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PDF content reads as follows:

- Review of Literature and Current Practices
- Sample Collection and Preparation
- Laboratory Testing for Dynamic Modulus ($|E^*|$)
- Analyses of Dynamic Modulus Test Results
- Laboratory testing for Binder Shear Modulus ($G^*$) and Phase Angle ($\delta$)
- Development of $|E^*|$ Database and Models
- Plan for Next Quarter
Motivation

- $E^*$ is one of the key input parameters for the structural design of flexible pavement

- In this study - $E^*$ of NMDOT mixes will be determined

- Study outcome will allow NMDOT pavement designers to select $E^*$ for design input
Asphaltic Material

- Asphalt concrete is a viscoelastic material
- Viscoelasticity is the property that exhibit both viscous and elastic characteristics in a material
- Due to the viscous part, asphaltic materials show time dependent deformation
Asphalitic Material

- In purely elastic materials the stress and strain are in phase
- In purely viscous materials, there is a 90 degree phase difference between stress and strain
- In asphalitic materials the behavior is somewhere in between purely elastic and purely viscous materials
- Phase lag less than 90 degree (typically 30 to 60 degrees)
Dynamic Modulus

- Important parameter for asphaltic (viscoelastic) material
- This represents the time-dependent stiffness characteristic
- The main input property of HMA in MEPDG
- Dynamic modulus is the ratio of peak stress to peak recoverable strain under oscillatory loading
Dynamic Modulus (continued)

- $E^*$ can be decomposed into storage and loss moduli
- Storage Modulus: measures the elastic portion of the response
  \[
  E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta
  \]
- Loss Modulus: measures the viscous response / the energy dissipated as heat
  \[
  E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta
  \]
- Complex modulus
  \[
  E^* = E' + i E''
  \]
- Dynamic modulus = absolute value of complex modulus
  \[
  |E^*| = \sqrt{(E')^2 + (E'')^2} = \sqrt{\left(\frac{\sigma_0}{\varepsilon_0}\right)^2 \left(\sin^2 \delta + \cos^2 \delta\right)} = \frac{\sigma_0}{\varepsilon_0}
  \]
- Phase angles: \[
  \tan \delta = \frac{E''}{E'}
  \]
Review of laboratory $E^*$ test methods

- Dynamic modulus tests are conducted by applying sinusoidal load on an asphalt concrete mix specimen
- Test methods can vary based on the application of resonances, control methods, and type of load application.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Control type</th>
<th>Load application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free</td>
<td>Strain controlled</td>
<td>Axial</td>
</tr>
<tr>
<td>Forced</td>
<td>Stress controlled</td>
<td>Shear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torsion</td>
</tr>
</tbody>
</table>

- Based on the changing of test variables, testing procedure varies.

<table>
<thead>
<tr>
<th>Test procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature sweep: load frequency remains constant</td>
</tr>
<tr>
<td>Frequency sweep: test temperature remains constant</td>
</tr>
<tr>
<td>Stress amplitude sweep: temperature and frequency remains constant</td>
</tr>
</tbody>
</table>
Review of laboratory $E^*$ test methods (continued)

- ASTM D 3497-79 – Standard test method for dynamic modulus of asphalt mixtures
- Adopted as a standard by ASTM in 1979
- Load controlled testing
- Load kept constant - frequency sweep

- Uniaxial compressive haversine load between 0 to 241 KPa

- Temperature: 5, 25, and 40 degree C
- Frequencies: 1, 4, and 16 Hz

- As the temperature is increased, the load level is decreased to avoid damage of the specimen
- Specimen have a height to diameter ratio greater than two
Review of laboratory $E^*$ test methods (continued)

- Similar to the ASTM test

- Can be used to determine both dynamic modulus and phase angle
- ASTM method was limited to only dynamic modulus determination/not the phase angle
Confined dynamic modulus testing protocol
- Same test procedure as that of AASHTO TP-62
- Except a confinement pressure is applied to the specimen

<table>
<thead>
<tr>
<th>Confining pressure: 138 KPa and 206 KPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature: 10, 4.4, 21.1, 37.8, and 54.4°C</td>
</tr>
<tr>
<td>Frequencies: 0.1, 0.5, 1, 5, 10, and 25 Hz</td>
</tr>
</tbody>
</table>

