

Examining Delta Tc: Variability Factors and Relationships with Other Rheological Shape Parameters

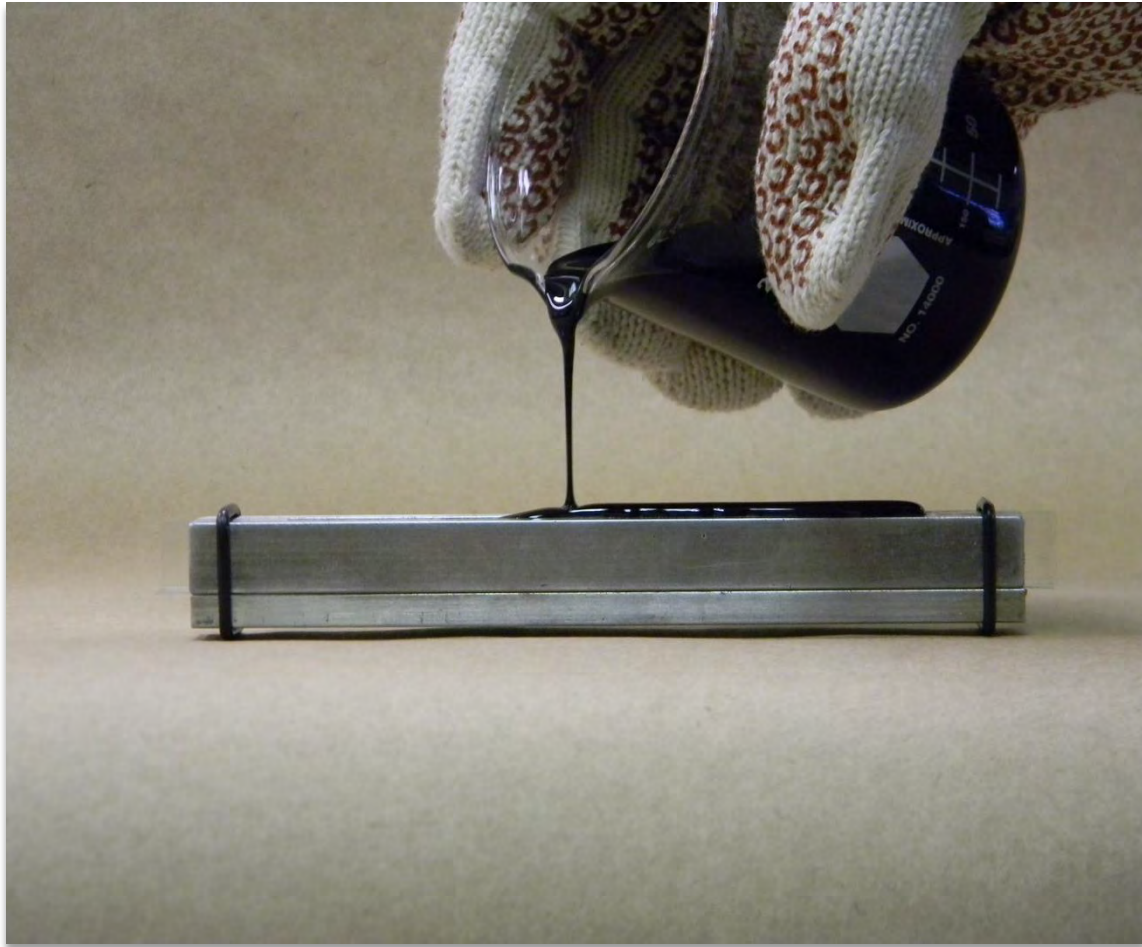
Wes Cooper, *Asphalt Institute*

NESMEA Annual Meeting

October 29, 2025 - Harrisburg, PA



Acknowledgements



- **Co-authors** - Jason Wielinski (AI) and Kelly Senger (IDOT)
- **ILS participants** – AI membership and IDOT testing community
- **IDOT and Asphalt Institute Technical Staff** – Mike Anderson (AI), Corey Nance (AI), Clay Snyder (IDOT)



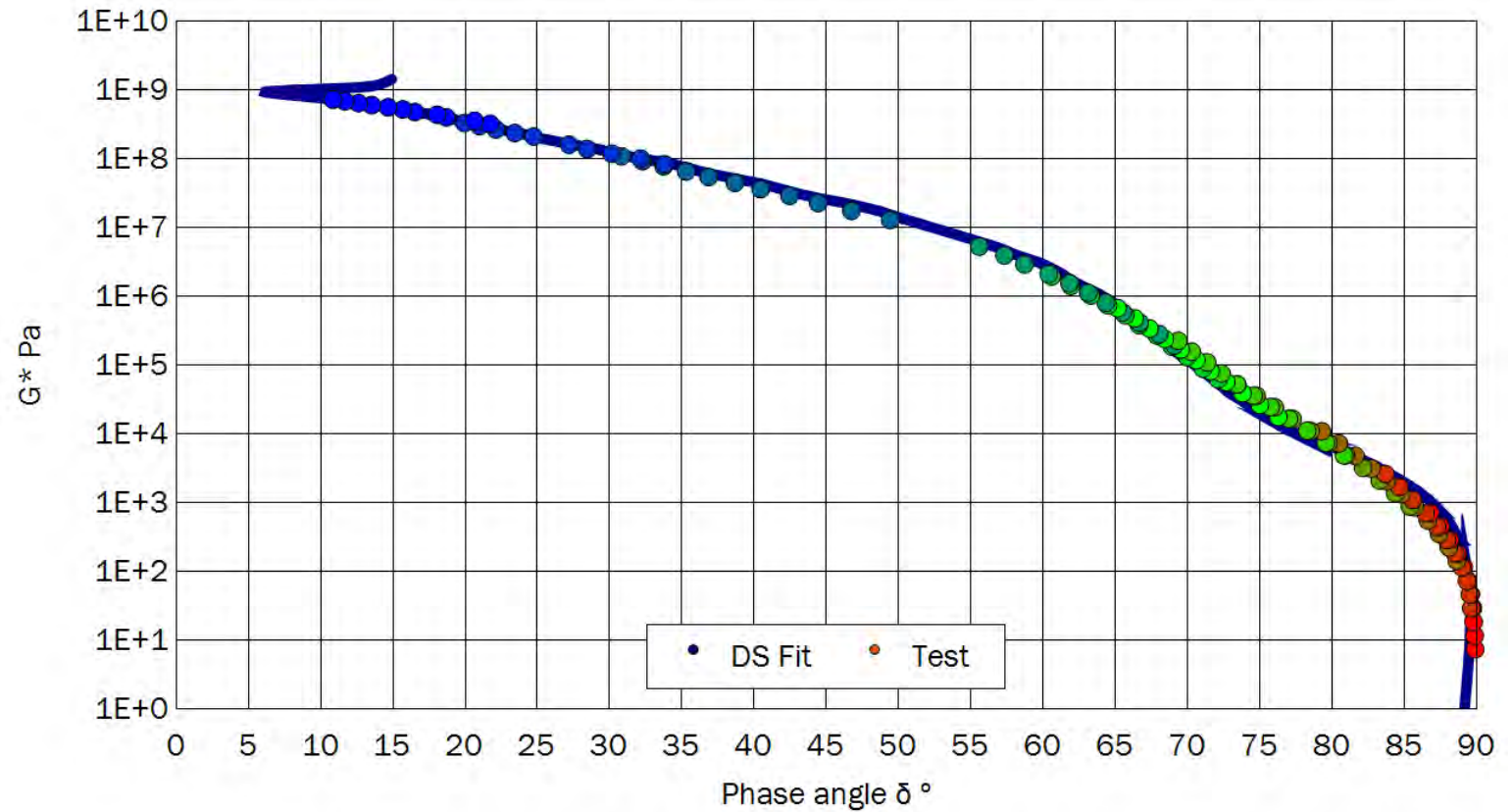
Background – Origins of ΔT_c

- Despite the advances of the PG system through SHRP, pavement durability has continued to be a primary concern for many state agencies
 - Non-load associated cracking (block cracking) remains an issue largely unaddressed by AASHTO M320
 - Thought to be related to loss of binder ductility with respect to stiffness
- Anderson et. al. first conceptualized Delta T_c (ΔT_c) as a means of characterizing binder durability and non-load associated cracking susceptibility
 - New take on an old concept (i.e. shape of master curve)
 - Similar to other “shape” parameters (R-value, cross-over modulus, etc.)



