Testing protocol to obtain failure properties of asphalt binders at low temperature using creep compliance and stress controlled strength test

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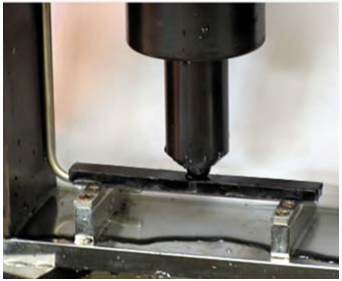
- Low temperature cracking is considered to be the critical distress in pavements built in cold regions.

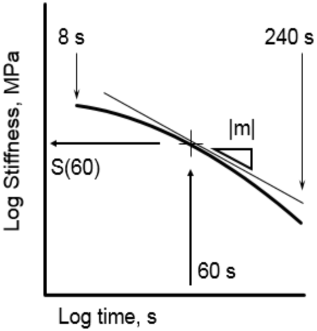
- For asphalt binder, two instruments were developed during SHRP research effort to investigate the low-temperature behavior of these materials:
  - ✓Bending Beam Rheometer (BBR) and
  - ✓Direct Tension Tester (DTT).

BBR: Bending Beam Rheometer

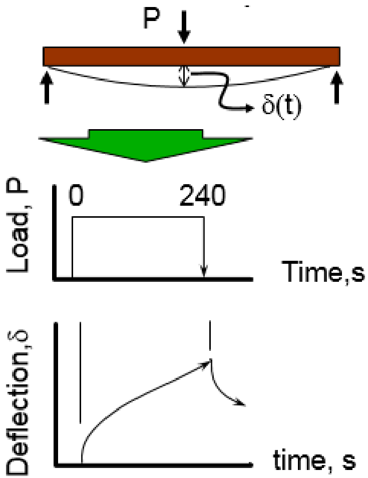
Provides indication of binders' ability to resist low temperature cracking

✓ stiffness and relaxation parameters





For the creep test , a load of 1N is applied for 240 sec.



The force and deflection were obtained as a function of time.

- ✓ Stress : (3Fxl) / (2*bxh^2)
- ✓ Strain: (6xδxh)/l^2

Here, F=Load, l=Length, b=width, h=thickness, δ=deflection

The Direct Tension (DT) is used to perform uniaxial tension tests at a constant strain rate of 3% per minute on dog-bone shaped specimens of asphalt binders until failure (AASHTO T 314-02 2002).

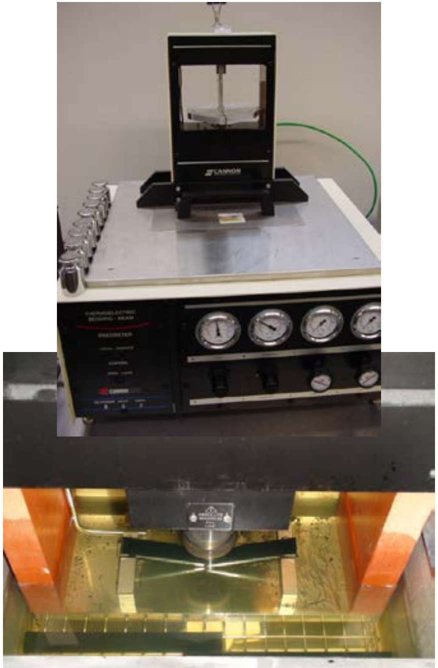
Measures the stress and strain at failure of a specimen of asphalt binder

- Direct Tension Test (DTT) is currently used only when asphalt binder doesn't pass the BBR test (S $\leq$ 300MPa; m-value $\geq$ 0.300)

Concerns about DTT

- ✓ The results are less repeatable due to a complex sample preparation
- ✓ Difficult (impossible) to achieve strain-controlled loading
- ✓ Expensive testing machine
- ✓ Many agencies do not perform DTT tests and completely rely on BBR creep properties.

Modified BBR Frame: BBR PRO



- Modified BBR frame, with proportional valve that offers
  - ✓ Complex control of the pressure in the air bearing system (including <u>cycles of loading/unloading</u>)
  - ✓ Capable of applying <u>loads at different loading rates</u>
  - ✓ Bigger load cell for asphalt mixture three point bending strength.

- For the Strength Test, a constant loading rate is applied until the beam breaks

DTT vs BBR Strength (Previous Investigation)

Initial Concerns

- Different Failure Mechanism
  - ✓DTT fails binder sample under tension (strain-controlled test)
  - ✓BBR fails binder beam under bending (stress-controlled test)
- Different Cooling Medium:
  - ✓Potassium Acetate for DTT
  - ✓Ethanol for BBR
- Different Sample Volume

Investigation was performed to understand if the two devices and corresponding test methods produce equivalent results.

