A Simplified Method to Estimate the Low Temperature Cracking Required Input for the AASHTOWare ME Software Using E* Data

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Objectives

- Provide a simple approach to generating AASHTOWare PAVEMENT-ME inputs without the need to run cold temperature IDT tests
  - ✓ Use E* tests
  - ✓ Conduct mastercurve analysis and interconversion
  - ✓ Produce data in automated manner that can be used with AASHTOWare PAVEMENT-ME
  - ✓ Verify data as creep curves and predicted thermal cracking temperatures

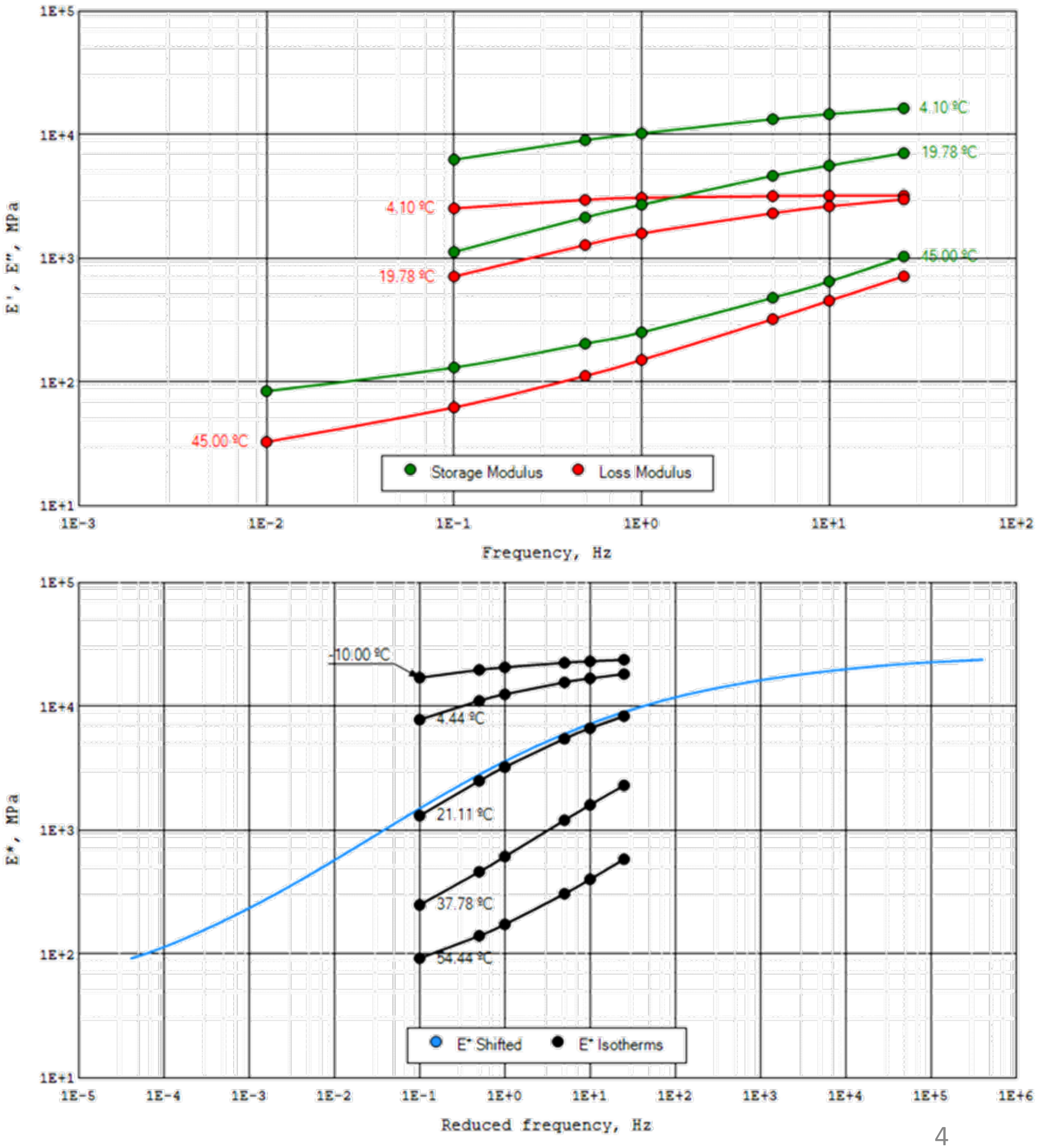
The challenge

- Rutgers poised the question:
  - ✓ Can with software – we take the E* data for these mixes and rapidly produce the IDT data needed input for AASHTOWare Pavement ME?
  - ✓ The mixes were selected to give a wide variation in performance
  - ✓ We used the RHEA™ software to provide the computations
    - Conceptually the calculations could be added to the AASHTOWare Pavement ME software – but RHEA ™ provides a readily implemental way of testing this approach and can be done today!

Mixture Abbreviation	Description	Tests Conducted
9.5 ME	9.5mm NMAS PG64E-22 binder 15% RAP	AASHTO Designation T378 E* measurements Test temperatures, 4 & 20°C, 10, 1 & 0.1 Hz Test temperature, 45°C, 10, 1, 0.1 & 0.01 Hz AASHTO R84 Generate Mixture Master Stiffness Curves
12.5mm SMA	Stone Matrix Asphalt 12.5mm NMAS PG64E-22 0% RAP	
BRIC	Binder Rich Intermediate Course 4.75mm NMAS PG64V-28 0% RAP	
HPTO	High Performance Thin Overlay 4.75mm NMAS PG64E-22 0% RAP	
25M64	25mm NMAS PG64S-22 25% RAP	