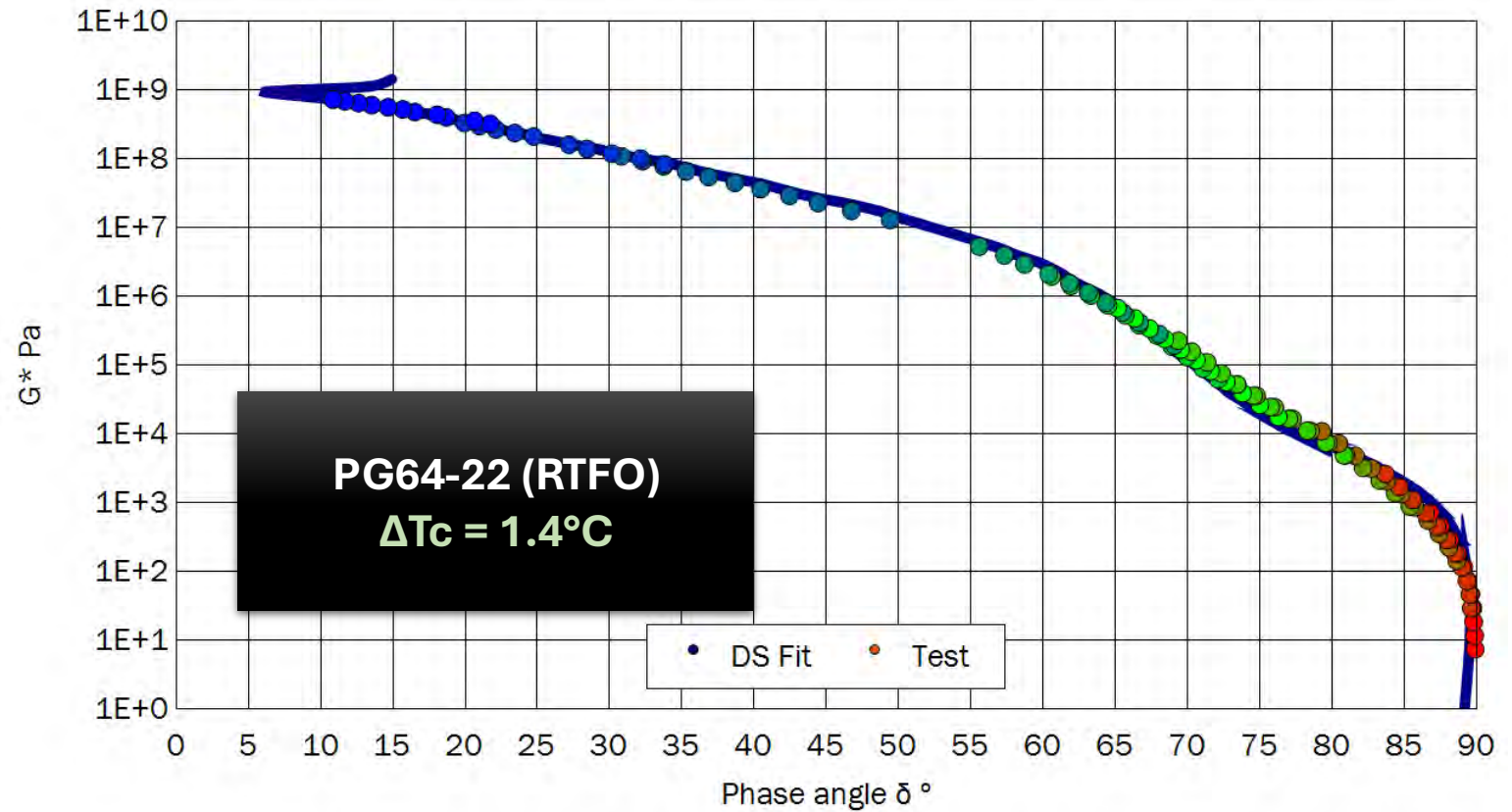
Background – What is ΔT_c ?

- Rheological “shape” parameter
 - Not currently included in AASHTO M 320/M 332
 - Provides a means of normalizing relaxation with respect to stiffness
 - Controls the shape of the stiffness master curve



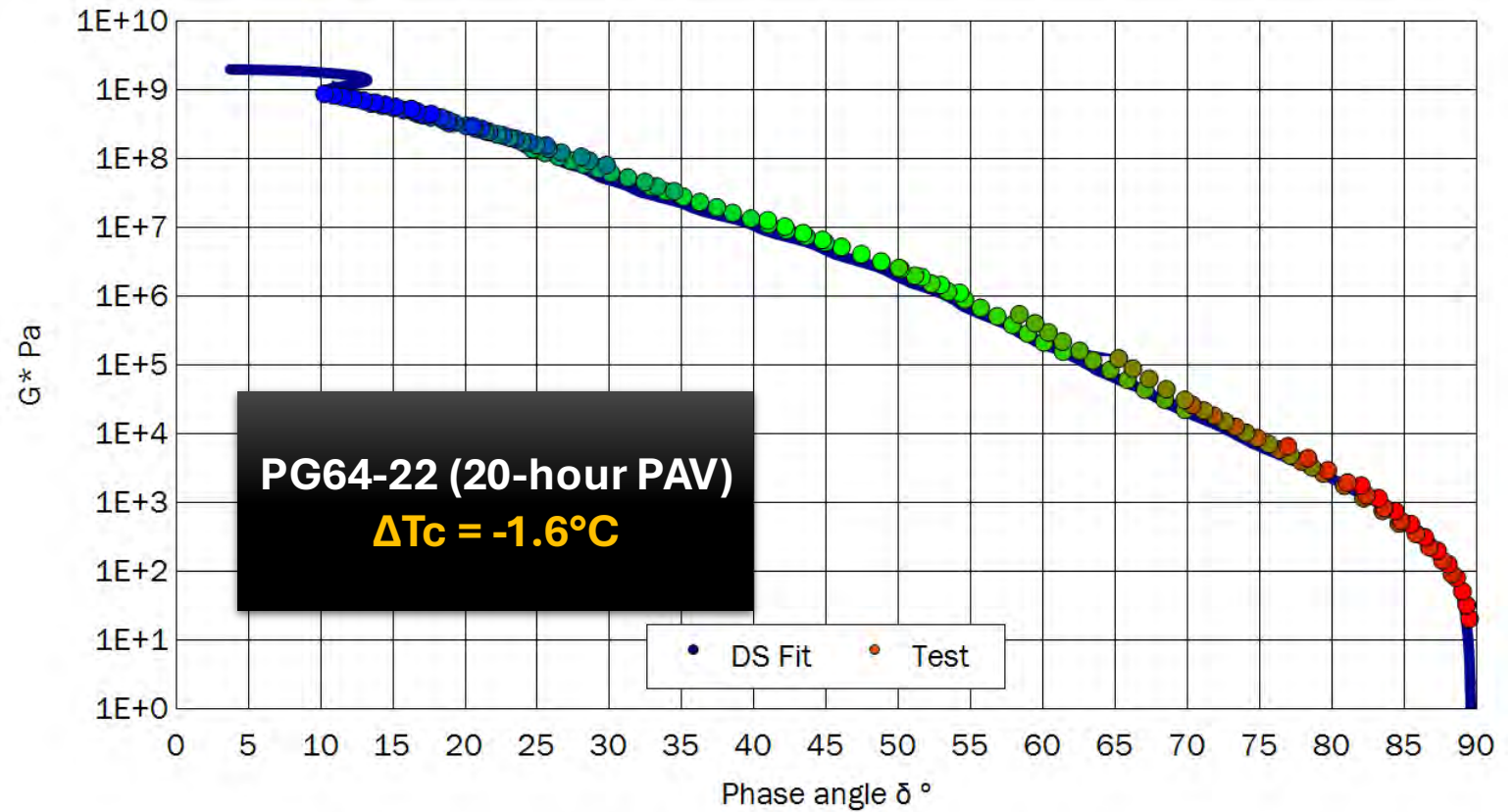
Background – What is ΔT_c ?

- Calculated from BBR data
 - $\Delta T_c = T_{c,S} - T_{c,m}$
- Positive ΔT_c = “S=controlled”
- Negative ΔT_c = “m=controlled”
 - Most binders are “m-controlled” in long-term aged state
- The questions is “how negative is too negative?”



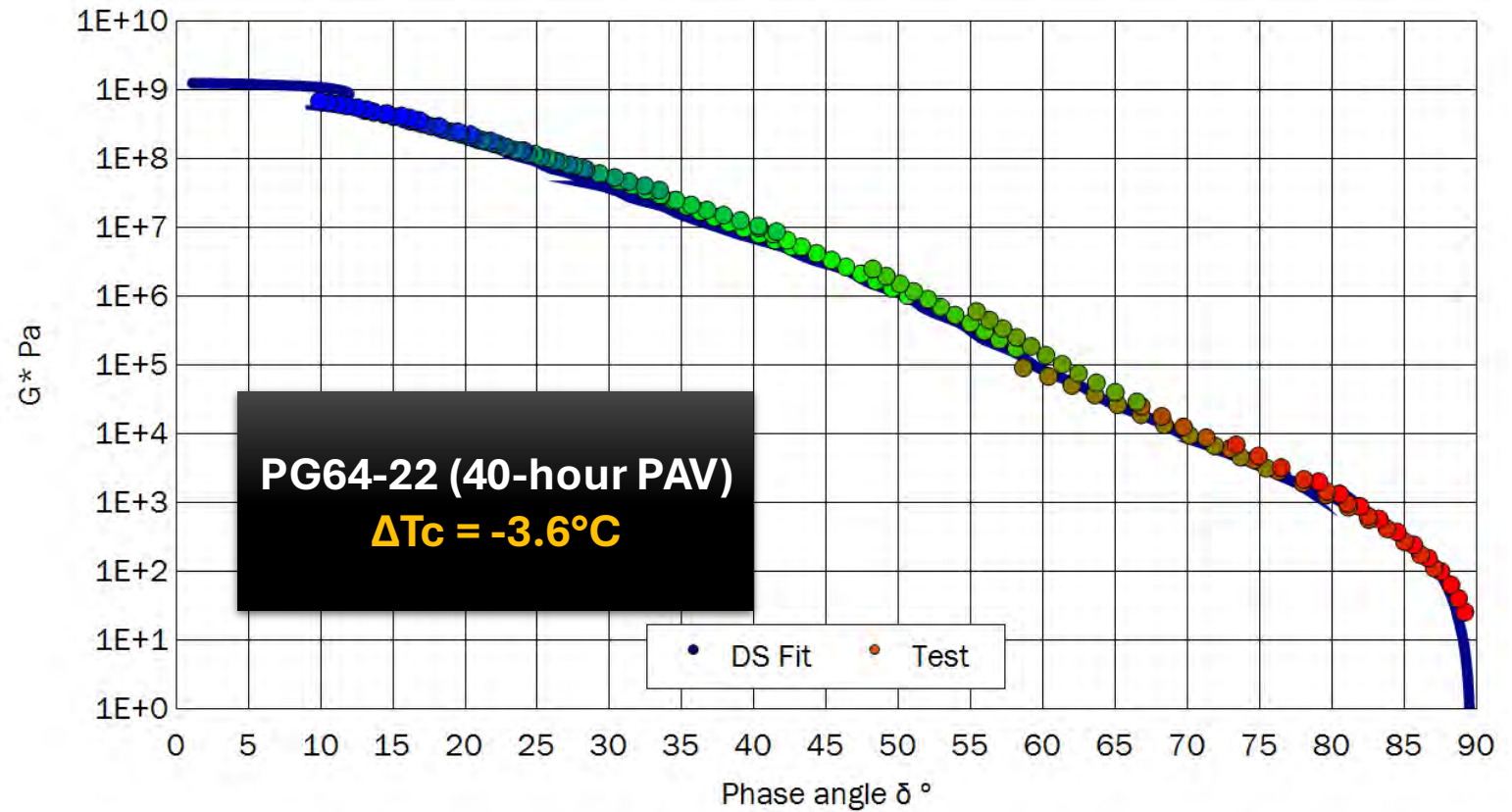
Background – What is ΔT_c ?