More complex than unconfined dynamic modulus test
Better to categorize and contrast the field performance of the different mixtures
Review of laboratory $E^*$ test methods (continued)

- Simplified dynamic modulus testing
  - In case of AASHTO TP-62 test protocol, there is a large amount of overlap in the measured data that is not needed for the development of the master curve
  - This is an alternative testing protocol which requires testing at only three temperatures and four rates of loading
  - The master curve obtained found to be similar to standard test

Temperatures: 4.4, 21.1, and 46.1°C

Frequencies: 10, 1, 0.1, and 0.01 Hz
Review of laboratory $E^*$ test methods (continued)

- Dynamic shear modulus test
  - Simple shear tester (SST) is used to perform this test.
  - Strain controlled
  - A shear load is applied to an asphalt concrete specimen with diameter of 150 mm and height of 50 mm in this test

Temperature: 4, 20 and 40°C

Frequencies: Maximum 10 Hz and minimum 0.1 Hz
Review of laboratory $E^*$ test methods (continued)

- Indirect tension test
  - Kim (2009) proposed a relationship to evaluate from indirect tension test (IDT) data
  - Main reason is the limitation of finding 150 mm sample from field

- Hollow cylinder tensile test
  - Buttlar et al. (Buttlar et al. 2002) explored the adoptability of using the HCT
  - The test is conducted by applying pressure to the internal wall of a hollow cylindrical specimen using flexible membrane
  - The applied pressure produces hoop stress on the wall
  - By implementing closed form solutions for thick walled cylinders the tensile strength and creep compliance is calculated
  - The size of the specimen used is of 115mm height, 150mm outside diameter, and 106mm inside diameter
Review of laboratory data analysis methods

- Fast Fourier Transform (FFT)
  - FFT is one of the reliable filtering methods that can be used to process the stress and strain signal
  - The FFT is an algorithm for transforming data from time domain to frequency domain

- Time domain methods
  - Method A: Spencer’s 15-point data filtering and central waveform bracketing
  - Method B: Spencer’s 15-point data filtering and peak picking
  - Method C: Second-order polynomial over 25% of data and peak picking
  - Method D: Second-order polynomial over 10% of data and peak picking
  - Method E: No filtering and central waveform bracketing
  - Method F: No filtering and peak picking
  - Method G: Sinusoidal over 100% of data and regression coefficients
Review of factors that affect $E*$

- Rate of loading
- Temperature
- Aging
- Moisture
- Binder stiffness
Review of factors that affect $E^*$ (continued)

- Aggregate stiffness
  - The increase in the dynamic modulus is limited for increase in aggregate stiffness
  - Even if the aggregate modulus is increased, the dynamic modulus of the asphalt concrete is found to be reduced beyond a threshold aggregate modulus of 5000 MPa

- Air void
  - Higher air void results in lower value of dynamic modulus
  - Not only the amount of air voids but also their size and distribution have significant effect
  - Thoroughly distributed air voids enhance the stiffness of asphalt concrete
Review of $E^*$ modeling

- Viscosity-based Witczak predictive model

\[
\log |E^*| = -1.249937 + 0.029232 \rho_{200} - 0.001767 (\rho_{200})^2 - 0.002841 \rho_4 \\
- 0.058097 V_a - 0.802208 \left( \frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} \right) \\
+ \frac{3.871977 - 0.0021 \rho_4 + 0.003958 \rho_{3/8} - 0.000017 (\rho_{3/8})^2 + 0.00547 \rho_{3/4}}{1 + e^{(-603313 - 0.313351 \log(f) - 0.393532 \log(\eta))}}
\]

- Limitation: Reliance on other models to predict dynamic shear modulus
Review of $E^*$ modeling (continued)

- $G^*$-based Witczak model

\[
\log |E^*| = -0.349 + 0.754 \left( |G_b^*|^{-0.0052} \right) \\
2.558 + 0.032V_a + 0.713 \left( \frac{V_{b\text{eff}}}{V_{b\text{eff}} + V_a} \right) + 0.0124 \rho_{38} + 0.0001 \left( \rho_{38} \right)^2 + 0.00 - 0.0098 \rho_{34} \\
1 + e^{(-0.7814-0.5785 \log |G_b^*|-0.8834 \log (\delta_b))}
\]

- Phase angle of the binder associated with $G^*$

- Dynamic Shear Modulus of binder

- Air void content

- Asphalt content

- Aggregate gradation parameters
Review of $E^*$ modeling (continued)