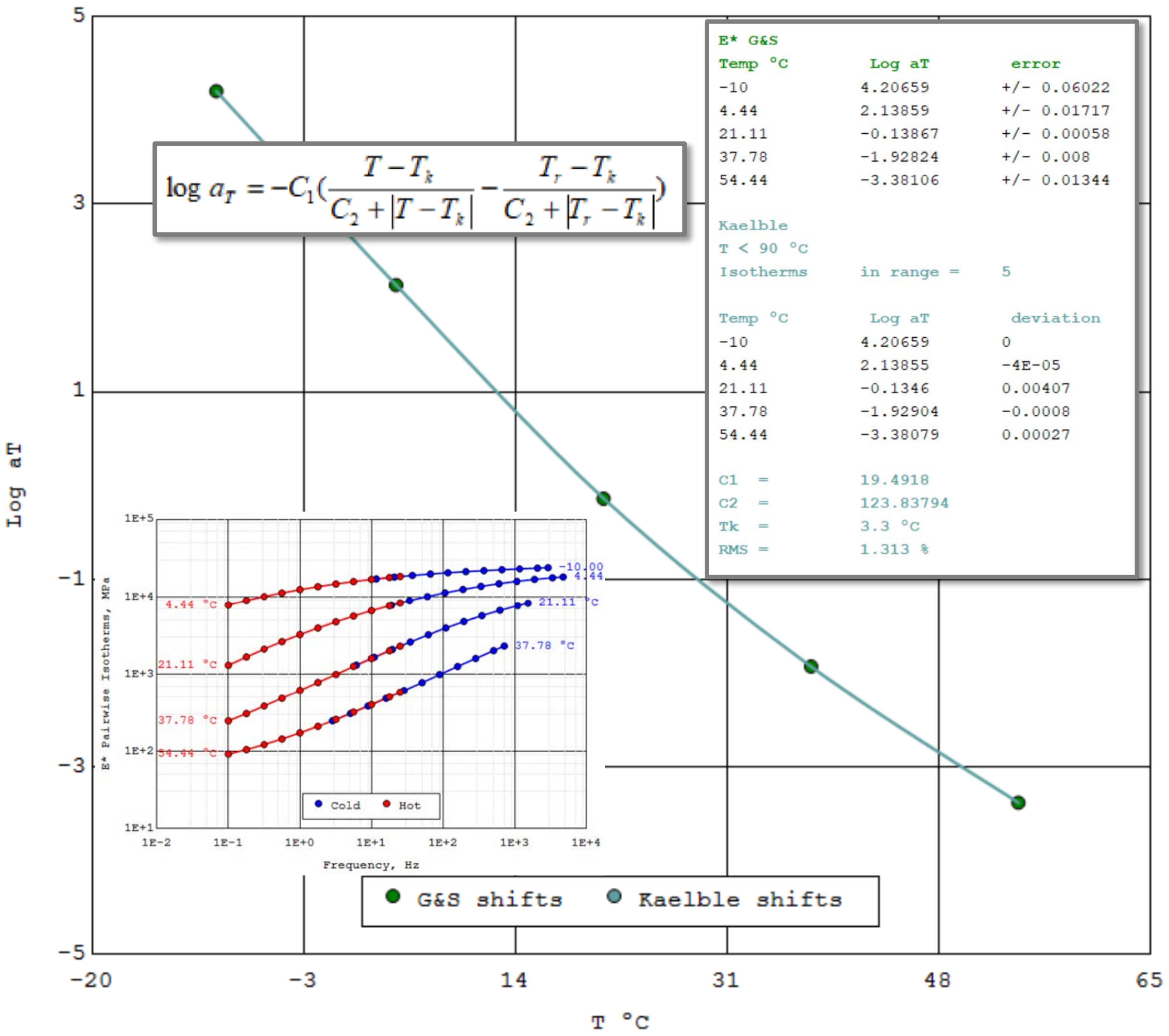
|E*| data collection

- Test data collection:
  - ✓ Test data is collected using the conventional AASHTO T378 data set. Typical isotherms of stiffness IE*I are obtained.
  - ✓ Using standard method the extrapolated isotherms are computed using the Hirsch method in AASHTO T378.
- Test data collection:
  - ✓ Data is shifted using the Gordon and Shaw method to produce a master curve of |E*|



Shift factors

- Gordon and Shaw method
  - ✓ Density correction performed using the Rouse method provides for a small vertical shift
  - ✓ Pairwise shifting to determine shift factors
- Modified Kaelble equation fitted to shift factors provides a robust method for interpolation
  - ✓ Offers one more degree of shifting compared to WLF so will always fit better
  - ✓ Captures an inflection point in curve