DTT vs BBR Strength (Previous Investigation)

- ✓ Preliminary BBR strength and DTT strength tests were performed on a common set of asphalt binders, and the results were analyzed using simple size effect theory.
- ✓ Three types of cooling media were used for BBR strength testing: ethanol (E), potassium acetate (PA) and air.
- ✓ For DTT, all testing was performed in PA as required in the current specification (AASHTO T314, 2012).

Reference:

Falchetto, A. C., Turos, M. I., & Marasteanu, M. O. (2012). Investigation on asphalt binder strength at low temperatures. *Road Materials and Pavement Design, 13*(4), 804-816.

Marasteanu, M., Buttlar, W., Bahia, H., Williams, C., Moon, K. H., Teshale, E. Z., ... & Ahmed, S. (2012). Investigation of low temperature cracking in asphalt pavements national pooled fund study-phase II.

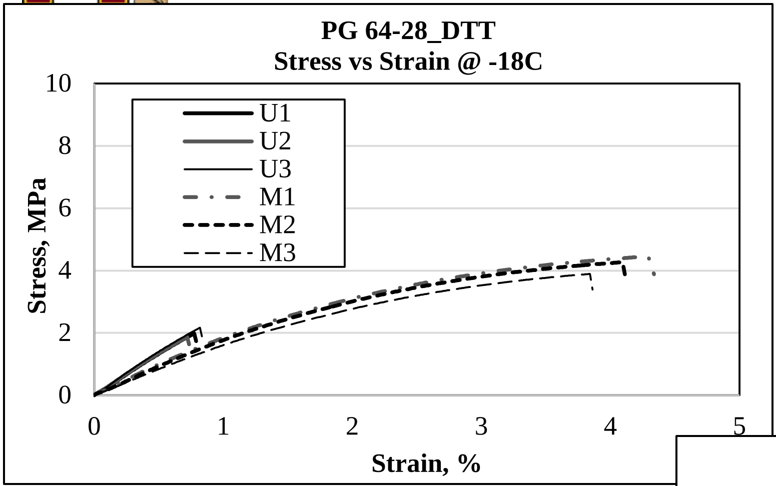
DTT vs BBR (Previous Investigation)

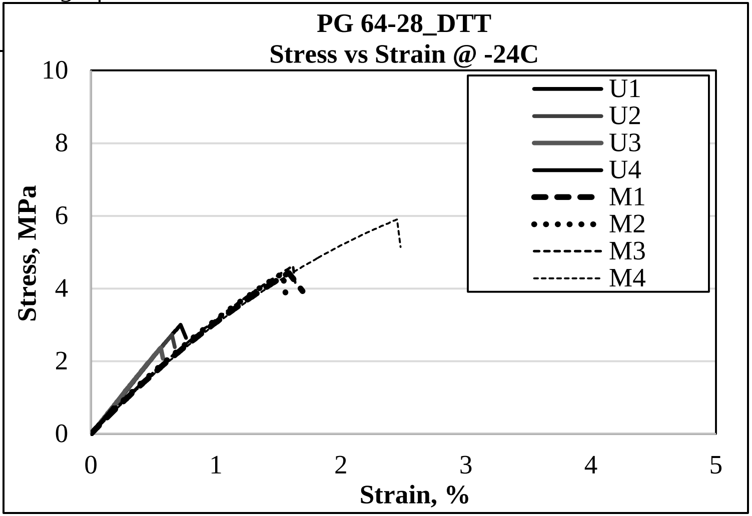
- Previous investigation concluded that
  - Only potassium acetate and air are appropriate cooling media for failure tests
  - DTT and BBR strength methods provide similar information about the failure properties of asphalt binders at low temperature
    - ✓ Different volumes of material tested in the two different methods need to be accounted for
- The next obstacle
  - ✓ *selecting the appropriate loading rate to obtain comparable results and to keep the testing time within reasonable limits.*