- **Hirsch model**

\[
|E^*| = P_c \left[ 4,200,000 \left( 1 - \frac{VMA}{100} \right) + 3G_b^* \left( \frac{VFA\cdot VMA}{10,000} \right) \right] + \frac{(1 - P_c)}{\left( 1 - \frac{VMA}{100} \right)^2} + \frac{VMA}{4,200,000} + \frac{VMA}{3G_b^*(VFA)}
\]

- $P_c = \frac{20 + \frac{3G_b^*(VFA)^{0.58}}{VMA}}{650 + \frac{3G_b^*(VFA)^{0.58}}{VMA}}$

- $\phi = -21 (\log P_c)^2 - 55 \log P_c$

- Strength of this model is the empirical phase angle equation, important for inter-conversion of the dynamic modulus to relaxation modulus or creep compliance

- Limitation: strong dependence on volumetric parameters
Review of interconversion between $E^*$ and material function

- Conversion of creep compliance into dynamic modulus
  - Jeong et al. (2007) validated the interconversion between dynamic moduli and creep compliances
  - They used a Prony series model to fit the creep compliance master curve

\[
D(t_r) = D_g + \sum_{i=1}^{n} D_i (1 - e^{-t_r/\tau_i})
\]

- The real and imaginary parts of the complex compliance are then

\[
D'(\omega) = D_g + \sum_{j=1}^{n} \left( \frac{D_j}{\omega^2 \tau_j^2 + 1} \right) \quad D''(\omega) = \sum_{j=1}^{n} \left( \frac{\omega \tau_j D_j}{\omega^2 \tau_j^2 + 1} \right)
\]

- The complex compliance and the dynamic modulus then determined as

\[
|D^*(\omega)| = \sqrt{(D'(\omega))^2 + (D''(\omega))^2} \quad E^*(\omega) = \frac{1}{D^*(\omega)}
\]
Task 2: Selection of asphalt mixes

- Total mix number of mixes = 3 SPs x 6 Districts x 3 PGs = 54 mixes
- Total number of master curves = 54 mixes x 3 samples of each mix = 162 master curves

<table>
<thead>
<tr>
<th>Mix type</th>
<th>Mix sources</th>
<th>PG Binders</th>
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<tbody>
<tr>
<td>SP-II</td>
<td>District 1</td>
<td>PG 64-28</td>
</tr>
<tr>
<td>SP-III</td>
<td>District 2</td>
<td>PG 70-22</td>
</tr>
<tr>
<td>SP-IV</td>
<td>District 3</td>
<td>PG 76-22</td>
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<td>District 4</td>
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<td>District 5</td>
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<td></td>
<td>District 6</td>
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</table>
E* Testing Machine

- We use GCTS ATM-025, E* Testing Machine
- It can be configured to test asphalt in a variety of modes.
- Includes:
  - Environmental Chamber
  - Digital Servo Controller
  - Temperature Control Unit
  - Operating System and Devices

- The environmental chamber is capable of controlling temperature over a range of -30°C to +150°C
- The temperature in the chamber can be controlled with an accuracy of ±0.5°C
- The Digital Servo Controller has a capacity of controlling up to 24 sensors
Adaptive controller system in GCTS ATM-025 allows the system to precisely match the desired cyclic stress amplitudes throughout the tests.

The GCTS ATM-025 system can be connected to two load cells.

Top actuator is connected with a load cell that is capable of measuring loads up to 25kN.

The bottom actuator is used with a load cell that has a maximum capacity of 100kN.

The resolution of the top actuator load cell is 5N.
Gyratory Compactor

- Equipped to set
  - the maximum number of gyration of the mold or
  - a minimum height requirement for the sample inside the mold.

- Any of these criteria can rule out further compaction of the specimen, allowing a good control over the air void requirement of the sample
• Coring Machine

- The GCTS Asphalt coring machine ACD-150 is capable of achieving a large range of spindle speeds to provide optimum performance when preparing test specimens.
- The coring rate is controlled by hydraulic pressure.
- The coring machine has automatic down-feed mechanism with a total travelling distance of 250 mm.
- The diamond core barrel of the coring machine has a diameter of 100 mm.
Lab Specimen Saw

- The GCTS Lab Specimen Saw (RLS-3HA) is designed to cut cylindrical asphalt samples.
- The device is built with stainless steel bearing guide rollers to guide the vise carriage smoothly on precision ground.
- This machine has a mechanism to use water to cool down the blade without affecting the asphalt sample.
- A hydraulic feed allows control of cutting speed without slowing down the blade RPM for better cuts.
Automatic Positioning Fixture

- GCTS Automatic Positioning Fixture (GPF-100) is used to fix loading buttons to the final specimen.
- This allows easy specimen preparation for dynamic modulus testing.
The use of spring loaded LVDTs are recommended in the AASHTO TP-62.