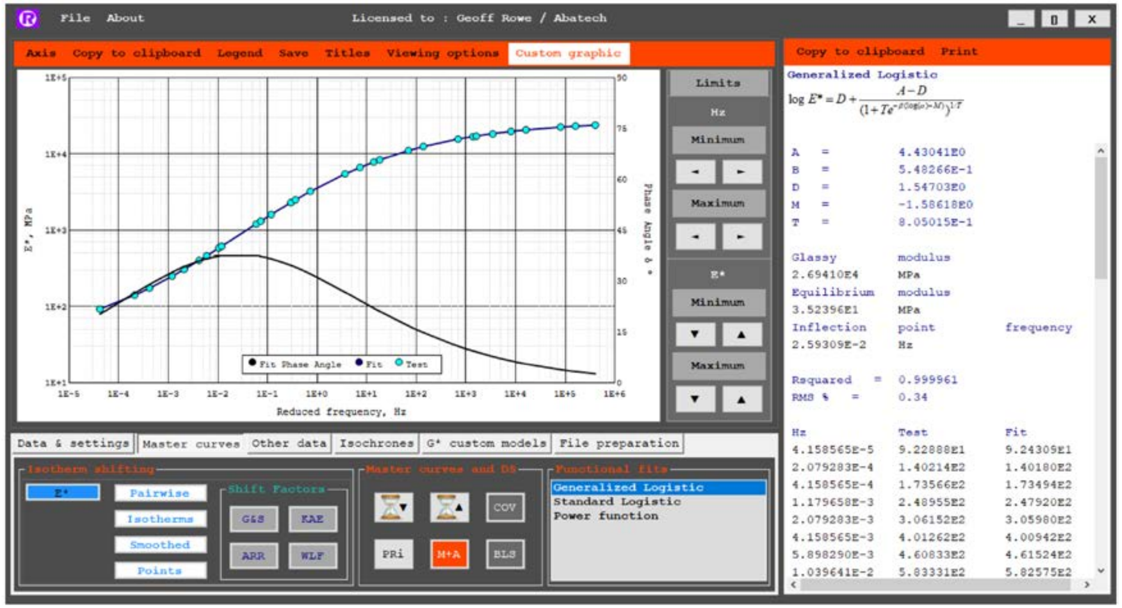
Discrete spectra analysis

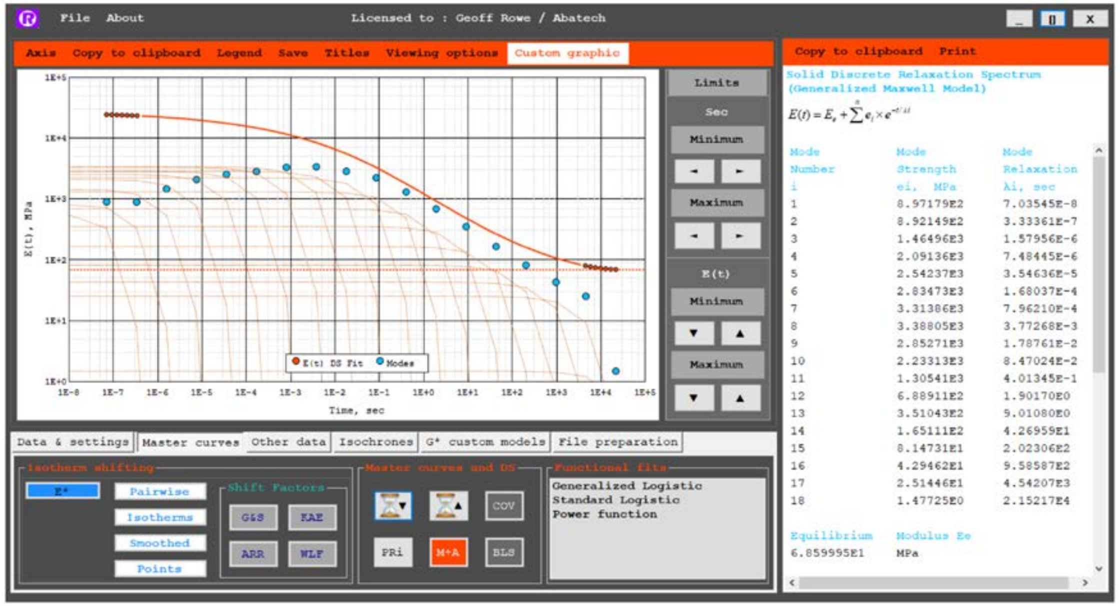
$$E'(\omega) = E_e + \sum_{n=1}^{n=i} e_i(\omega\lambda_i)^2/[1+(\omega\lambda_i)^2]$$

$$E''(\omega) = \sum_{n=1}^{n=i} e_i(\omega\lambda_i)/[1+(\omega\lambda_i)^2]$$

$$E(t) = E_e + \sum^{n} e_i \times e^{-t/\lambda i}$$

- Discrete spectra is fitted using the Baumgaertel and Winter (1989) method
  - ✓ The DS is fitted to the fit of the master curve
  - ✓ Model is a visco-elastic solid
- In this example we see a sigmoid model fit to the data with rms% error 0.34% - which is good! Normally a bit higher.
  - ✓ Three models fits always evaluated
- E(t) computed from the DS
  - ✓ Frequency → to time





E(t) → D(t)

- The relaxation E(t) and retardation D(t), are related by the convolution integral

$$\int_{-\infty}^{t} E(t')D(t-t')dt' = t$$

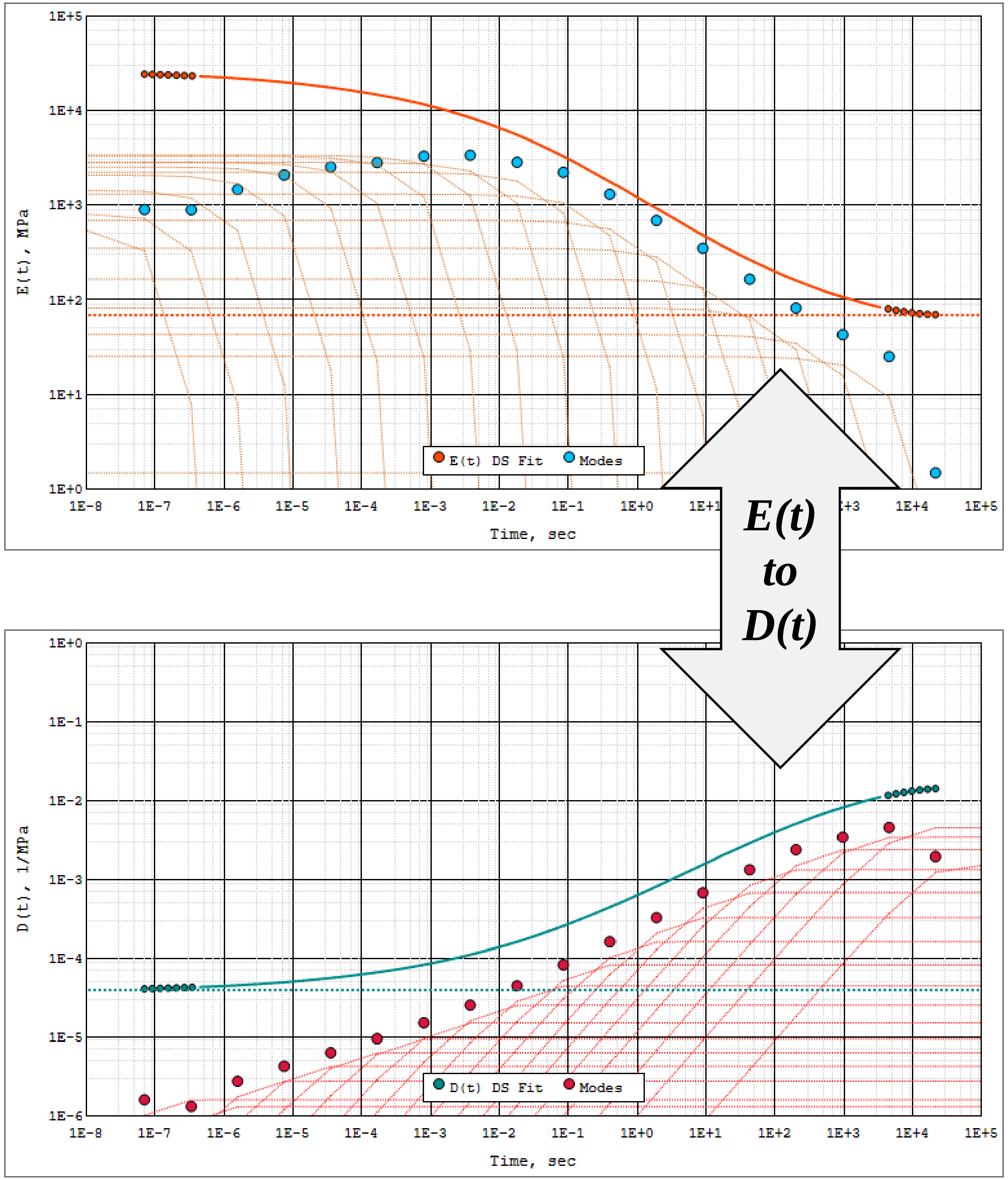
- Taking Laplace transforms to solve the unknown parameter D(t), enables the determination of the retardation master curve