- Calculated from BBR data
 - $\Delta T_c = T_{c,S} - T_{c,m}$
- Positive ΔT_c = “S=controlled”
- Negative ΔT_c = “m=controlled”
 - Most binders are “m-controlled” in long-term aged state
- The questions is “how negative is too negative?”



Background – What is ΔT_c ?

- Calculated from BBR data
 - $\Delta T_c = T_{c,S} - T_{c,m}$
- Positive ΔT_c = “S=controlled”
- Negative ΔT_c = “m=controlled”
 - Most binders are “m-controlled” in long-term aged state
- The questions is “how negative is too negative?”



Background – Lingering Unknowns

- To date, ΔT_c has been the durability parameter of choice for state agencies
 - Kansas, Utah, Florida, Oklahoma, Vermont and others
 - Other states collecting data and assessing implementation
 - Many use PAV40 aging in conjunction with ΔT_c
- Despite the increasing use of ΔT_c , questions and concerns regarding reproducibility and aging continue to linger
 - Potential for increased variability with poorer material workability after PAV40 aging
 - “Layered” variability (multiple aging processes, multiple BBR isotherms)
 - No specified PAV40 methodology in AASHTO R 28 or otherwise



Background - An Exercise in Industry and Agency Collaboration

- In 2023, Illinois Department of Transportation (IDOT) implemented PAV40 ΔT_c requirement for non-polymeric binders
 - In 2021, IDOT/IAPA proactively reached out to AI to study impact of implementation
 - AI-led collaboration with IDOT, IAPA, and Illinois suppliers
 - Wayne Jones (ret.) → replaced by J. Wielinski in 2022
 - Goal: *identifying and mitigating concerns related to the testing dynamics of the ΔT_c parameter*
- An interlaboratory study (ILS) was designed to quantify variability of ΔT_c within the Illinois testing community after 40 hours of PAV aging
 - Additional data related to aging practices (vacuum degassing, PAV40 protocols) were collected from participants to provide further insight into variability factors

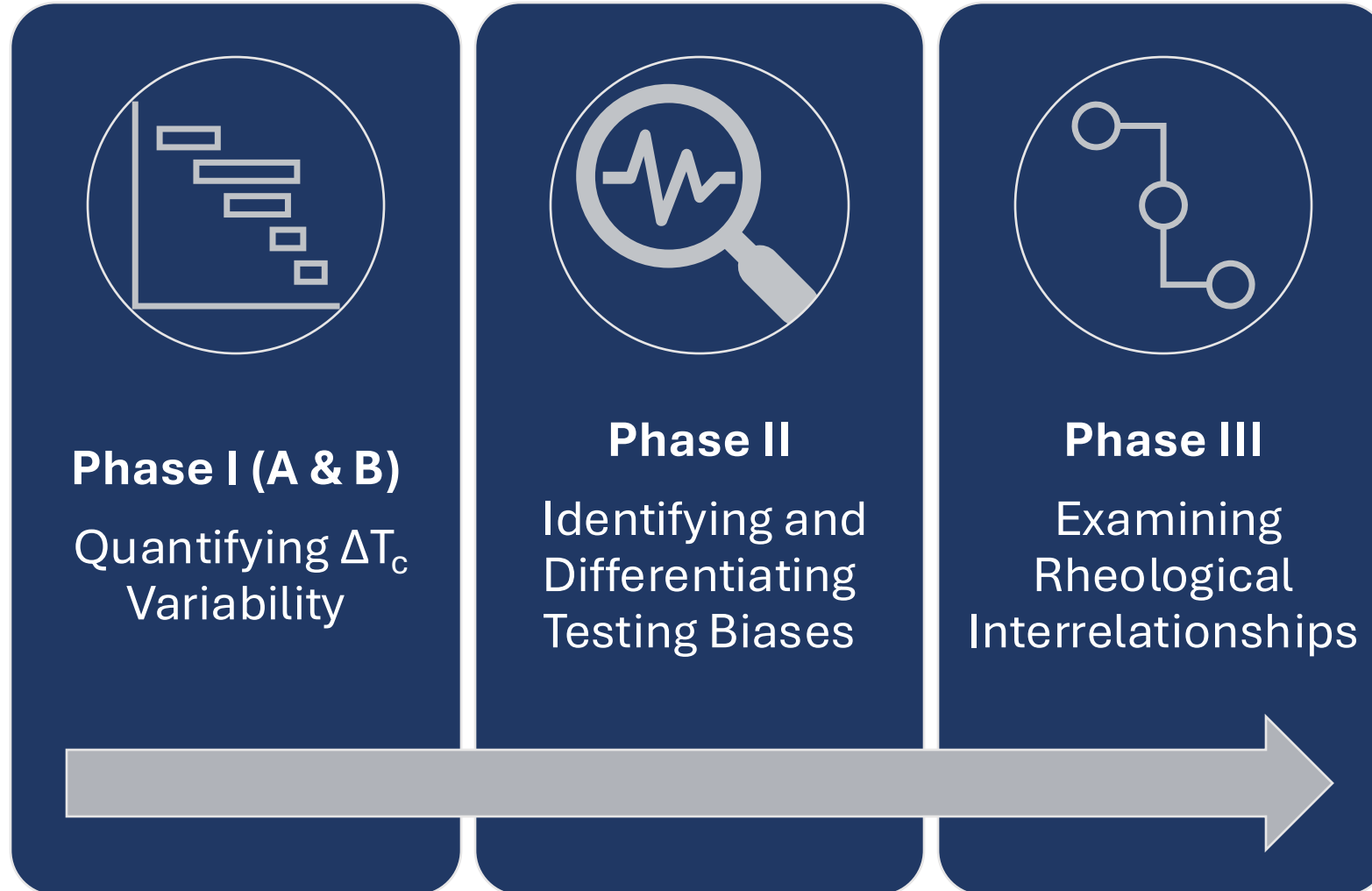


Background – An Expanded Study to Address a Growing Need

- Results of ILS indicated the need to broaden study
- Feedback from IDOT and participants indicated an interest in:
 - Verifying reproducibility measures obtained in Phase I-A
 - Isolating sources of measurement variability
 - Contextualizing PAV40 reproducibility by comparing with PAV20 data
 - Determining biases and statistical differences between PAV40 aging protocols
 - Exploring early indicators of PAV40 ΔT_c using PAV20 shape parameters
- Need for clarity goes beyond Illinois...
 - Recently completed work within Asphalt Institute Technical Advisory Committee to assess similar issues



An Emerging Framework



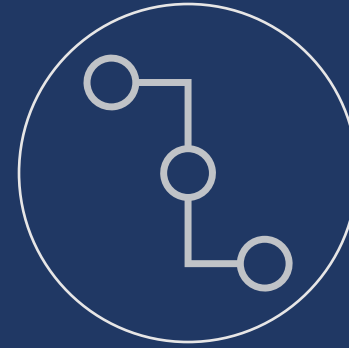
Phase I-A: Initial ILS



Phase I (A & B)
Quantifying ΔT_c
Variability



Phase II
Identifying and
Differentiating
Testing Biases



Phase III
Examining
Rheological
Interrelationships



Phase I-A: ILS Structure

- Phase I-A: Initial ILS
 - 18 participating labs
 - 2 binders from different sources (PG58-28 and PG64-22)
 - Participants performed RTFO and PAV40 conditioning on each binder, followed by testing for ΔT_c per AASHTO TP 113 (now AASHTO R 118)
 - Raw BBR data and aging information were collected
- Outside of instructions to follow the stated test methods, latitude was given to each lab regarding vacuum degassing and PAV40 aging methodology
 - This was intentional because we wanted a realistic picture of what reproducibility would look like based on lab SOPs and capabilities