AASHTO TP-62 recommends measuring deformations at a minimum of two locations 180° apart.

By increasing the LVDTs to three locations located 120° apart the required number of replicates for testing can be reduced.

LVDT mounting buttons are glued to the specimen using epoxy.

The gauge length is maintained to be 100 mm and the Automatic Positioning Fixture is used to fix LVDT mounting buttons 50 mm away from the mid height of the specimen.

Two 0.5-mm-thick latex sheets are provided as end treatment.
Test Procedure

- Axial LVDTs are attached to the specimen and adjusted to provide enough of the range available for the accumulation of permanent deformation.
- AASHTO TP-62 specification recommended the minimum time to reach equilibrium for each of the test temperatures.
- A dummy specimen with a thermocouple cored in to the center is also used to monitor and justify the specimen temperature.
- The specimen is then placed on the base platen. While placing caution need to be taken to avoid eccentric loading on the sample.
- The sample and the top platen are concentric with the top actuator loading point.
- A contact load equal to 5 percent of the dynamic load is then applied.
- The uniformity of the load over the specimen is then checked at the conditioning stage by applying 50 percent of the required load and observing the response from the LVDTs.
Test Procedure (continued)

- The position of the specimen is moved and adjusted very carefully to balance the LVDT measurements until the AASHTO TP-62 recommended uniformity is reached.
- Once the deformations are uniform, the full haversine loading is applied to the specimen.
- The full dynamic load is adjusted to produce axial strains of about 55 micro-strains.
- The AASHTO recommended stain range is 50 to 150 micro-strains. This is to avoid excessive damage of the sample by producing more permanent deformation.
- The general range recommended for the entire dynamic modulus test over all temperatures is between 15 and 2800 KPa.
- A two-minute rest period between frequencies in the frequency sweep is applied during testing.
Analysis of Test Results

- The data collected using the GCTS SCON 2000 data acquisition system are the time, axial force and the displacements of the linear variable differential transducers (LVDT).

- Even though the system is capable of collecting and storing the entire set of data from the test start to end, to reduce load on the system and increase efficiency, the is collected and stored only for the last five cycles of loading.
Raw Data

- The displacements of the two LVDTs is recorded and stored separately.
- For the calculation of strain the average of the two is taken.
- Before the tests are performed, the AASHTO requirements for specimen geometry are checked for the perpendicularity, waviness and accuracy of dimensions.
- The displacement data collected from the LVDTs are divided by the axial gage length to get the actual axial strain.
- For each test temperature and frequency combination data points are collected and stored for the last five cycles.
- Each data file collects the required data for all frequencies under the test temperature.
- The data is arranged from 25 Hz and ends at 0.01 Hz for each of the test temperatures.
Stress-Strain Data

- The stress and strain data obtained from feedback signal is not perfectly sinusoidal. This is because of the test equipment limitations.
- The noise in the feedback signal accompanied with the recoverable deformation and permanent deformation affect the computed modulus and phase angle values.
- The GCTS CATS software uses the AASHTO TP-62 analysis method.
- The AASHTO TP-62 employs a method to transform and fit the discrete time-stress data and time strain data to a sinusoidal function.
- Then dynamic modulus values are calculated by determining the stress amplitude and strain amplitude from the fitted sinusoidal curve.
- The phase angle is determined by determining the difference of the phase angles of the strain and stress sinusoidal fit curves.
- All calculations are made from the last five loading cycles.
Stress-Strain Data (continued)

- The peak stress ($\sigma_o$) is defined as:
  \[ \sigma_o = \frac{\bar{P}}{A} \]

- where, $\bar{P}$ is average of the load amplitudes for the last five loading cycles; $A$ is the cross sectional area of the specimen.