$$D(t) = Dg + \sum^{n} d_i (1 - e^{-t/\Lambda i})$$

D_g Instantaneous compliance

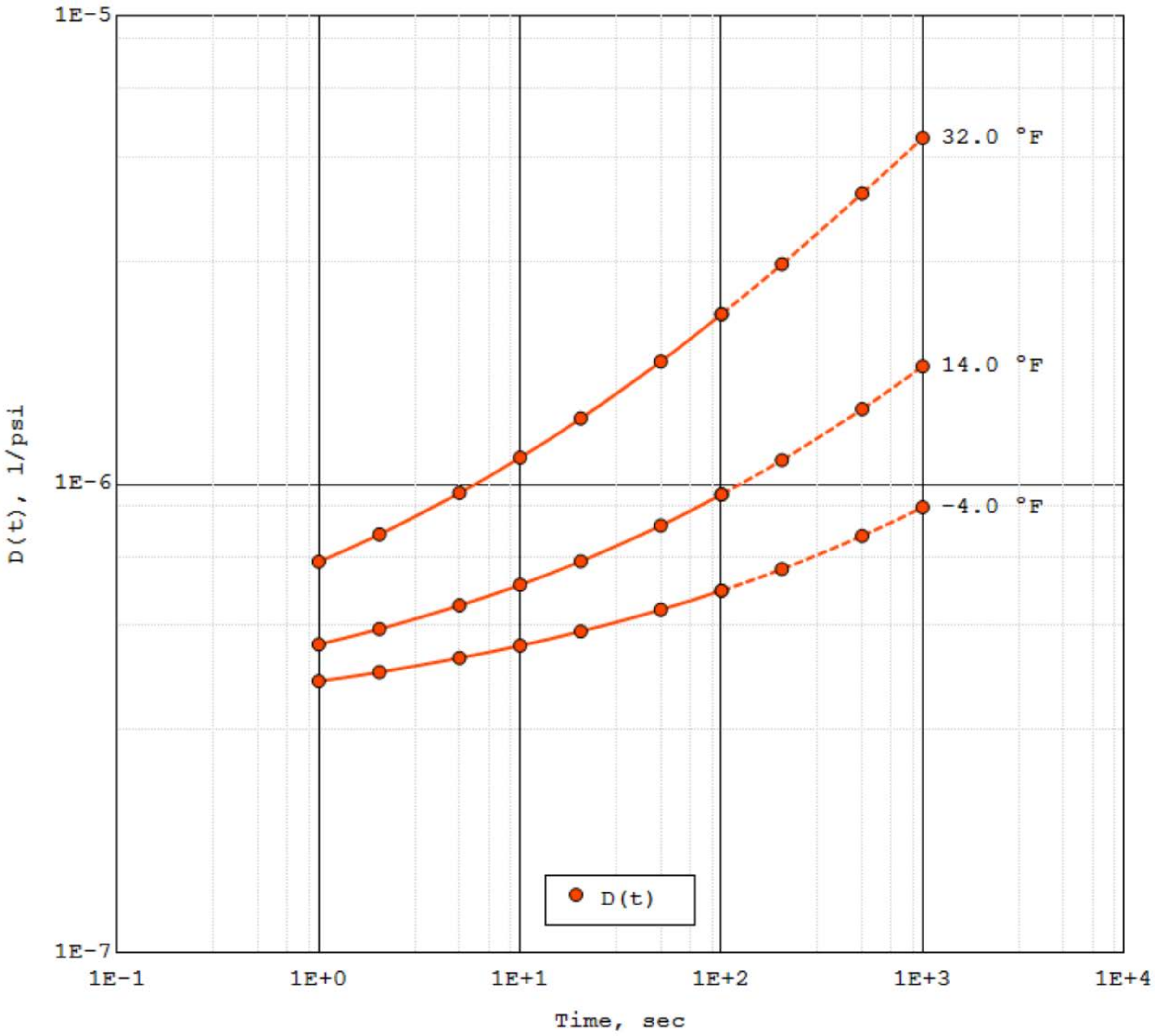
d_i Compliance of mode number i

Λ_i Retardation of mode number i



AASHTOWare Pavement ME Design Input

- Using a reverse shift process from the D(t) master curve, isotherms of compliance D(t) are obtained
- The automation process enables instantaneous output of the data in a format that can be directly used in the AASHTOWare Pavement ME software



AASHTOWare Pavement ME Design Input
Mix Creep compliance D(t) 1/psi
@ 1, 2, 5, 10, 20, 50 and 100 seconds

	Calculated	D(t) up to:	100 sec.
Sec.	T = -4 °F	T = 14 °F	T = 32°F
1	3.80476E-7	4.55850E-7	6.84270E-7
2	3.97775E-7	4.91559E-7	7.82729E-7
5	4.26530E-7	5.52054E-7	9.59979E-7
10	4.53210E-7	6.11034E-7	1.14195E-6
20	4.86032E-7	6.85845E-7	1.38424E-6
50	5.40425E-7	8.17550E-7	1.83168E-6
100	5.93776E-7	9.52072E-7	2.31098E-6