DTT vs BBR Strength

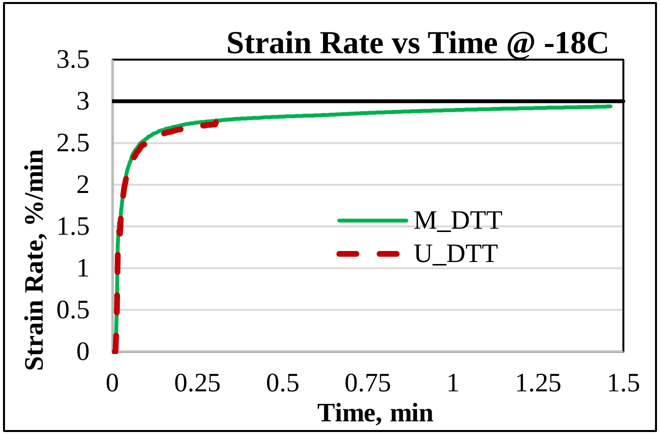
- To better understand the limitations and benefits of the two methods, linear viscoelasticity concepts are used to analyze the experimental data obtained on two binders:
  - Plain PG64-28 (U)
  - SBS-modified PG64-28 (M).
- The binders have similar creep properties, as indicated by the similar performance grade, however, the DTT responses are quite different