- Recoverable axial strain ($\varepsilon_o$) is defined as:
  \[ \varepsilon_o = \frac{\bar{\Delta}}{GL} \]

- where, $\bar{\Delta}$ is average of the deformation amplitudes for the last five loading cycles; $GL$ is the gauge length.

- Dynamic Modulus $|E^*|$ is defined as:
  \[ |E^*| = \frac{\sigma_o}{\varepsilon_o} \]

- Phase angle ($\phi$) is defined as:
  \[ \phi = \frac{t_i}{t_p} * 360 \]

- where, $t_i$ is the average phase lag between a cycle of stress and strain (sec); $t_p$ is the average time for stress cycle (sec).
Dynamic Modulus Data Analysis

Time Temperature Superposition Principle (TTSP)

- Time temperature superposition principle is applied on the dynamic modulus data collected from the tests conducted at different temperatures and frequencies.
- This principle allows us to move horizontally the dynamic modulus data at different temperatures on the loading time scale or loading frequency scale to produce one smooth curve dependent only on loading frequency or time.
- The amount by which dynamic modulus data is shifted to fit in a smooth curve at a reference temperature is referred to as shift factor, $a(T)$.
- Shifting is achieved by dividing the loading time in the time domain or multiplying the loading frequency in the frequency domain by the shift factor to get the reduced time or reduced frequency.
- The smooth curve that is developed by shifting the dynamic modulus data is referred to as mastercurve.
The mastercurve can be developed for any reference temperature chosen arbitrarily.

At the reference temperature the shift factor is 1 and its logarithm is zero.

Reduced frequency:

\[ f_r = f \times a(T) \]

Then,

\[ \log(f_r) = \log(f) + \log[a(T)] \]

Otherwise, reduced

\[ t_r = \frac{t}{a(T)} \]

Then,

\[ \log(t_r) = \log(t) - \log[a(T)] \]

The smooth curve that is developed by shifting the dynamic modulus data is referred to as mastercurve.
The use of TTSP to develop master curve have two advantages.

The first and the foremost is it reduces the three dimensional data (dynamic modulus, loading time/frequency and temperature) into two dimensional data by eliminating the temperature variable.

This makes it easy to compare test results conducted at different conditions.

The other advantage is the possibility of interpolation to get intermediate data within the test data range.
There are different shift factor functions which can be used to fit the shift factors trend.

Among these,
- the Arrhenius equation and
- the Williams, Landel, and Ferry (WLF) equation are widely used

Other function that is available for fitting the shift factor data is a second degree polynomial.

\[ \log a_T = aT^2 + bT + c \]
Dynamic Modulus Data Analysis

The Mastercurve

- The function that is predominantly used for developing mastercurve for dynamic modulus data is the sigmoid function.

\[
\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(t_r)}}
\]

- Here, \(|E^*|\) is dynamic modulus; \(t_r\) is reduced frequency; \(\delta\) is minimum modulus value; \(\alpha\) is span of modulus values; \(\beta, \gamma\) are shape parameters.

- The parameter, \(\gamma\) indicates how steep the function is i.e. how fast the modulus is changing from the minimum value to the maximum.

- The parameter, \(\beta\) represents the horizontal position at which the rate of change of modulus changes from positive to negative.

- \(\delta\) is associated with the minimum value of asphalt mix modulus generally caused by high temperature.
Dynamic Modulus Data Analysis

The Mastercurve (continued)

- At high temperatures the modulus of the binder becomes insignificant and aggregate interlock plays a significant role in determining compressive stiffness.
- This behavior of asphalt mix is captured by the parameter $\delta$.
- The largest modulus which is associated with binder modulus at very low temperature is represented in the sigmoidal function by the sum of parameters $\delta$ and $\alpha$.
- This highest modulus is also referred to as glassy modulus.
- There are different methods that can be used to fit the sigmoidal function to shifted dynamic modulus data.
- Witczak and Sotil (2004) have investigated a variety of methods and recommended to optimize all four parameters of the sigmoidal function together with the three coefficients of the polynomial shift factor function.
Varma et al. (2013) used a viscoelastic genetic algorithm for inverse analysis of asphalt layer properties such as relaxation modulus, dynamic modulus from falling weight deflections.

According to Varma et al. (2013) the elastic analysis cannot produce the viscoelastic properties of the asphalt concrete layer.

The FWD load-response history of a single FWD drop and variation in temperature along the depth of AC layer during the drop are used to perform analysis.