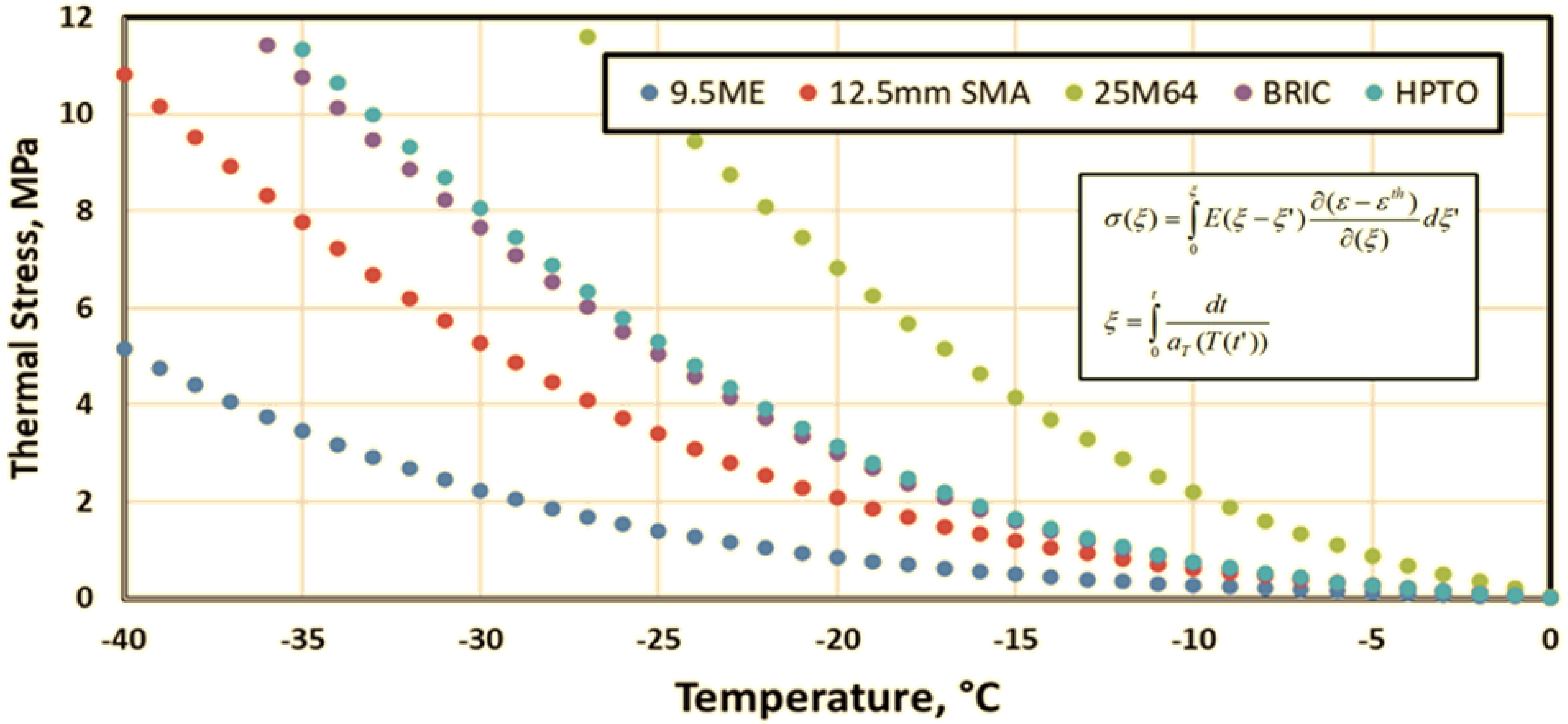
	Calculated	D(t) up to:	1000 sec.
Sec.	T = -4 °F	T = 14 °F	T = 32°F
1	3.80476E-7	4.55850E-7	6.84270E-7
2	3.97775E-7	4.91559E-7	7.82729E-7
5	4.26530E-7	5.52054E-7	9.59979E-7
10	4.53210E-7	6.11034E-7	1.14195E-6
20	4.86032E-7	6.85845E-7	1.38424E-6
50	5.40425E-7	8.17550E-7	1.83168E-6
100	5.93776E-7	9.52072E-7	2.31098E-6
200	6.60008E-7	1.12769E-6	2.95697E-6
500	7.77016E-7	1.44976E-6	4.18413E-6
1000	8.94172E-7	1.78856E-6	5.49879E-6

-	Horizontal	Shifts	-
:	T = -4 °F	T = 14 °F	T = 32°F
at	5.40276E0	4.20659E0	2.82225E0

-	Vertical	Shifts	-
:	T = -4 °F	T = 14 °F	T = 32°F
vt	-6.3451E-2	-4.6626E-2	-3.0515E-2

Thermal stress calculations

- After we have the D(t) data we can compute the thermal stress build up
  - ✓ The calculations shown here have used the TSAR software – which is essentially the same computation process as used in the AASHTOWare Pavement ME software
  - ✓ Data shows the effect on the calculation of various mix types



Questions?

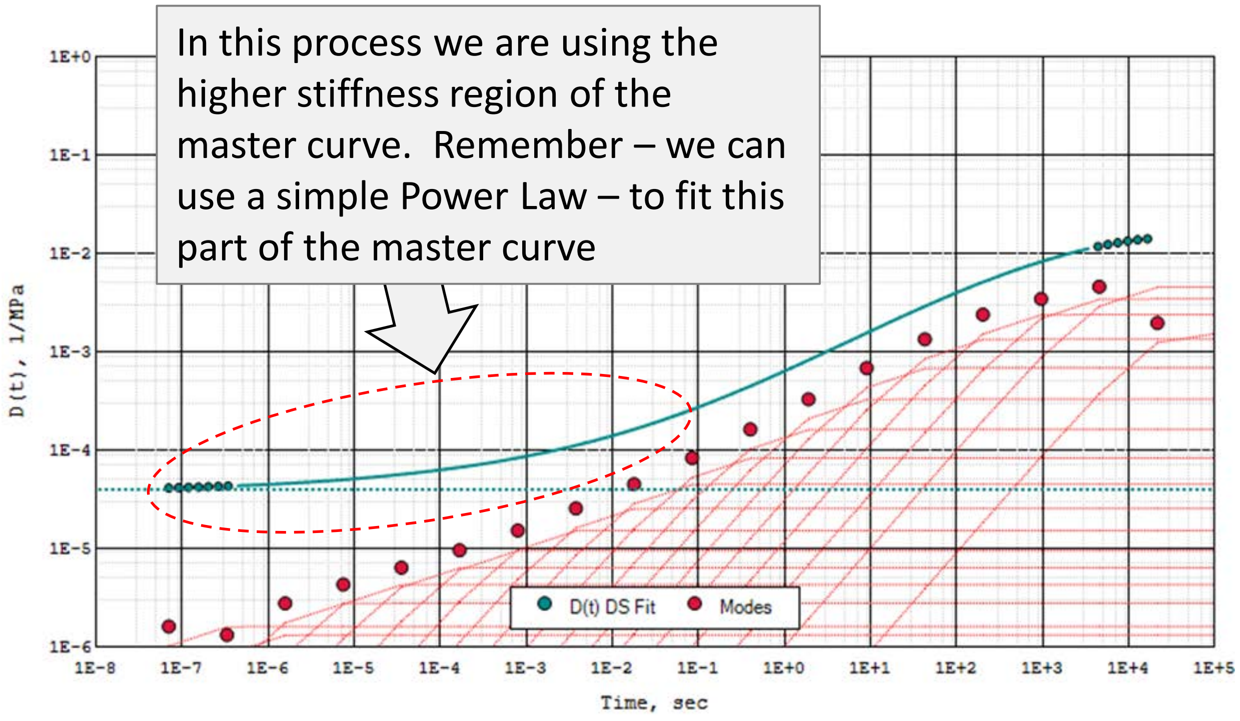
- How is this used and how good is the analysis process?
- We used a validation data set as shown →
- Lets review some questions!