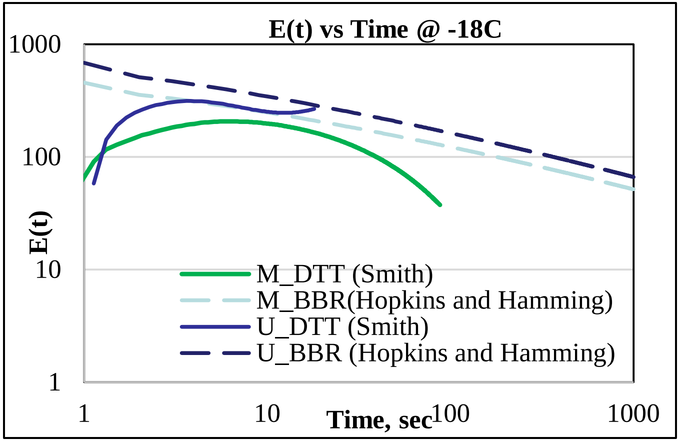
DTT Stress-Strain Curves

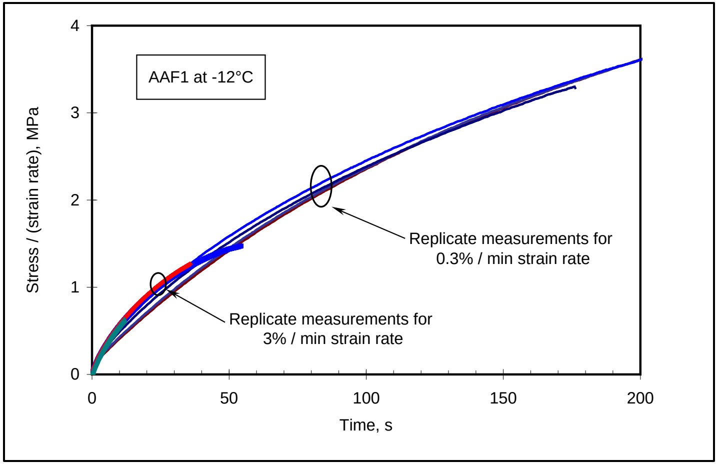




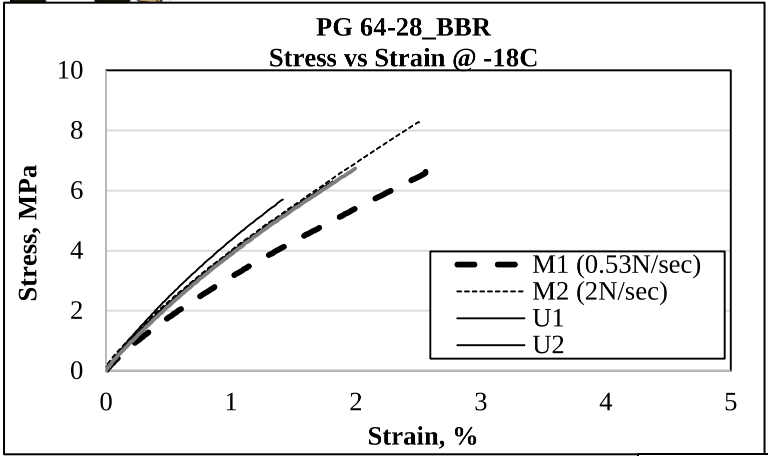
DTT Limitations

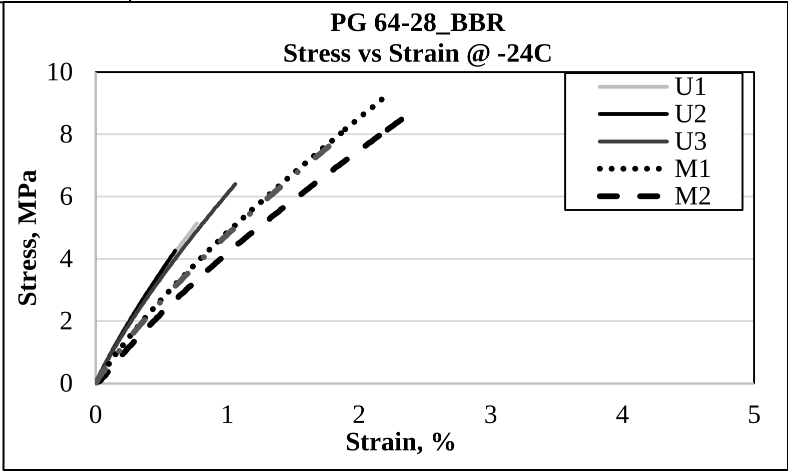






BBR Stress-Strain Curves





Loading Rate for BBR Strength

- The BBR strength results for all binders varied between 2 and 10MPa and never go above 12 MPa
  - Can be set as upper limit to be reached within a reasonable period of time.
  - Similar to the approach used for DTT, one can set a loading rate such that 12MPa is reached in 60 seconds (0.65N/sec)

- In some cases, beams do not break, which means higher loading rate (or lower test temperature must be used).
  - To be able to calculate a loading rate that would result in less than the maximum deflection of 7mm (equivalent to a strain of 2.6%), prior information related to the strain evolution with time is needed.

What Loading Rate for BBR Strength?

- Use linear viscoelasticity: in a test in which the stress is increased linearly starting from zero, the resulting strain will reflect the superposition of a series of retarded compliances. If $\dot{\sigma} = \mathrm{d}\sigma/\mathrm{d}t$, then:

$$\gamma = \dot{\sigma} t J_g + \dot{\sigma} \int_0^t \int_{-\infty}^{\infty} L\left(1 - e^{-u/\tau}\right) d \ln \tau \, du + \frac{\dot{\sigma} t^2}{2\eta_o}$$

$$\gamma = \dot{\sigma} t J_g + \dot{\sigma} \int_{-\infty}^{\infty} L\left[t - \tau\left(1 - e^{-t/\tau}\right)\right] d \ln \tau + \frac{\dot{\sigma} t^2}{2\eta_o}$$

- When the stress-strain curve under this condition is differentiated, the result is the creep compliance:

$$\frac{d\gamma}{d\sigma} = (1/\dot{\sigma}) \frac{d\gamma}{dt} = J_g + \int_{-\infty}^{\infty} L\left(1 - e^{-t/\tau}\right) d \ln \tau + t/\eta_o = J(t)$$

What Loading Rate for BBR Strength?

This also means that if creep compliance is known, the variation of strain with stress is known for a constant loading rate test.

If the loading rate is known, then the entire stress-strain curve can be determined for a given stress rate. An example is shown next.

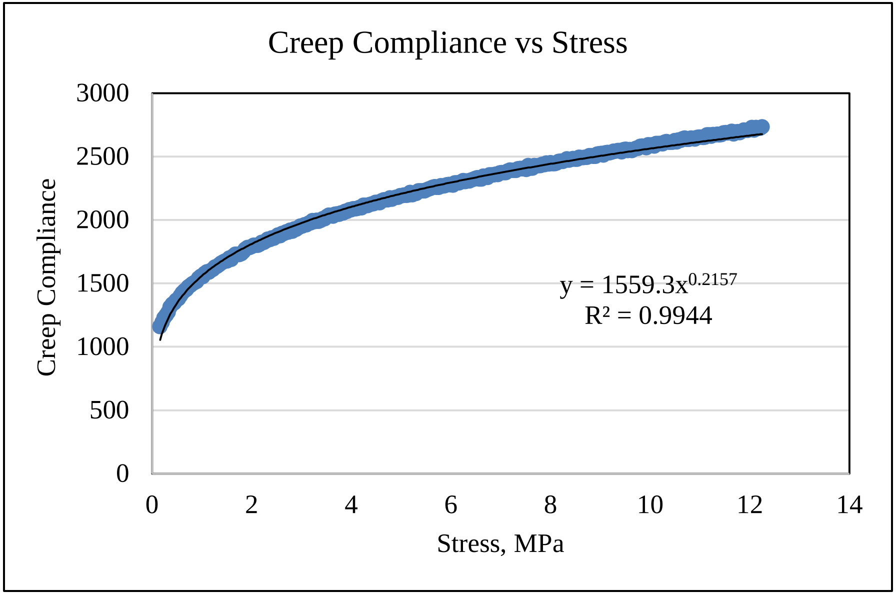
What Loading Rate for BBR Strength?