Varma et al. offered a genetic algorithm based optimization scheme to search for the pavement properties.
Varma et al. (2013) proposed approach

- The asphalt pavement system is modeled as a layered half-space, with the top layer being linear visco-elastic solid.
- The base, sub-base, sub-grade, and bed rock are assumed linear elastic.
- The visco-elastic properties to be back calculated from FWD data include two functions: a time function and a temperature function.
- The time function refers to the relaxation modulus $E(t, T_0)$.
- The temperature function refers to the time-temperature shift factor $a_T$.
- The shift factor $a_T$ allows applying $E(t, T_0)$ for any temperature level $T$ by simply replacing physical time with a reduced time $t_R = \frac{t}{a_T}$; therefore $a_T$ is a function of both $T$ and $T_0$ such that when $a_T = 1$, $T = T_0$. 

\[
E(t, T_0) = \frac{t}{a_T} 
\]
Asphalt Concrete

Composition of Asphalt Concrete

- Aggregates
- Asphalt Cement/Binder
- Asphalt Modifier & Others - e.g. Versabind

Asphalt Concrete
Asphalt Cement

- A dark brown to black, highly viscous, hydrocarbon produced from petroleum distillation residue.

- Distillation can occur naturally, resulting in asphalt lakes, or occur in a petroleum refinery using crude oil.
Asphalt Cement (Continued)

- It functions as a waterproof, thermoplastic, viscoelastic adhesive in HMA.

- Accounts for between 4 and 8 percent of HMA and makes up about 25 to 30 percent of the cost of pavement.

- The most important physical properties are:
  - Durability
  - Rheology,
  - Safety and
  - Purity

- Durability is a measure of how asphalt binder physical properties change with age.

As asphalt binder ages

Viscosity / Stiffness increases

Becomes more brittle
**Asphalt Cement (Continued)**

- Rheology is the study of deformation and flow of matter.

  - Pavement that deforms or flows too much
    - Suffers excessive rutting and bleeding
  - Pavement that deforms and flows too less
    - Suffers excessive fatigue cracking

- At extremely high temperatures, asphalt cement can release enough vapor to form volatile concentration immediately above the asphalt cement to a point where it will ignite (flash) when exposed to a spark or open flame.

  - This is called the flash point. For safety reasons, the flash point of asphalt cement is tested and controlled.

- Asphalt cement must consist of pure bitumen. Impurities hamper the cementing properties of asphalt.
Asphalt Grading Systems

- Three most common grading systems are:
  - Penetration Grading
  - Viscosity Grading
  - Superpave Performance Grading

- Each grading system ranges from simple to complex and represent an evaluation of the ability to characterize asphalt binder

- Most state agencies uses the Superpave grading system, now a days.
Penetration Grading

- A standard needle is allowed to penetrate an asphalt binder sample with a 100 g load placed on it.

- The basis depends on the penetration depth in 5 seconds.

- Test is simple and easy to perform.

- It does not measure any fundamental parameter and can only characterize asphalt binder at one temperature, typically room temperature.

- Typical asphalt binders used in the United States are 65-70 pen and 85-100 pen.

1 pen = 0.1 mm of penetration by the standard needle.
Viscosity Grading System

- Measures penetration, as in the penetration grading system as well as measures the viscosity of the asphalt binder at 140 °F and 275 °F.

- The test can be conducted on virgin asphalt binder (AC) or aged asphalt binder (AR).

- Grades are listed in poises (cm-g-s) or poises divided by 10.

- This system is better than the penetration grading system, as it determines the viscosity of the binder, a fundamental physical property of fluid flow.

- Typical asphalt binder used in US: AC – 10, AC – 20, AC – 30, AR – 4000 and AR – 8000, of which AC – 20 is the most common.

- This type of grading system still lacks the low temperature rheology of Asphalt Binder.
Superpave Performance Grading

- Developed as a part of the superpave research effort to characterize asphalt binders fully and more accurately.

- The idea behind the Performance Grading was based on the fact that the binder properties for the HMA pavement under concern should be related to the conditions under which the pavement operates.

- Therefore, a binder used in Hawaii would be different than that one used in, say, Alaska.