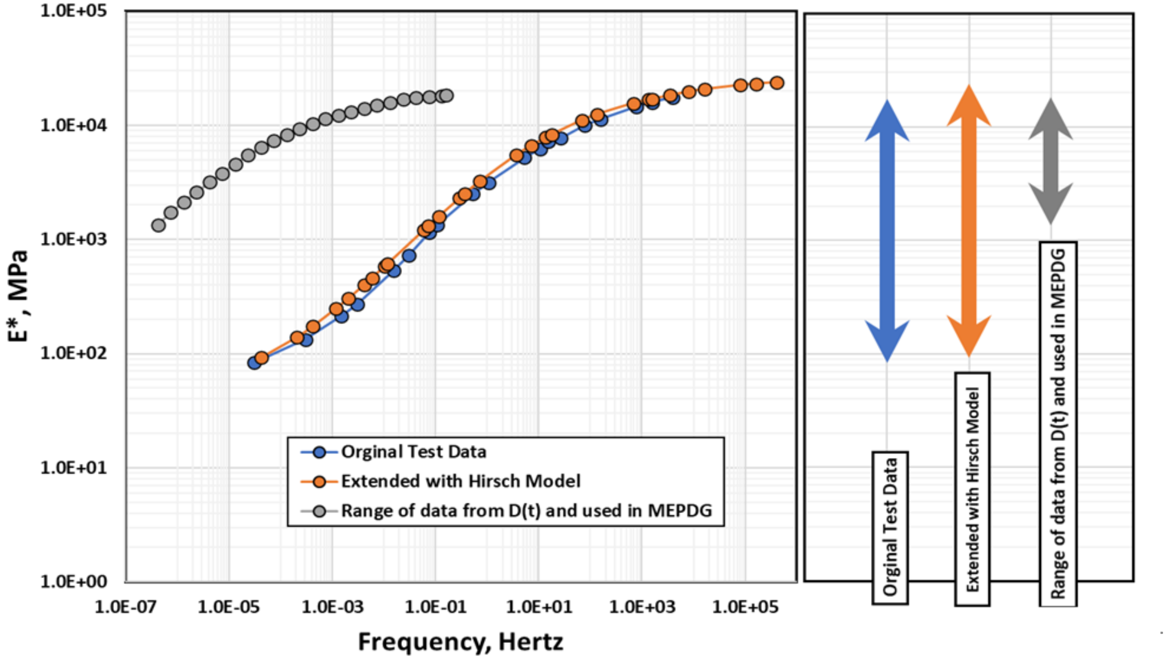
<table>
<tr><th colspan="2">Mixture ID</th><th>Description</th><th>PG Grade</th><th>Mixture Tests Conducted</th></tr>
<tr><td rowspan="4">NH Mixes</td><td>Mix 026</td><td rowspan="4">Lab Mix & Compacted
12.5mm NMAS
1,000,000 ESALs
7 +/- 0.5% Air Voids
5.4% AC</td><td>66.5-25.2</td><td rowspan="4"><u>AASHTO T 378 E* measurements</u>
Temperatures: 4, 20 and 35°C and
Frequencies: 25, 10, 5, 1, 0.5 & 0.1 Hz
<u>AASHTO T 322 IDT creep</u>
Temperatures: 0, -10 & -20°C
1,000 second loading times</td></tr>
<tr><td>Mix 027</td><td>73.4-24.6</td></tr>
<tr><td>Mix 028</td><td>80.7-25.4</td></tr>
<tr><td>Mix 029</td><td>73.8-25.3</td></tr>
<tr><td rowspan="4">NJ Mixes</td><td>9.5H76 #1</td><td rowspan="4">Plant Mix/Lab Compacted
9.5 & 12.5mm NMAS
M = 75 N_{des} Gyrations
H = 100 N_{des} Gyrations
6.5 +/- 0.5% Air Voids
AC% ≈ 5 to 5.5%</td><td>76-22
15% RAP</td><td rowspan="4"><u>AASHTO T 378 E* measurements</u>
Temperatures: 4, 20, and 35 or 45°C
Frequencies: 25, 10, 5, 1, 0.5 & 0.1 Hz)
<u>AASHTO T 322 IDT creep</u>
Temperatures: 0, -10 & -20°C
100 second loading time</td></tr>
<tr><td>9.5H76 #2</td><td>76-22
15% RAP</td></tr>
<tr><td>12.5H76</td><td>76-22
15% RAP</td></tr>
<tr><td>12.5M64</td><td>64-22
15% RAP</td></tr>
</table>

Extrapolation

- How much are we extrapolating data?
- Comments!

