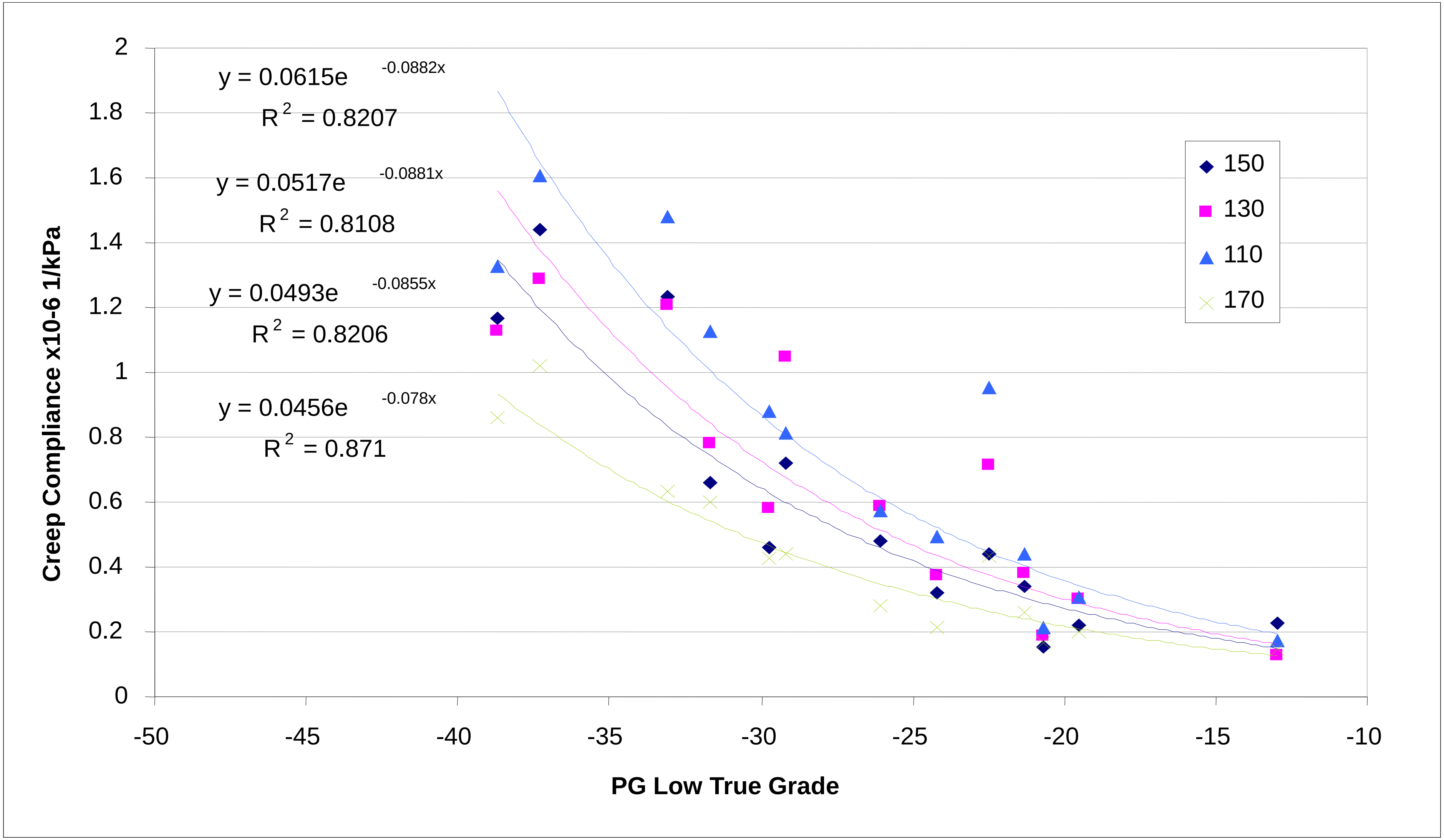
Observations on Binder Degradation from SEP test

- Opacity increases with temperature
- Opacity does not appear to be related to grade, or modification
- Four binders had mass losses > 1.0% which has been linked to high odor potential
- 8 of 13 binders increased high PG grade one level (e.g. PG 70- to a PG 76)
- 7 of 13 binders increased low PG grade level (e.g. -28 to a -22)