- Two numbers are reported to specify the superpave grading.

\[ \text{PG 70 - 22} \]

- Average seven-day maximum pavement temperature
- Minimum pavement design temperature
Superpave Asphalt Binder Tests & Specification: Features

- Intended for both modified and unmodified asphalt binders.
- Test criteria remains constant for given climatic conditions and traffic levels.
- Physical properties measured by superpave binder tests are directly related to field performance.
- Superpave binder specification required the binder to be tested after simulating three critical stages:
  
  (1) Original asphalt binder condition  
  (2) Short-term aged condition  
  (3) Long-term aged condition

- The entire range of pavement temperatures experience at the project site is considered.
Superpave Asphalt Binder Tests & Specification: Features (continued)

- Tests and specifications are designed to provide an asphalt binder grade that optimizes performance related to three specific types of HMA pavement distresses: rutting, fatigue cracking, and thermal cracking.

- Rutting typically occurs at high temperatures, fatigue cracking at intermediate temperatures, and thermal cracking at low temperatures.

- The test procedures and specifications were developed in SI units.
Physical Tests for Performance Graded Asphalt Binders

Testing Apparatus and Devices

1. Rolling Thin-Film Oven (RTFO),
2. Pressure Aging Vessel (PAV),
3. Rotational Viscometer (RV),
4. Dynamic Shear Rheometer (DSR),
5. Bending Beam Rheometer (BBR), and
6. Direct Tension Tester (DTT).
Rolling Thin-Film Oven (RTFO) Test

- Provides simulated short term aged asphalt binder for physical property testing.

- Asphalt binder is exposed to elevated temperatures to simulate manufacturing and placement aging.

- Also provides a quantitative measure of the volatiles lost during the aging process.

- Un-aged asphalt binder is placed in a cylindrical jar, then placed in a carousel inside a designed oven.

- The oven is heated to 325°F (163°C) and the carrousel is rotated at 15 RPM for 85 minutes.

- Heat and air flow and slowly mixes each sample.

- The mass change of asphalt sample is recorded at the end.
Pressure Aging Vessel (PAV) Test

- Provides simulated long term aged binder for further testing of its physical properties.

- Asphalt binder is exposed to heat and pressure to simulate in-service aging over a 7 to 10 year period.

- The RTFO aged asphalt binder sample is taken and placed into the Pressure Aging Vessel.

- In the Pressure Aging Vessel, the sample is then ages for 20 hours at a pressure of 305 psi.

- The sample is then stored for further physical property tests.
Rotational Viscometer (RV) Test

- Used to determine the viscosity of asphalt binder at high temperatures, typically during its manufacturing and construction stages.

- Since manufacturing and construction temperatures are fairly similar regardless of the environment, the test always conducted at 275 °F.

- It ensures that the asphalt binder has sufficient fluidity for pumping and mixing.

- The torque required to maintain a constant rotational speed (20 RPM) of a cylindrical spindle is measured while submerged in an asphalt binder.

- This torque is then converted to viscosity of the asphalt.
Dynamic Shear Rheometer (DSR) Test

- Used to characterize the viscous and elastic behavior of asphalt binders at medium to high temperatures.
- The actual temperatures anticipated in the area where the asphalt binder will operate determine the test temperature to be used is DSR testing.
- The DSR test is capable of quantifying both elastic and viscous properties of asphalt binder.
- It measures the complex shear modulus ($G^*$) and phase angle ($\delta$) of an asphalt specimen.
The test temperature, specimen size and plate diameter depend upon the type of asphalt binder being tested.
Dynamic Shear Rheometer (DSR) Test (continued)

- A small sample of asphalt binder is sandwiched between two plates.

- The DSR oscillation rate is specified to 10 radians/second (1.59 Hz) by the standard to simulate the shearing action corresponding to a traffic speed of about 55 mph.
Bending Beam Rheometer (BBR) Test

- Provides a measure of low temperature stiffness and relaxation properties of asphalt binders
- Gives an indication of an asphalt binder’s ability to resist low temperature cracking.
- The BBR test results are used in combination with the Direct Tension Test (DTT) to determine low temperature Performance Grade of an asphalt binder.
- The actual temperatures anticipated in the region will determine the test temperatures to be used in BBR testing.
Bending Beam Rheometer (BBR) Test (continued)

- BBR test uses a small asphalt beam, simply supported, immersed in cold liquid bath.

- A load is applied to the center of the beam and its deflection is measured against time.

- Stiffness is calculated based on measured deflection and standard beam properties.

- A measure of how the asphalt binder relaxes the load induced stresses is also measured.