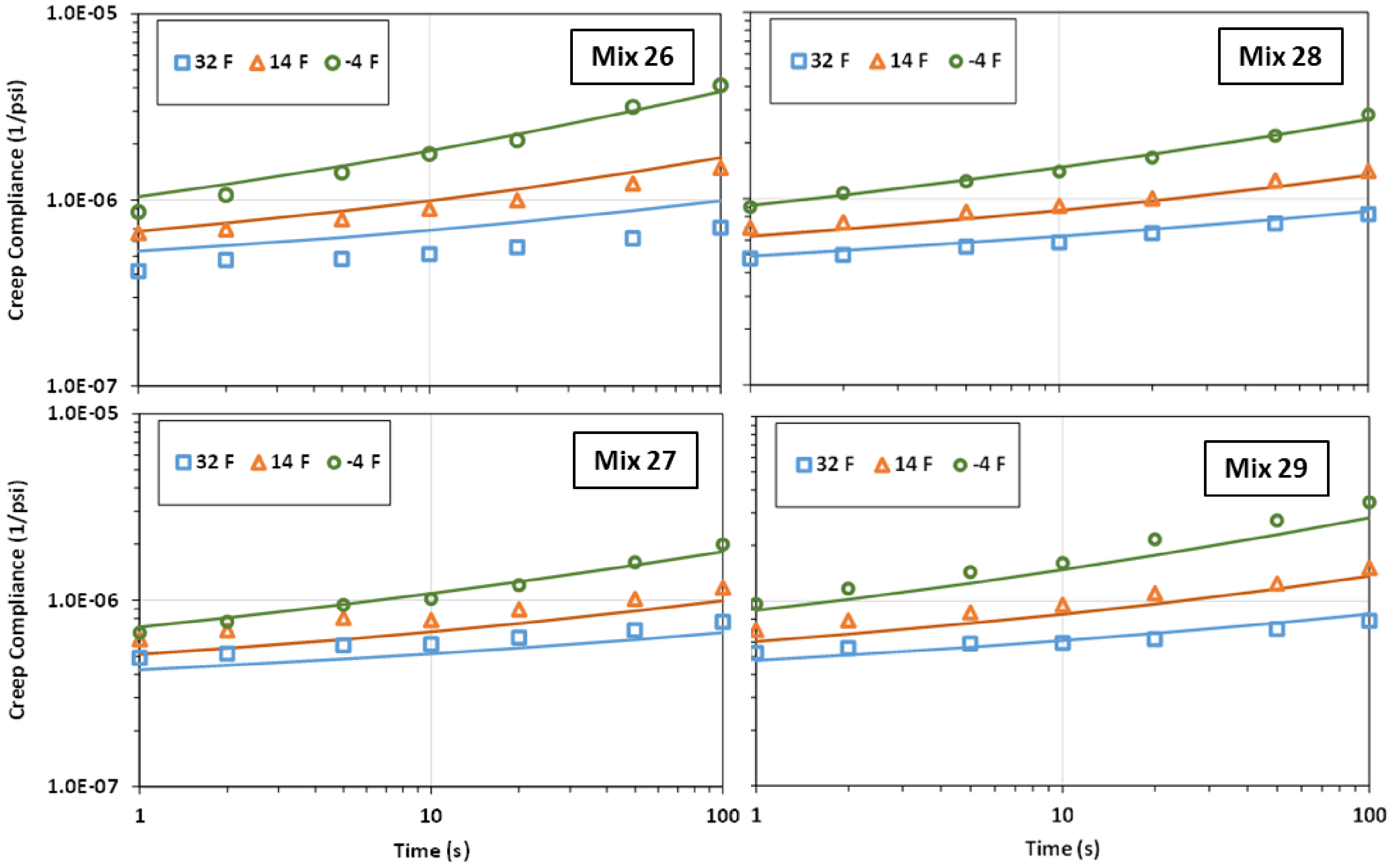
1. The high stiffness, low compliance part of the master curve is used
2. The "Blue" data points represent the initial data collected – it can be seen that a very minimal extrapolation is conducted using the Hirsch model
3. The "Grey" points show the E* equivalents of the interconverted D(t) data – it can be seen that the stiffness range does not extend beyond that given by the Hirsch model
4. The calculations of D(t) are associated with a time shift (here shown as frequency) extrapolation!





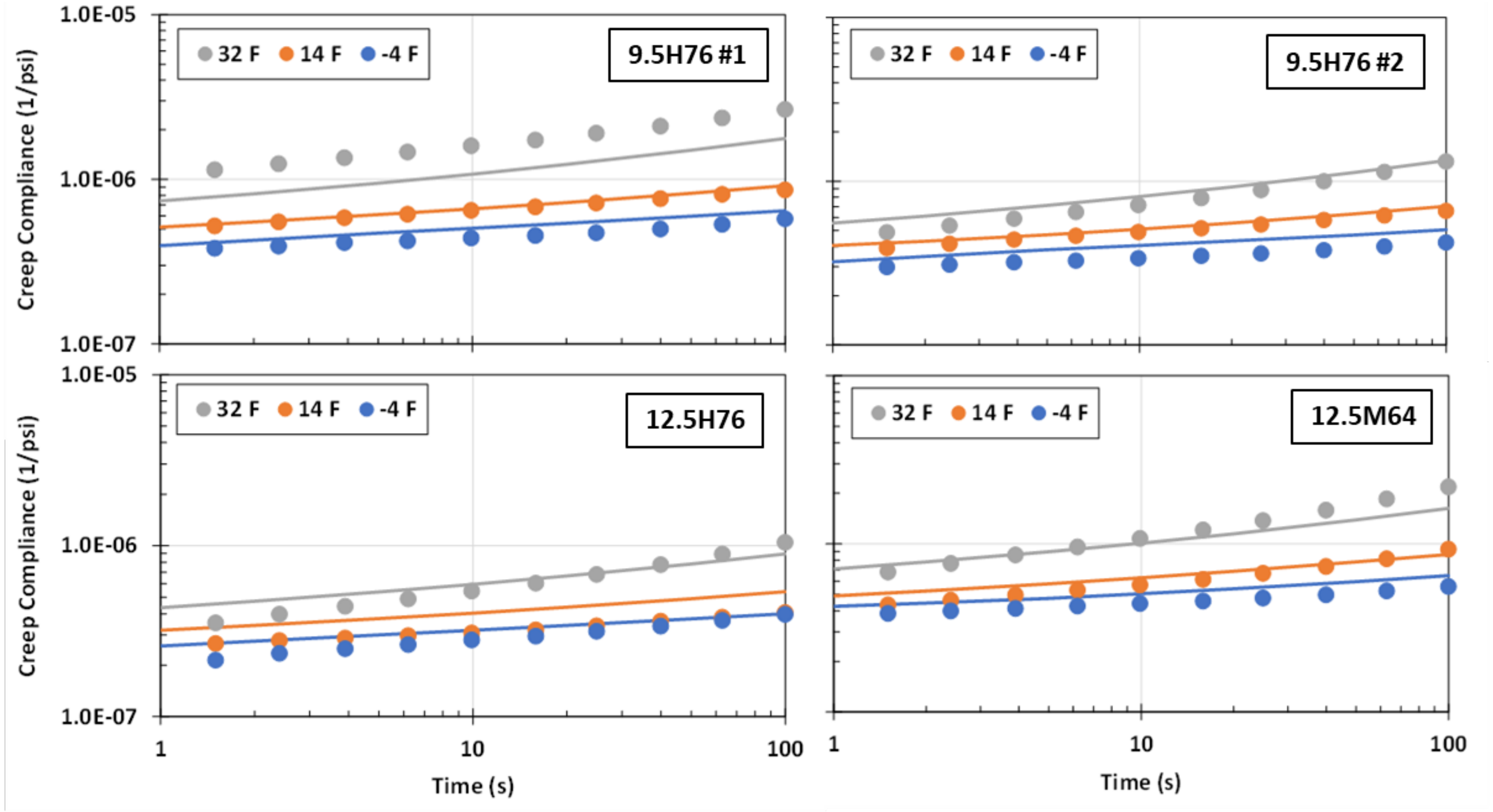
How does this compare to measured D(t) [1 of 3]