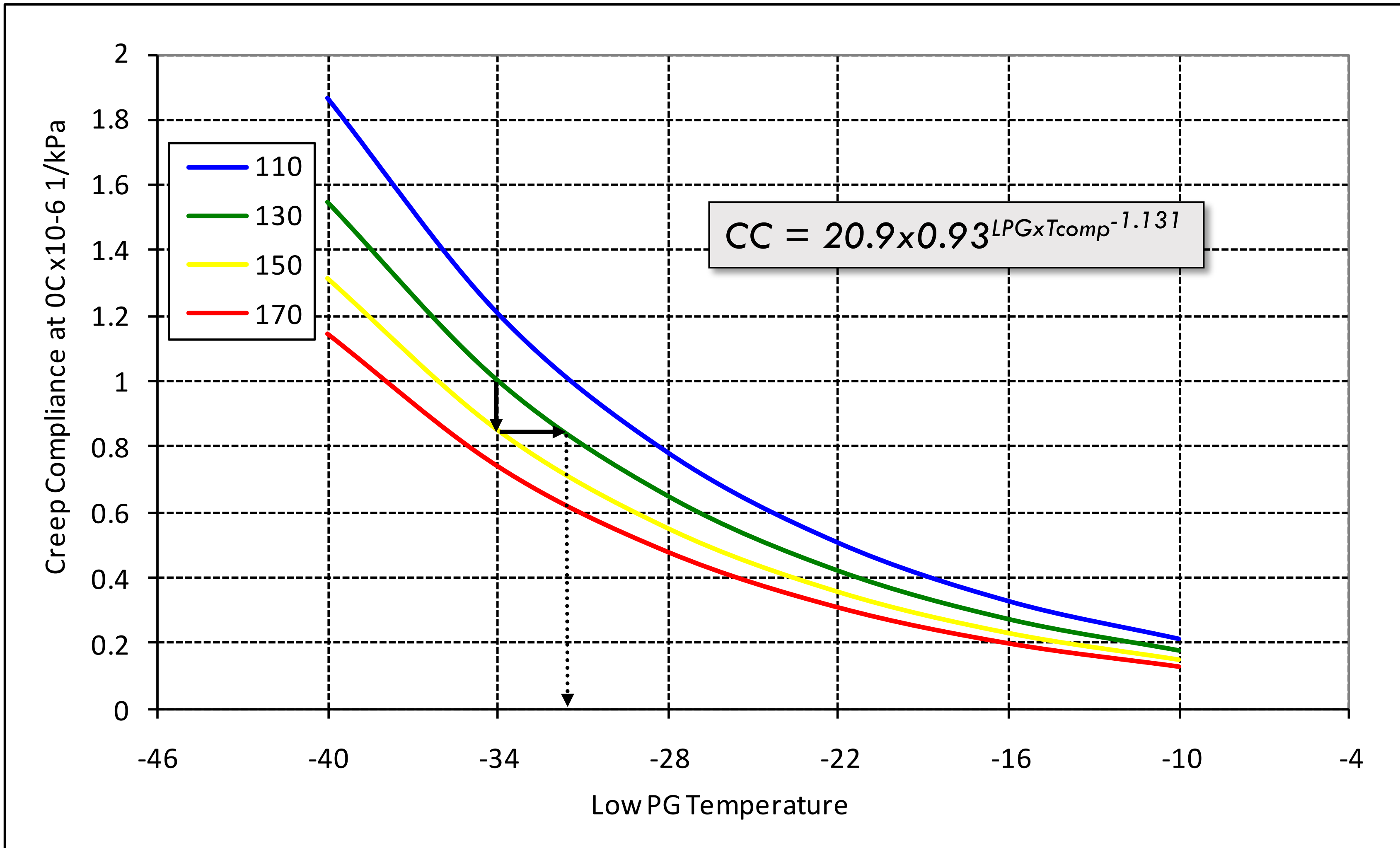
Creep Compliance and Strength

- Specimens compacted at 110, 130, 150, and 170°C
- AASHTO T 322
  - Compliance at -20, -10, 0°C
  - Strength at -10 or 0

Creep Compliance –
PG Low Temp. Relationships



Creep Compliance – PG Low Temp Relationships



Recommendations

- Steady Shear Flow or Phase Angle (Casola) Method are options for determining mixing and compaction temperatures
- Both methods can be easily included in routine PG binder testing
- These methods should be further evaluated by users to compare the results to their current recommendations and assess the validity of results

Limitations

- The recommended procedures are based only on binder characteristics. Other factors that effect coating and compactability include:
  - Aggregate & mineral filler characteristics
  - RAP & other recycled materials
  - Warm mix additives/processes
- The methods are not suitable for binders containing…
  - Some WMA technologies
  - Rubber

Different Views on Lab and Field Use of Mixing and Compaction Temperatures

- Some agencies set strict tolerances on discharge temperatures for plant mix using equiviscous temperatures.
- Some agencies consider equiviscous mixing and compaction temperatures applicable to the lab and use global temperature ranges in the field.

Any Questions?