Phase I-A: Findings

Test Result	Sample	No. Labs	Average	Standard Deviation (1s)	Coefficient of Variation (1s%)	Acceptable Range of Two Results	
						d2s	d2s%
AASHTO PP113 $\Delta T_c, ^\circ$	ILS-PG58-28-1	18	-3.9	1.0	25.5%	2.8	72.2%
	ILS-PG64-22-1	18	-6.5	0.9	14.1%	2.6	39.8%

With these multi-lab d2s values, an acceptance criteria of -5.0°C may present the potential for agency/supplier disputes



Phase I-A: Findings

- BBR isotherms showed poor m-value reproducibility with respect to AASHTO T 313
- Estimated stiffness varied more in *magnitude*, but m-value varied more in *frequency*
- Notably, half of the labs (9 of 18) did not properly bracket S and/or m when determining ΔT_c

ILS-PG58-28-1	Estimated Stiffness				m-value			
	-6°C	-12°C	-18°C	-24°C	-6°C	-12°C	-18°C	-24°C
No. of data points	-	14	13	8	-	14	13	8
Average	-	134	261	477	-	0.322	0.282	0.239
Max	-	143	274	516	-	0.331	0.300	0.250
Min	-	116	245	433	-	0.315	0.265	0.213
Range	-	27	29	83	-	0.016	0.035	0.037
1s	-	7	10	30	-	0.005	0.009	0.012
d2s	-	20	27	86	-	0.014	0.025	0.033
d2s%	-	14.9%	10.5%	18.0%	-	4.5%	8.9%	13.8%

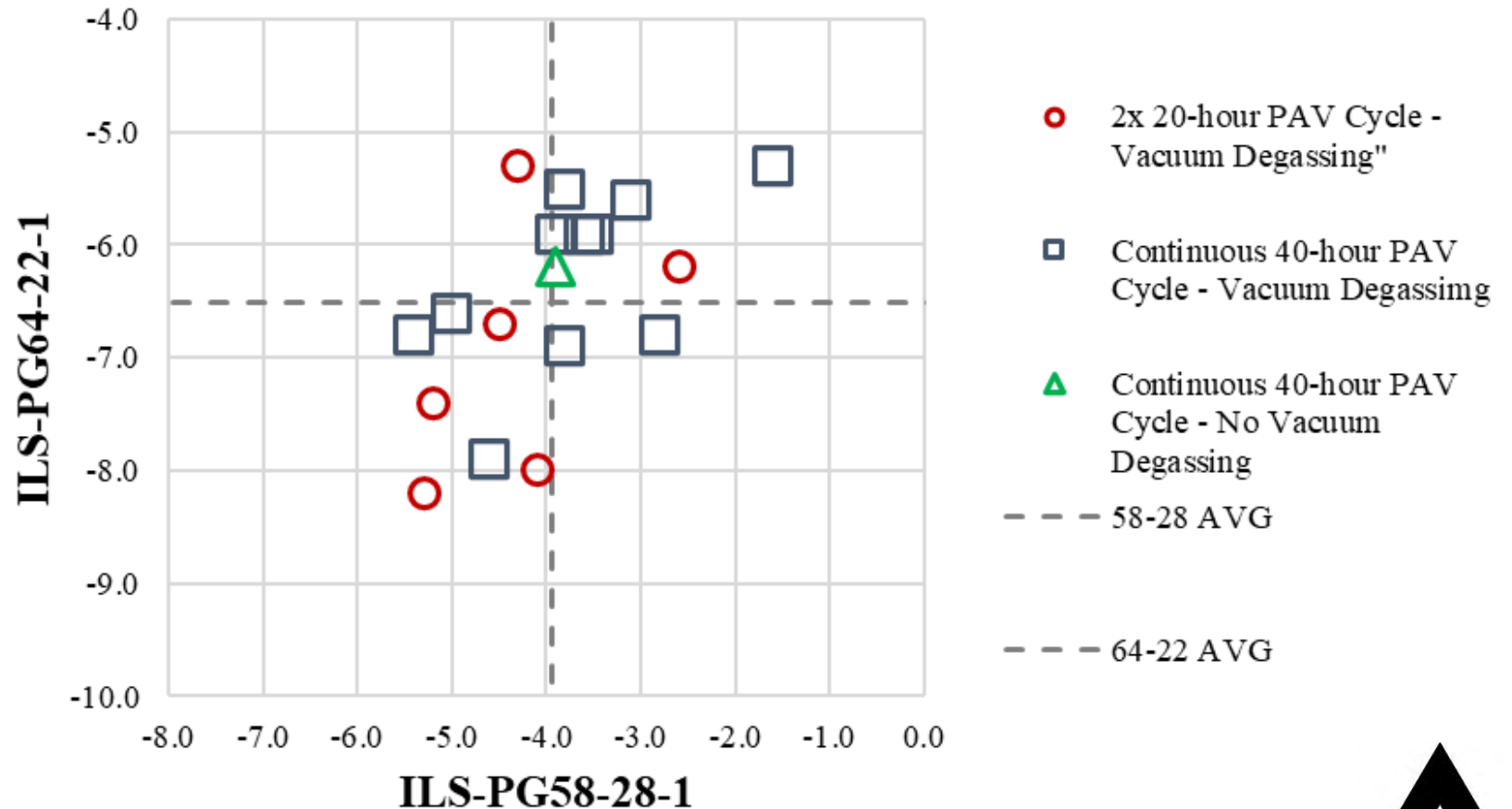
ILS-PG64-22-1	Estimated Stiffness				m-value			
	-6°C	-12°C	-18°C	-24°C	-6°C	-12°C	-18°C	-24°C
No. of data points	15	13	8	-	15	13	8	-
Average	120	236	413	-	0.315	0.271	0.236	-
Max	132	252	440	-	0.330	0.281	0.245	-
Min	112	209	388	-	0.300	0.261	0.227	-
Range	20	43	52	-	0.030	0.020	0.018	-
1s	6	11	19	-	0.008	0.006	0.006	-
d2s	16	30	53	-	0.022	0.016	0.017	-
d2s%	13.7%	12.8%	12.9%	-	7.0%	5.9%	7.2%	-

*Results in *red* indicated values that exceeded allowable range for S (**15.7%**) and m (**5.8%**) in AASHTO T 313



Phase I-A: Findings

- 12 of 18 labs used **continuous 40-hour PAV** procedure
 - PG58-28 showed bias toward more positive ΔT_c , indicating less aging
 - Distribution was fairly even for PG64-22
- 6 of 18 labs used **2x PAV20**
 - Nearly all PG58-28 and 64-22 fell below average, indicating more aging
- Only one lab did not vacuum degas prior to testing



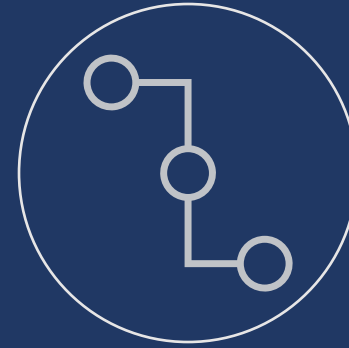
Phase I-B: Secondary ILS



Phase I (A & B)
Quantifying ΔT_c
Variability



Phase II
Identifying and
Differentiating
Testing Biases



Phase III
Examining
Rheological
Interrelationships



Phase I-B: ILS Structure

- Phase I-B: Second ILS
 - 15 labs, 5 binders (three PG58-28 and two PG64-22)
 - Includes a “control” PG58-28 aged and degassed at the Institute
 - Participants performed RTFO, PAV20 and PAV40 conditioning on non-control binder, followed by testing for ΔT_c per AASHTO TP 113 (now AASHTO R 118)
 - Raw BBR data and aging information were collected



Phase I-B: Findings

Test Result	Sample	No. Labs	Average	Standard Deviation (1s)	Coefficient of Variation (1s%)	Acceptable Range of Two Results	
						d2s	d2s%
AASHTO PP113 ΔT_c , °C (PAV20)	ILS-PG58-28-2	15	0.3	0.5	185.5%	1.5	524.9%
	ILS-PG58-28-3	15	0.0	0.6	6035.4%	1.6	17080.1%
	ILS-PG64-22-2	15	0.3	0.6	192.1%	1.6	543.6%
	ILS-PG64-22-3	15	0.7	0.6	76.2%	1.6	215.7%

Test Result	Sample	No. Labs	Average	Standard Deviation (1s)	Coefficient of Variation (1s%)	Acceptable Range of Two Results	
						d2s	d2s%
AASHTO PP113 ΔT_c , °C (PAV40)	ILS-PG58-28-2	15	-2.1	0.7	34.3%	2.0	97.1%
	ILS-PG58-28-3	15	-3.1	0.9	30.4%	2.6	86.0%
	LS-PG58-28-2-AIPAV40	15	-1.9	0.6	32.5%	1.7	92.1%
	ILS-PG64-22-2	15	-2.1	0.7	32.5%	2.0	91.9%
	ILS-PG64-22-3	15	-1.2	0.7	56.1%	1.9	158.7%