- First, a BBR creep test is performed and the creep compliance is calculated as a function of time.
- Assumption creep compliance D(t) follows a power law.
- Consider hypothetical BBR strength test performed using constant stress rate $\dot{\sigma}$. The stress at any time can be simply calculated as $\sigma(t) = \dot{\sigma} * t$
- Relate creep compliance from BBR creep test to stress from BBR strength test using a power law:

$$D(t) = a * \{\dot{\sigma} * t\}^b = a * \{\sigma(t)\}^b \qquad (1)$$

- Coefficients *a* and *b* can be simply calculated from fitting equation to creep compliance vs stress plot, for an assumed loading rate. The loading rate is required to match the times for the creep compliance (vertical axis) and the stress data (horizontal axis).

What Loading Rate for BBR Strength?



What Loading Rate for BBR Strength?

- First derivative of strain-stress curve is creep compliance, *D*(*t*), and, therefore:

  $$D(t) = \mathrm{d}\varepsilon(t)/\mathrm{d}\sigma(t) = a * \{\sigma(t)\}^b$$

  (1a)

- The strain can then be obtained as:

  $$\varepsilon(t) = \frac{a*\{\sigma(t)\}^{b+1}}{b+1} + c \qquad (2)$$

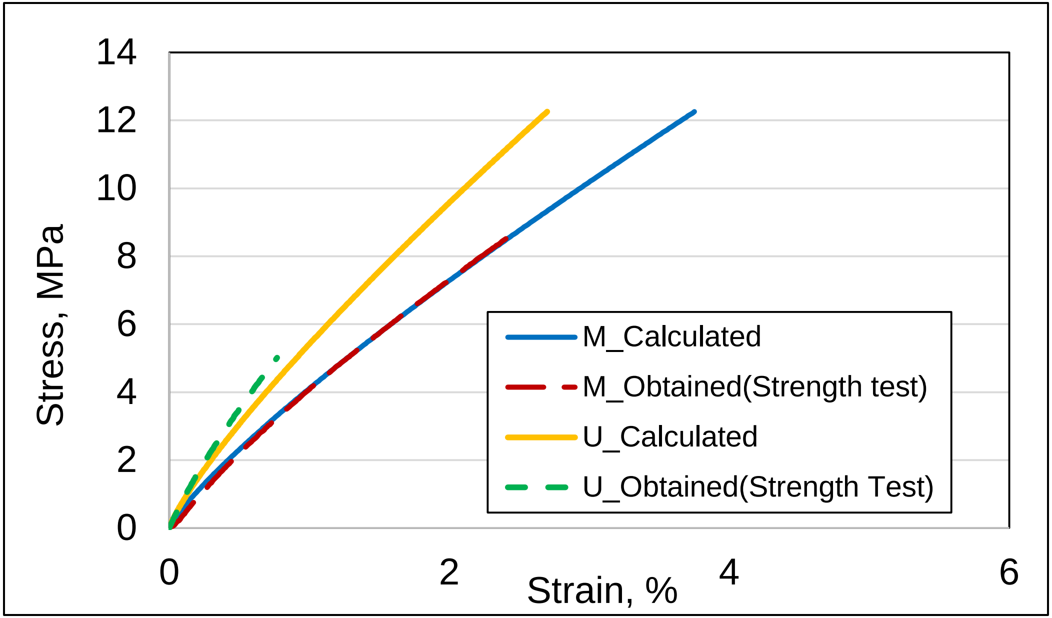
  Constant *c* is zero, since the plot starts in the origin.