- NH mixes 26 to 29
- Some differences observed
  - ✓ Differences tend to be large at lower values of compliance
  - ✓ No consistent bias



How does this compare to measured D(t) [2 of 3]

- NJ mixes with 15% RAP
- Some differences observed
  - ✓ Differences tend to be large at higher values of compliance
  - ✓ No consistent bias



How does this compare to measured D(t) [3 of 3]

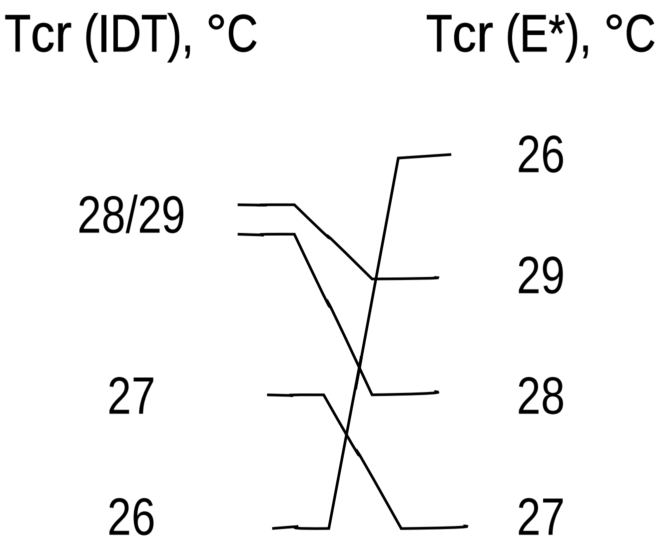
- Difference (2ds%) around 20% if two large values removed!

Validation Asphalt Mixures		-4˚F			14˚F			32˚F		
		Ave. Error (1/psi)	Ave. % Error	2ds%[1]	Ave. Error (1/psi)	Ave. % Error	2ds%[1]	Ave. Error (1/psi)	Ave. % Error	2ds%[1]
New Hampshire Mixtures	026	1.63E-07	9.6	22%	1.12E-07	10.8	28%	1.82E-07	**32.9**	30%
	027	6.32E-08	5.2		1.42E-07	16.9		7.58E-08	12.6	
	028	5.66E-08	3.2		6.52E-08	6.9		3.19E-08	5.2	
	029	2.80E-07	13.2		1.14E-07	11.6		4.43E-08	7.0	
New Jersey Mixtures	9.5H76 #1	6.00E-08	13.0		2.40E-08	3.4		5.47E-07	16.1	
	9.5H76 #2	6.30E-08	17.9		2.86E-08	5.7		8.46E-08	13.3	
	12.5H76	3.58E-08	14.1		9.53E-08	**29.4**		6.83E-08	14.8	
	12.5M64	6.82E-08	14.9		4.72E-08	9.9		1.81E-07	13.5	
Average per Temp		*9.87E-08*	*11.4*		*7.85E-08*	*11.8*		*1.52E-07*	*14.4*	
Average All Temps		*Average Error (1/psi) = 1.097E-07; Average % Error = 12.6%*								
[1]Single Operator (Christensen and Bonaquist, 2004)										

Thermal stress – D(t) measured vs. estimated from E*

- Maximum difference 4.6°C
- This study needs to be extended to understand differences
  - ✓ IDT is more complex
- Need to compare with field performance with a larger range of materials

Mix	Tcr (IDT), °C	Tcr (E*), °C	Difference
26	-25.4	-29.1	+3.7
27	-25.8	-21.2	-4.6
28	-27.0	-27.0	0.0
29	-27.0	-27.3	+0.3



Summary

- A practical and implementable method has been developed by researchers in the north east USA to calculate thermal cracking of pavements using E* data collected as part of the development of master curves used to run the AASHTOWare PAVEMENT-ME software.
  1. Data collection, in a difficult to run test, is significantly reduced, offering significant cost savings to DOTs who are interested in the collection of this type and data and computation of low temperature cracking.
  2. The method can be implemented today in software that exists for the performance of the inter-conversions. The software takes data directly from E* test output and can output the formats for AASHTOWare PAVEMENT-ME analysis.

- This method has been implemented with software and the calculations of the required inputs can be performed with methods that are practically implementable by DOTs developing data bases of material performance, with data that can be processed with a few minutes of work.

Acknowledgements

- The Team -

Geoffrey M. Rowe Sérgio Raposo	Thomas Bennert Christopher Ericson Nick Cytowicz	Walaa S. Mogawer	Eshan V. Dave
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Thank you for listening