Phase I-B: Findings

Sample ID	PAV Conditioning Time, Hours	d2s%, Estimated Stiffness				d2s%, m-value			
		-6°C	-12°C	-18°C	-24°C	-6°C	-12°C	-18°C	-24°C
ILS-PG58-28-2	20	-	-	12.5%	9.9%	-	-	5.7%	7.5%
	40	-	17.5%	10.2%	10.6%	-	6.9%	6.6%	5.6%
ILS-PG58-28-2-AIPAV40	20	-	-	-	-	-	-	-	-
	40	-	11.4%	10.0%	9.6%	-	5.6%	5.7%	5.8%
ILS-PG58-28-3	20	-	-	12.7%	13.8%	-	-	6.5%	9.2%
	40	-	15.7%	10.1%	9.5%	-	8.3%	6.7%	6.7%
ILS-PG64-22-2	20	-	13.2%	13.6%	-	-	5.4%	8.3%	-
	40	29.9%	24.4%	13.8%	-	14.6	7.3%	11.6	-
ILS-PG64-22-3	20	-	12.5%	12.6%	-	-	6.4%	7.5%	-
	40	15.4%	15.4%	8.7%	-	6.6%	8.9%	8.5%	-

- Similar trends to Phase I-A for S and m
- This is a concerning pattern that may demand further evaluation

*Results in red indicated values that exceeded allowable range for S (15.7%) and m (5.8%) in AASHTO T 313



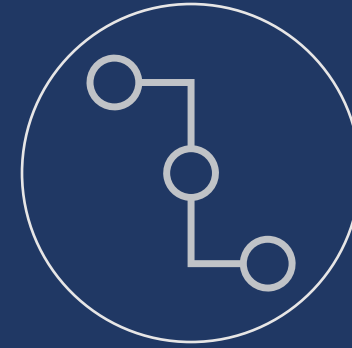
Phase II: A Deep-Dive into Testing Bias



Phase I (A & B)
Quantifying ΔT_c
Variability



Phase II
Identifying and
Differentiating
Testing Biases

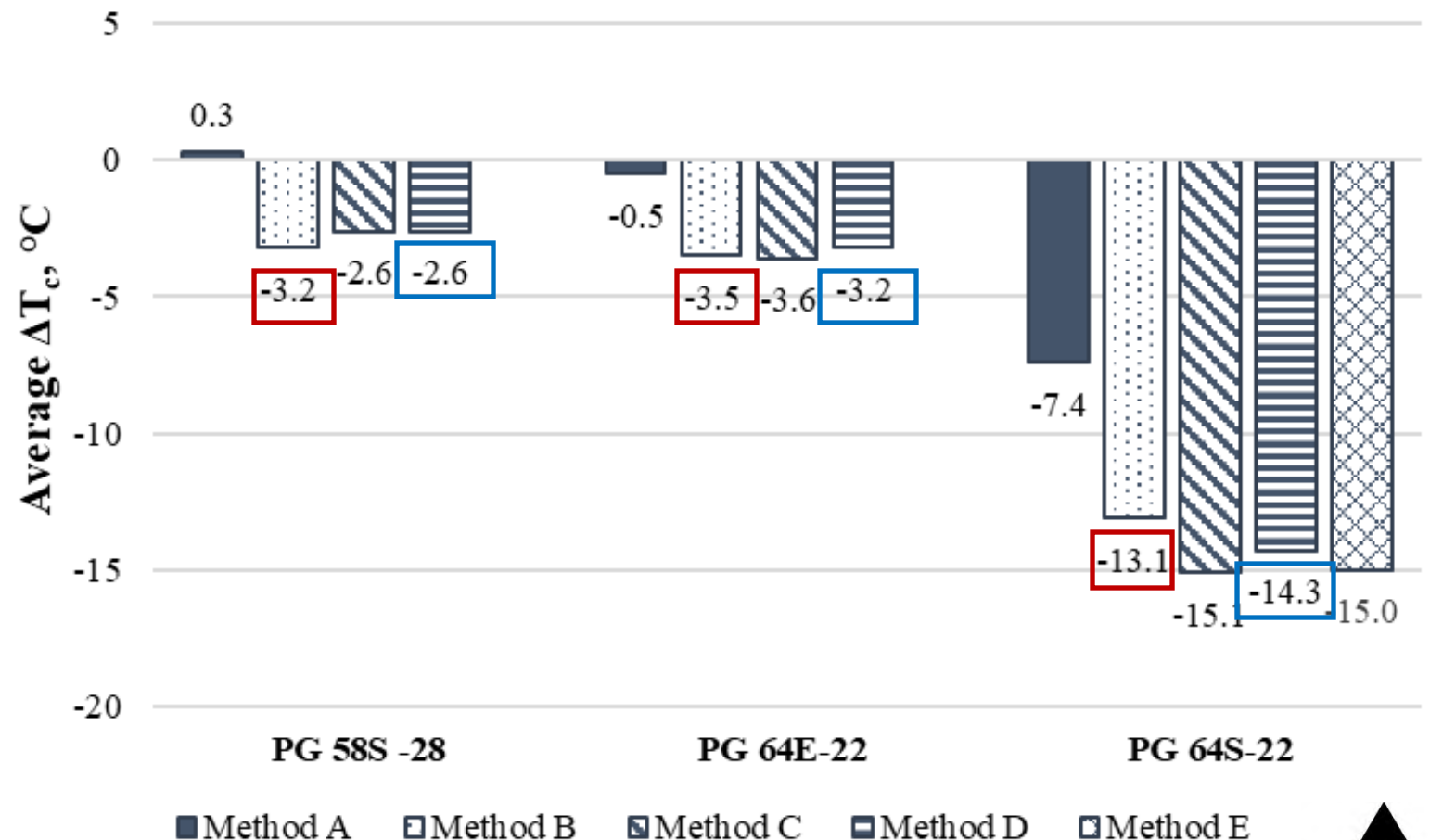


Phase III
Examining
Rheological
Interrelationships



Phase II: Previous Investigation

- Previous work done in this area highlighted need for further investigation (G. Harder and NEAUPG, 2019)
 - **Method B**: Back-to-back PAV20 cycles (no delay)
 - **Method D**: Continuous PAV40 cycle
- More materials needed!



Phase II: Materials



- 18 samples collected by IDOT representative
 - Eight (8) unmodified PG 58-28
 - Two (2) softener-modified PG 58-28
 - Seven (7) unmodified PG 64-22
 - One (1) softener-modified PG 64-22
- Wide spectrum of suppliers



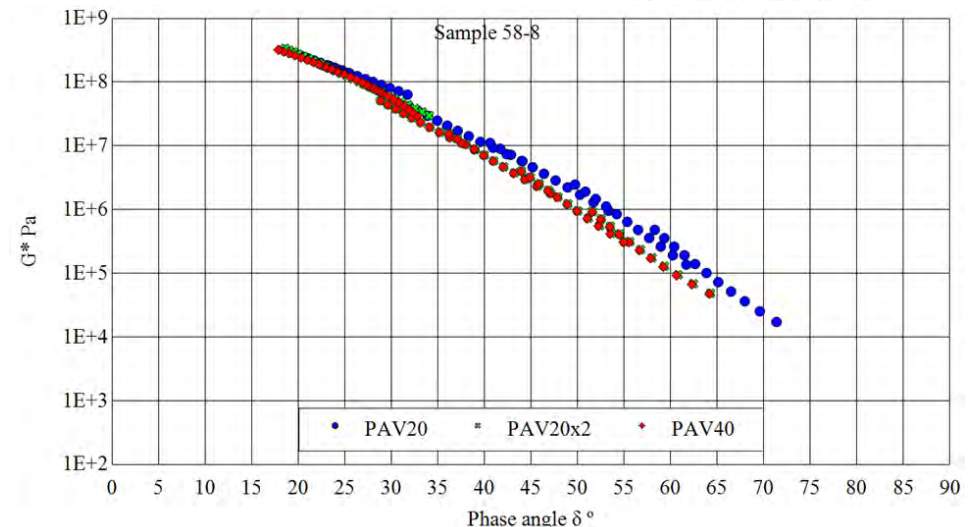
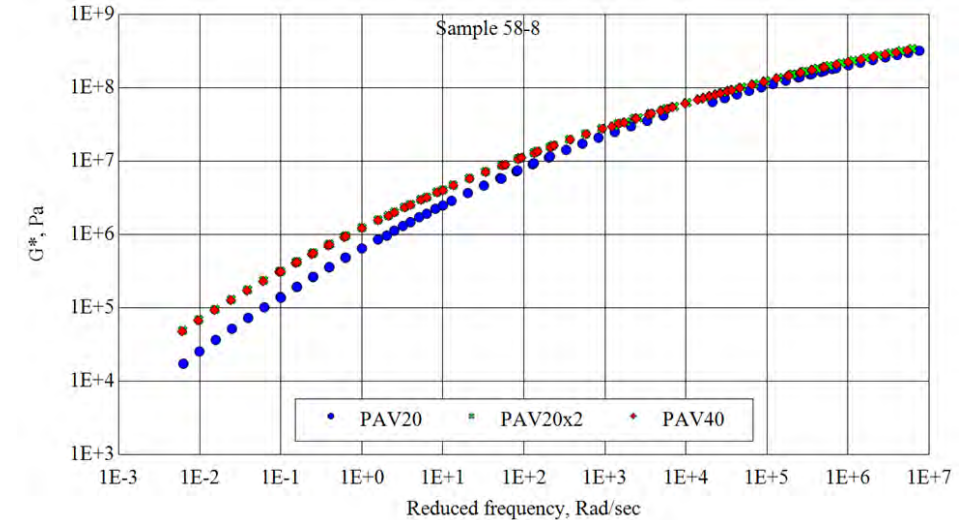
Phase II: Aging