- For the example shown in previous figure, using equation (2) and the values for *a* and *b*, the strain is calculated as

  $$\varepsilon(t) = \frac{\left[1559.3*\{\sigma(t)\}^{0.2157+1}\right]}{0.2157+1}$$

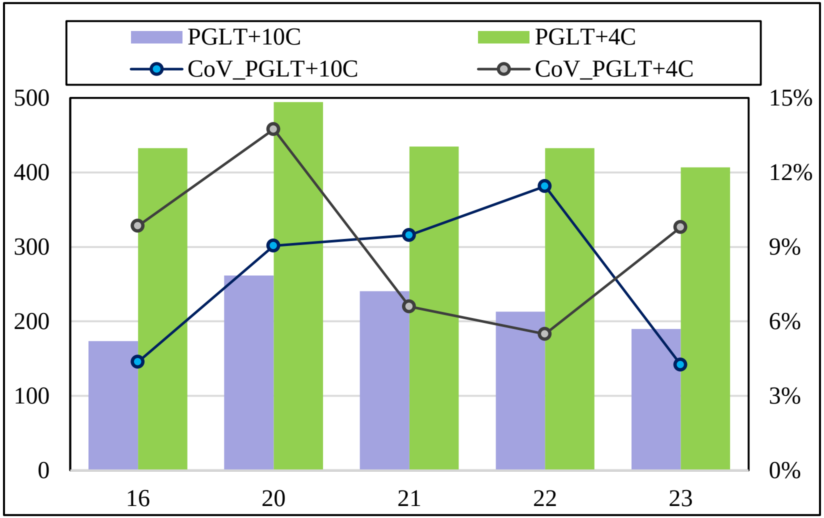
- Examples of predicted stress-strain curves for the two 64-28 binders at -24°C and a loading rate of 0.53N/s are shown in the next figure

Predicted vs Experimental



MnROAD 2016 Construction

Cell No.	Mix Design	Binder	Anticipated Cracking Potential
16	SPWEB540L	PG 64S-22	High
20	SPWEB540A	PG 52S-34	Moderate/high
21	SPWEB540C	PG 58H-34	Moderate
22	SPWEB540C	PG 58H-34	High
23	SPWEB540I	PG 64E-34 (highly modified)	Low

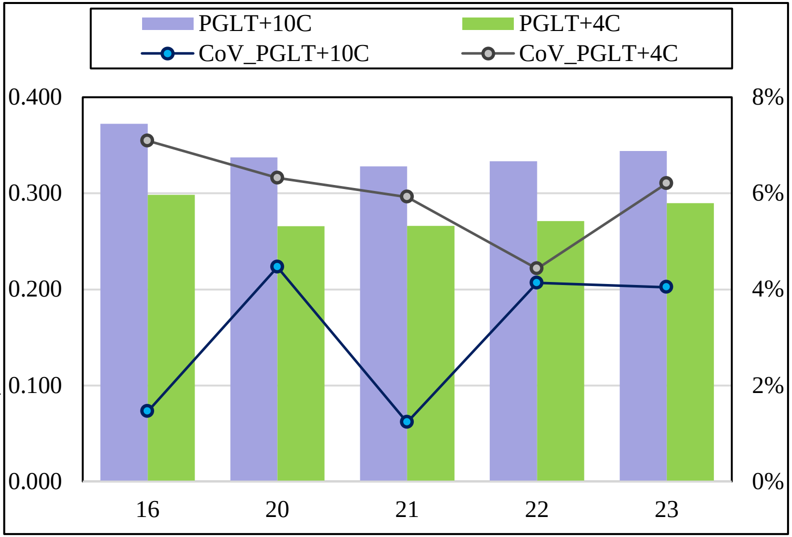


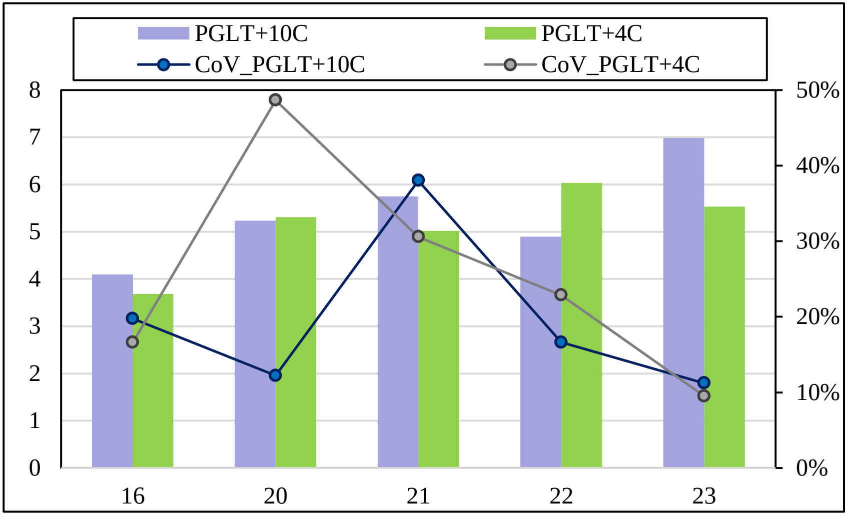
MnROAD 2016 Construction

Cell No.	Binder
16	PG 64S-22
20	PG 52S-34
21	PG 58H-34
22	PG 58H-34
23	PG 64E-34(highly modified)