- Procedure
 - Each sample was conditioned in Rolling Thin-Film Oven (RTFO) per AASHTO T240
 - After RTFO, each sample was split and conditioned separately in the Pressure Aging Vessel (PAV) per AASHTO R28 under each of the following conditions:
 - 20-hour PAV at 100°C and 2.1 MPa (**PAV20**)
 - 40-hour PAV at 100°C and 2.1 MPa using back-to-back PAV20 cycles (**PAV20x2**)
 - PAV samples were unloaded and reloaded between cycles
 - 40-hour PAV at 100°C and 2.1 MPa using continuous 40-hour cycle (**PAV40**)
 - PAV20, PAV20x2 and PAV40 residues were vacuum degassed per R28

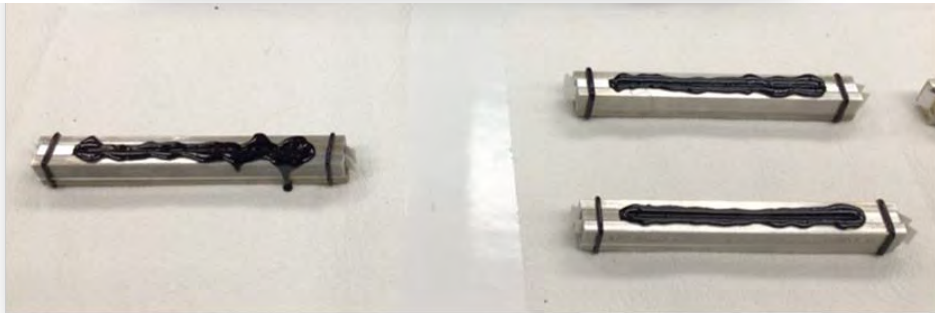


Phase II: Rheological Analysis

- BBR and Dynamic Shear Rheometer (DSR)
 - BBR: **R-value** per NCHRP 9-59 (form equation using coldest passing BBR isotherm) and **ΔT_c**
 - DSR: **$\delta_{G^*=10 \text{ MPa}}$**
- DSR data used in conjunction with converted BBR data to form master curves
- Additional rheological data serves as a comparison tool and quality check (redundancy)



Phase II Findings: Aging Effects

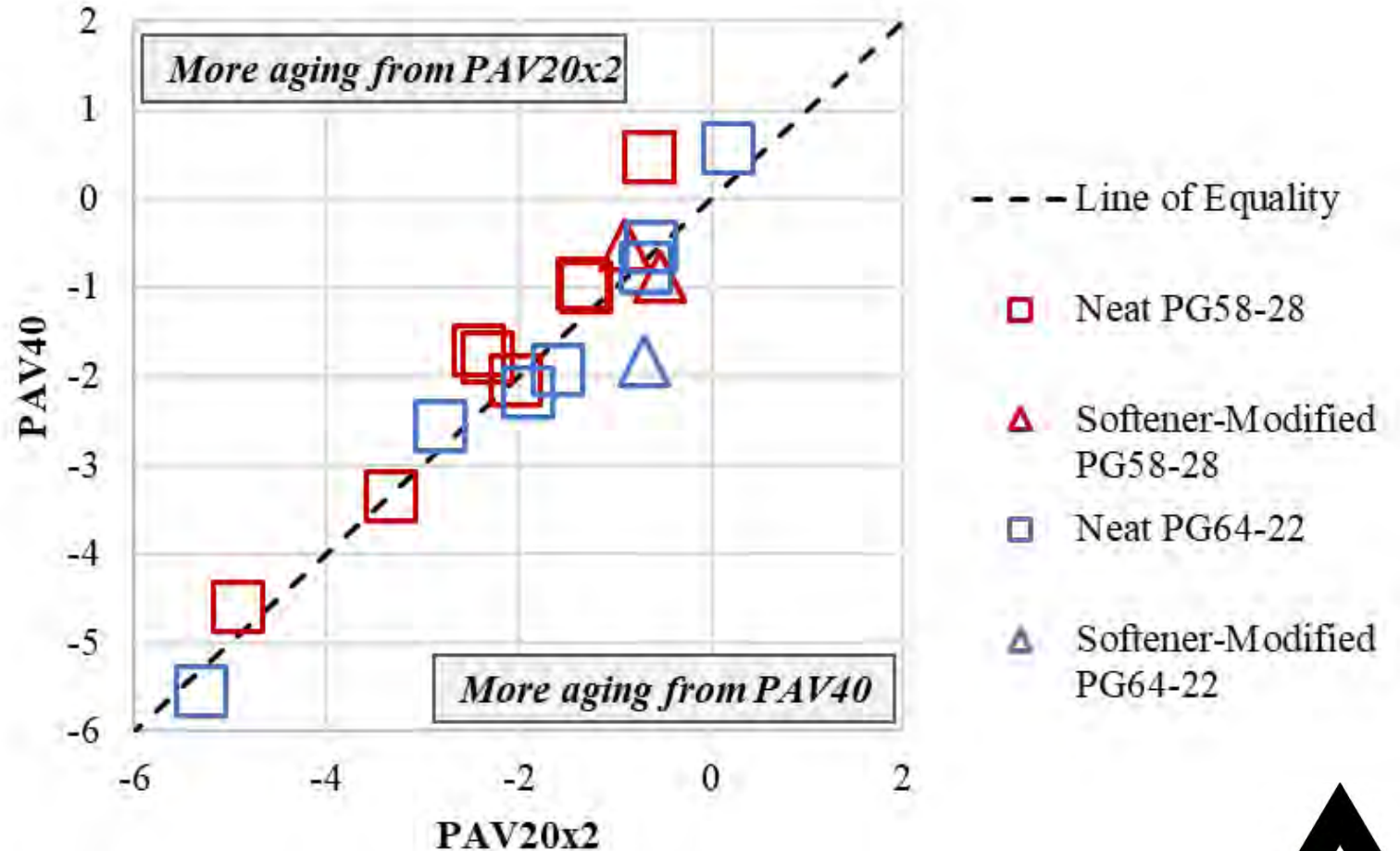


- What were we looking for?
 - **Bias:** does PAV40 consistently present *more* aging or *less* aging than PAV20x2 as measured by ΔT_c ?
 - If bias exists, do the other shape parameters confirm it?
 - **Statistical significance:** is any difference between the two methods (PAV40 and PAV20x2) statistically significant?



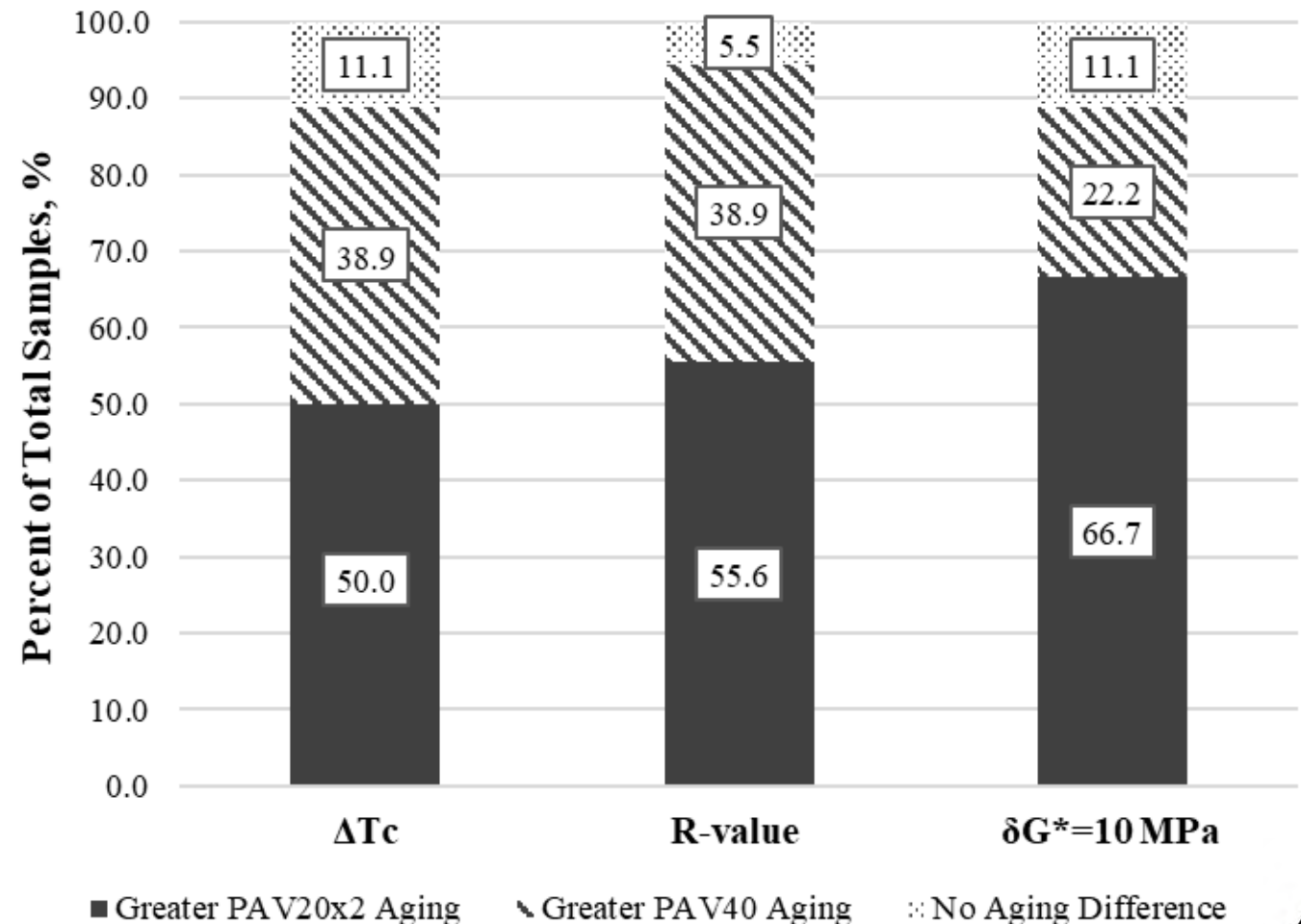
Phase II Findings: Aging Effects

- General trend was more aging when using PAV20x2
 - Especially notable for PG58-28 samples
- Average absolute difference between aging protocols for ΔT_c was **0.4°C** (all grades)
 - 2-tail T-test found this difference to be not significant



Phase II Findings: Aging Effects

- A greater sensitivity to more severe aging from PAV20x2 for all grades was noted using the $\delta_{G^*=10 \text{ MPa}}$ parameter
 - Perhaps related to sensitivity of DSR?



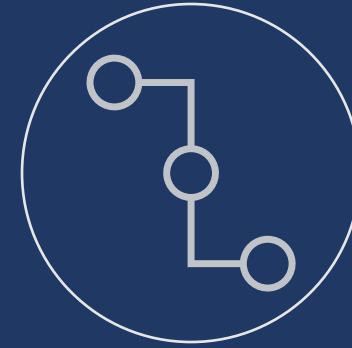
Phase III: Further Rheological Analysis



Phase I (A & B)
Quantifying ΔT_c
Variability



Phase II
Identifying and
Differentiating
Testing Biases

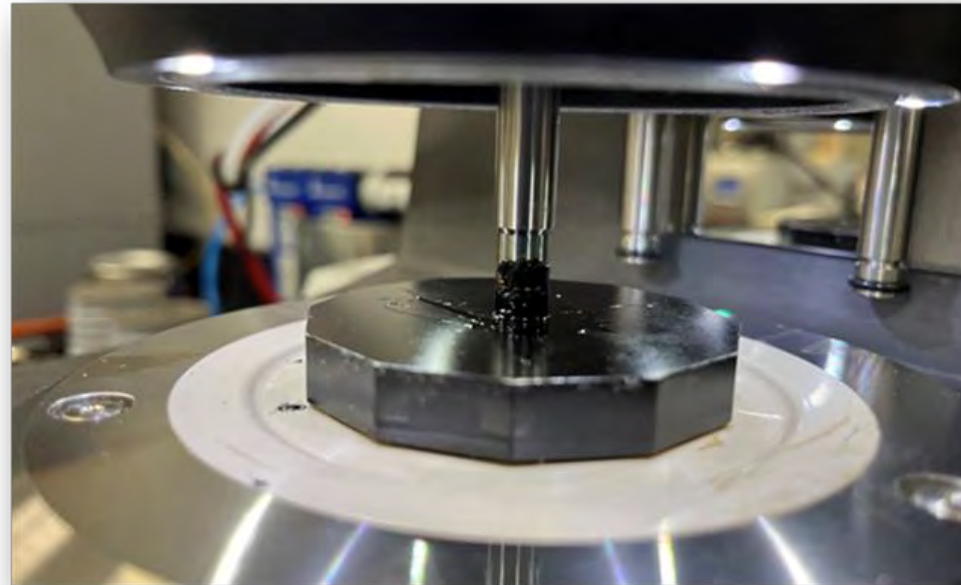


Phase III
Examining
Rheological
Interrelationships

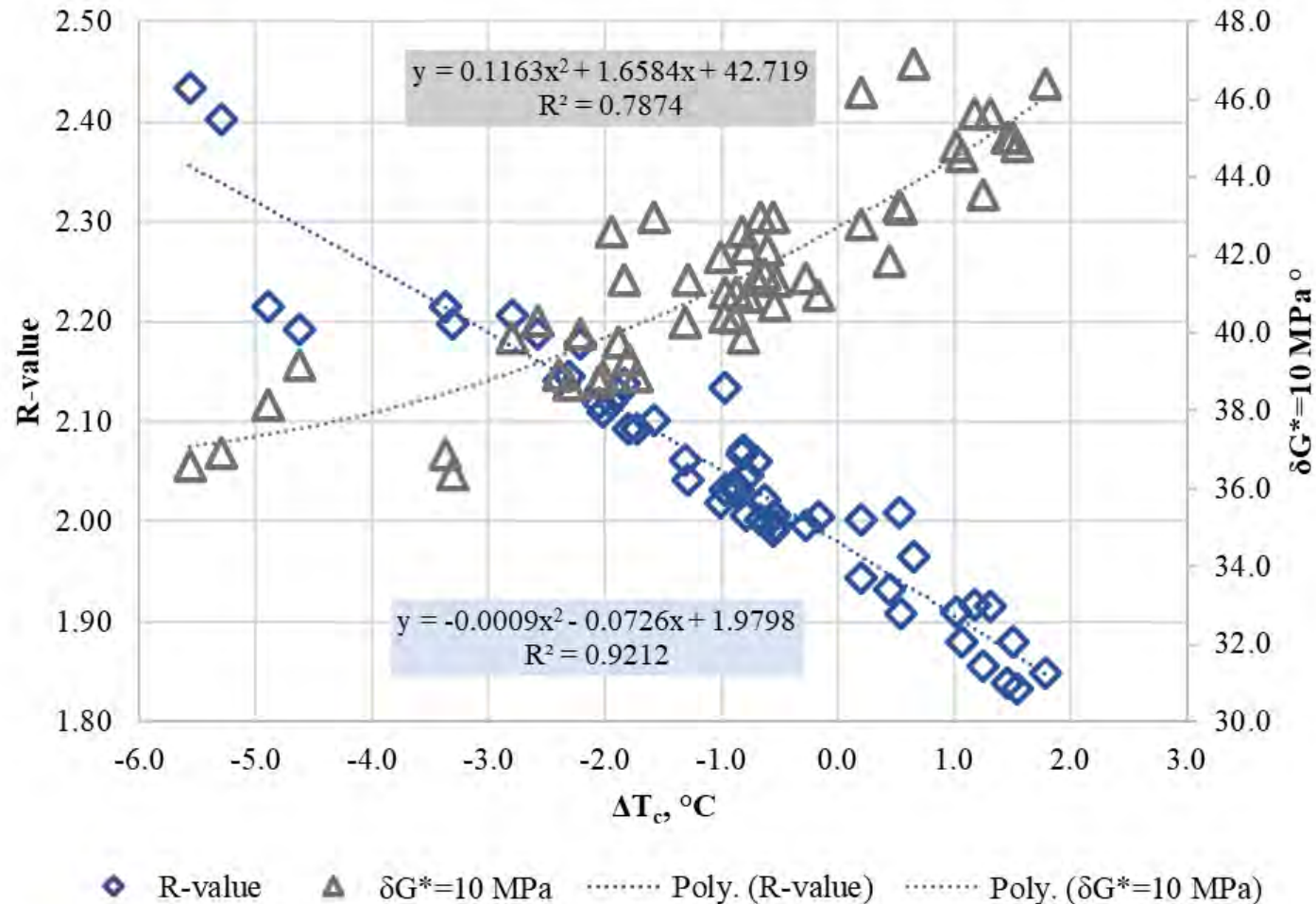


Phase III Findings: Interrelationships

- Rheological shape parameter relationships are well-established
- What do these relationships look like for the binders in this study?
- How do properties measured on PAV20 residue relate to ΔT_c on PAV40/PAV20x2 residue?
 - “Cross-aging” relationships
 - Could these be used as rapid screening tools for suppliers?