Average Creep Stiffness, MPa at 60sec

Average m-value at 60sec





MnROAD 2016 Construction	
Cell No.	Binder
16	PG 64S-22
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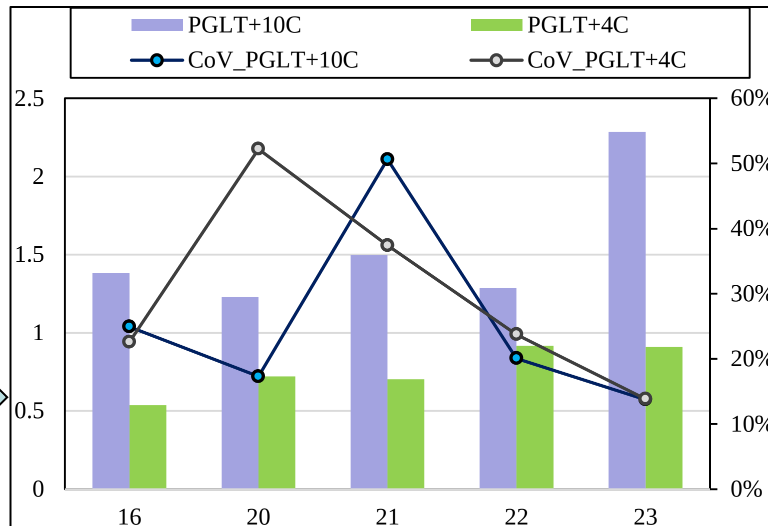
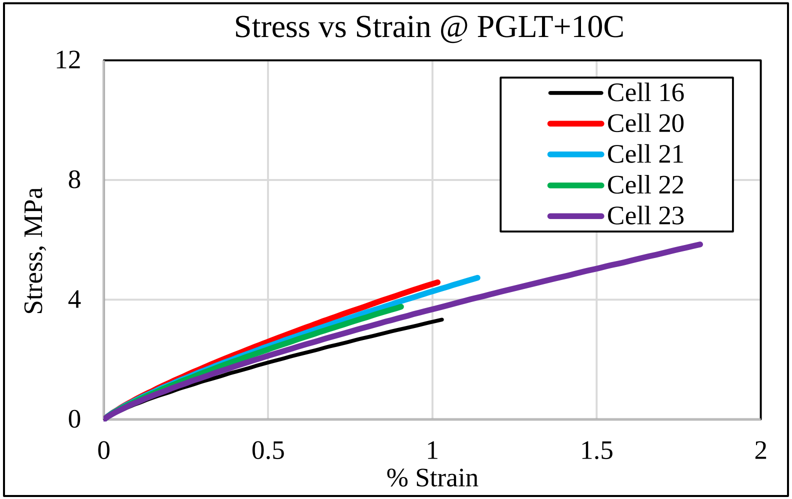
22	PG 58H-34
23	PG 64E-34(highly modified)

Average BBR Strength, MPa

Average BBR % Strain at Failure





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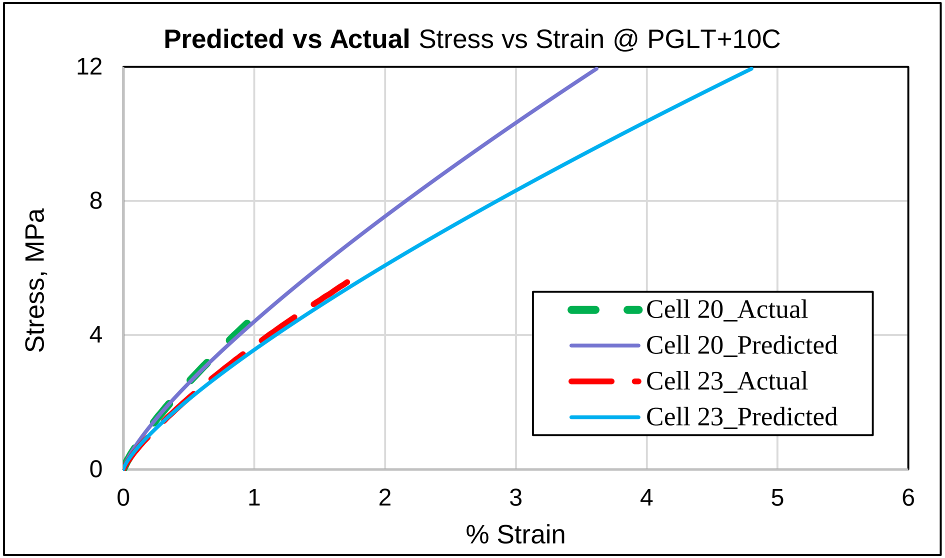

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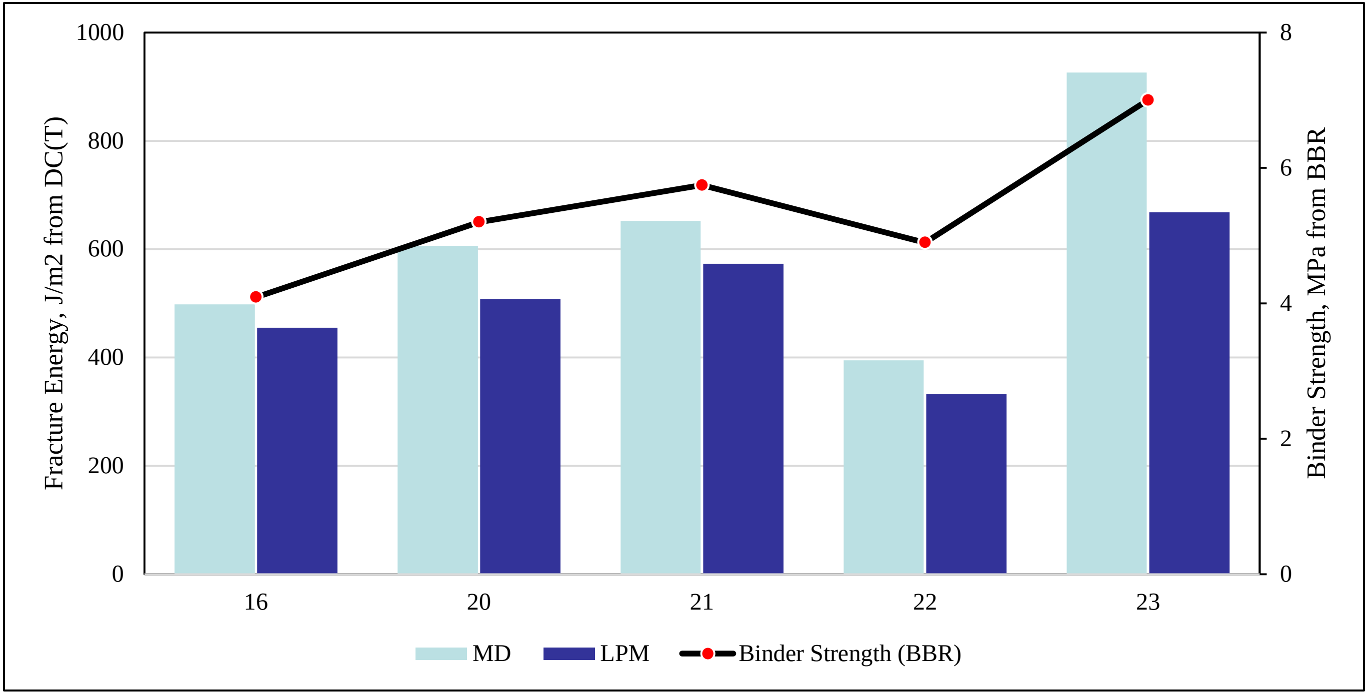

Procedure for BBR Strength

- Perform BBR creep tests at two temperatures, according to the current specifications, to determine the grade of the binder.
- Use experimental creep compliance to predict stress-strain curves for a stress rate of 0.65N/s, which will limit the duration of the test to 1 minute or less.
- Use stress-strain curves to determine if the 2.6% strain limit is reached within 1 minute. If the limit is reached, increase the stress rate accordingly. If the strain is less than 2.6%, perform strength test using the 0.65N/s rate.
- Perform BBR strength tests and obtain stress-strain curves and the stress and strain at failure.

Work in Progress

- This approach can only be used to select the best binder out of a group of binders that have similar PG lower limit based on creep data.

- Research is in progress to determine limiting parameters and criteria that would allow selecting asphalt binder similar to current PG specification.

Thank You!