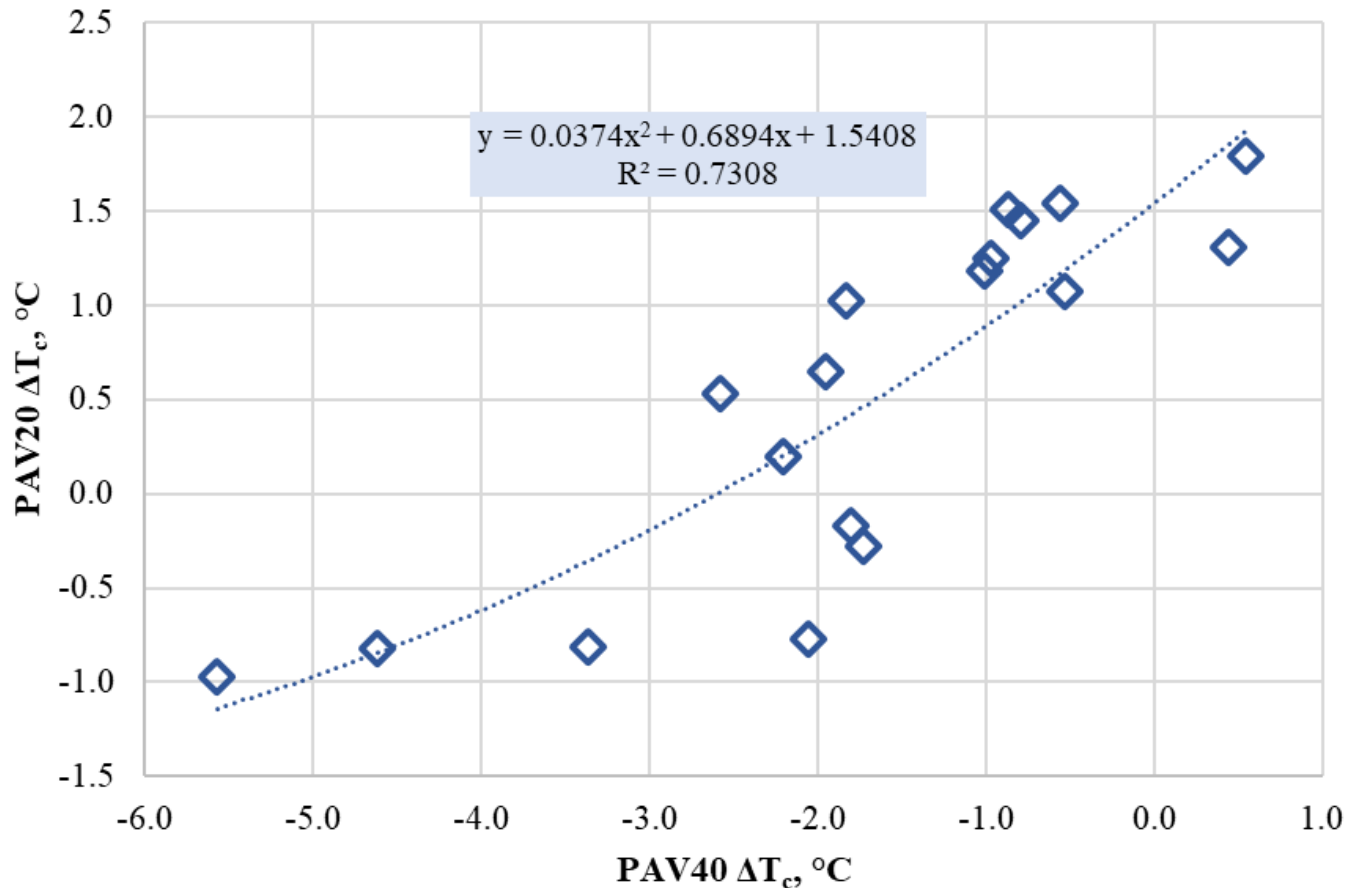
Phase III Findings: PAV40 Interrelationships



- Strong interrelationships between rheological shape parameter relationships for binders in this study
- PAV40 R-value showed better correlation to PAV40 ΔT_c
 - This makes sense, given that both use the same BBR dataset
- Using these relationships, a **-5.0 PAV40 ΔT_c** would equate to:
 - **PAV40 R-value of 2.32**
 - **$\delta_{G^*=10 \text{ MPa}}$ of 37.3 degrees**



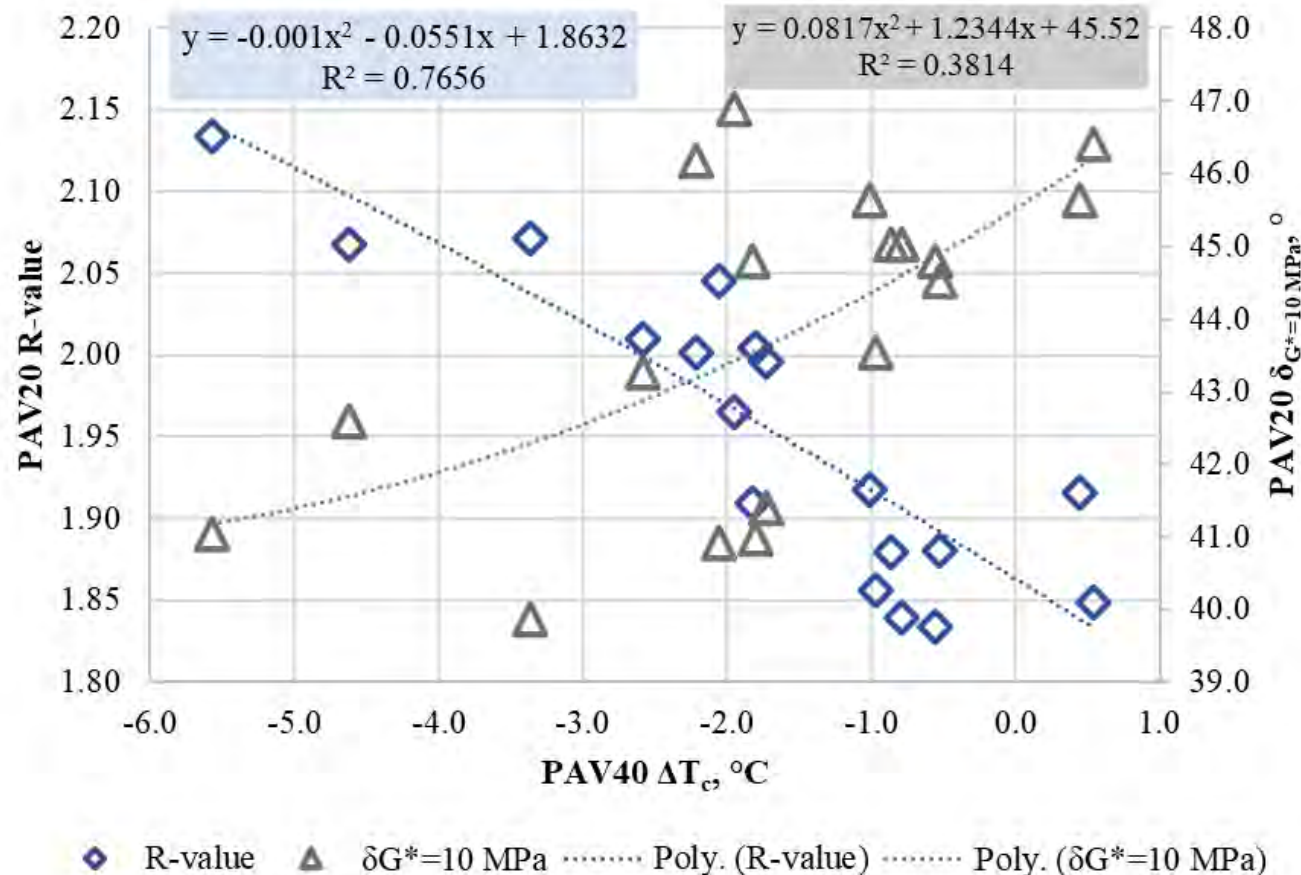
Phase III Findings: Cross-aging Interrelationships



- For binders in this study, a good relationship between PAV20 and PAV40 ΔT_c was established ($R^2=0.73$)
 - Using this relationship, a **-5.0°C PAV40 ΔT_c would equate to a PAV20 ΔT_c of -1.0°C**
 - For context, NCHRP 9-60 team is proposing a PAV20 ΔT_c threshold of -2.0°C



Phase III Findings: Cross-aging Interrelationships



- Notably, a slightly *better* relationship between PAV20 R-value and PAV40 ΔT_c was established ($R^2=0.76$)
 - PAV20 $\delta_{G^*=10 \text{ MPa}}$ not as strong ($R^2=0.38$)
 - In this case, a **-5.0°C PAV40 ΔT_c would equate to a PAV20 R-value of 2.10 and PAV20 $\delta_{G^*=10 \text{ MPa}}$ of 41.4**
 - If we use $G^*=8.967 \text{ MPa}$ as proposed by P. Kriz, this value shifts to **42.1** degrees



Primary Conclusions

- Variability in the determination of ΔT_c is primarily driven by error in BBR Estimated Stiffness and m-value
 - This varies with aging condition, test temperature and binder grade
 - Control sample indicated PAV aging has minimal impact on reproducibility
 - However, a multi-layered process will inevitably lead to poorer reproducibility
 - “Ghost” variability cannot be quantified, but should be considered
 - Ex. Technician fatigue
- On average, consecutive 20-hour PAV cycles (PAV20x2) showed slightly more aging than the continuous 40-hour PAV cycles (PAV40), but this bias was not found to be statistically significant
 - Greatest sensitivity was seen with phase angle at a constant modulus (DSR



Primary Conclusions

- PAV20 R-value was shown to be a potential cross-aging indicator of PAV40 ΔT_c for binders in this study
 - The fact that this relationship was even better than the relationship between PAV20/PAV40 ΔT_c speaks to higher repeatability of R-value compared to ΔT_c
 - e.g. one BBR isotherm vs. 2 or 3 isotherms – layered variability



Recommendations

- A wider spectrum of performance grades and binder sources should be included when establishing a precision and bias statement for ΔT_c
- A broader ruggedness study is recommended to evaluate other factors influencing variability in ΔT_c measurements.
 - Examples of factors not measured in this study include BBR manufacturer, thermometry, BBR standardization techniques, and BBR molding processes



Recommendations

- Even without an established precision and bias statement, suppliers shipping asphalt binder into states requiring PAV40 ΔT_c should be keenly aware of the reproducibility limitations
 - Larger test data margins for ΔT_c may be necessary to avoid agency-supplier disputes
- Agencies and suppliers desiring to use PAV20 R-value or PAV20 phase angle at a constant modulus as a screening tool for PAV40 ΔT_c may be able benchmark these relationships, but should understand that changes in grade, crude source or refining processes may alter the nature of these relationships





Questions?



ASPHALT INSTITUTE