- BBR tests are conducted on PAV aged asphalt binder.
Bending Beam Rheometer (BBR) Test (continued)
Direct Tension Tester (DTT) Test

- Provides a measure of low temperature stiffness and relaxation properties of asphalt binders.

- An indication of an asphalt binder’s ability to resist low temperature cracking.

- Results are used in combination with the BBR test results to determine an asphalt binder’s low temperature PG grade determination.

- Measures the stress and strain at failure of a specimen of asphalt binder pulled apart at a constant rate of elongation.

- Test temperatures are kept such that the failure will be from brittle or brittle-ductile fracture.

- This tests are conducted on PAV aged asphalt binder samples.
Time-Temperature Superposition Principle (TTSP)

- Is a concept typically used to determine temperature-dependent mechanical properties of linear viscoelastic materials like asphalt concrete from known properties at a reference temperature.

  - Elastic moduli of asphaltic materials
  - Increase with loading rate or frequency
  - Decrease when the temperature is increased

- As a fundamental property of linear viscoelastic material, the curves of the instantaneous modulus as a function of time or frequency for asphalt concrete
  - Do not change shape as the temperature is changed
  - But appear only to shift left or right.
This behavior of asphaltic material facilitates the idea that a mastercurve at a given temperature can be used as the reference to predict the modulus at various temperatures by applying only a shift operation.
Time-Temperature Superposition Principle (continued)

- The application of the time-temperature superposition principle typically involves:
  - Experimental determination of loading frequency-dependent curves at several temperatures for a small range of selected frequencies.
  - The computation of a translation factor to correlate these properties for the temperature and frequency range.
  - Development of a mastercurve based on experimental data showing the effect of frequency for a wide range of frequencies.
  - The application of the translation factor to determine temperature-dependent moduli over the whole range of frequencies.
Construction of Mastercurves

- The amount by which dynamic modulus data is shifted to fit in a smooth curve at a reference temperature is referred to as shift factor, $a(T)$.

- Shifting is achieved by dividing the loading time in the time domain or multiplying the loading frequency in the frequency domain by the shift factor to get the reduced time or reduced frequency.

- Mastercurve can be developed for any reference temperature chosen arbitrarily.

- At the reference temperature the shift factor is 1 and its logarithm is zero.

$$\text{Reduced frequency: } \begin{align*}
    f_r &= f \times a(T) \\
    \log(f_r) &= \log(f) + \log[a(T)]
\end{align*}$$

$$\text{Otherwise, reduced time: } \begin{align*}
    t_r &= \frac{t}{a(T)} \\
    \log(t_r) &= \log(t) - \log[a(T)]
\end{align*}$$
Advantages of Mastercurves

- It reduces the three dimensional data (dynamic modulus, loading time/frequency and temperature) in to two dimensional data by eliminating the temperature variable. This makes it easy to compare test results conducted at different conditions.

- The possibility of interpolation to get intermediate data within the test data range.
Shift Factor Functions

- Several available to fit shift factor trend with temperature.
- The most common, relatively easy one is the Second degree polynomial.

\[ \log a_T = aT^2 + bT + c \]
The Experimental Dynamic Modulus Mastercurve Fit

- The function that is predominantly used for developing mastercurve for dynamic modulus data is the sigmoid function.

\[ \log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log(f_r)}} \]

- $\delta$ is minimum modulus value
- $\alpha$ is span of modulus values
- $\beta, \gamma$ are shape parameters
- The parameter, $\gamma$ indicates how steep the function is i.e. how fast the modulus is changing from the minimum value to the maximum.
- $\beta$ represents the horizontal position at which the rate of change of modulus changes from positive to negative.
- $\delta$ is associated with the minimum value of asphalt mix modulus generally caused by high temperature.
- The largest modulus which is associated with binder modulus at very low temperature is represented in the sigmoidal function by the sum of parameters $\delta$ and $\alpha$. 
Dynamic Modulus Mastercurve Fitting Steps (Witczak and Sotil, 2004)

- **STEP 1:** Determine the Logarithm of test frequencies and dynamic moduli for all the temperatures.

- **STEP 2:** Select the reference temperature.

- **STEP 3:** Approximate initial estimate of shift factors for each temperatures. An initial log shift factor of 1 is chosen for all test temperatures and it is expected to see the shift factor value for the reference temperature to change to zero and values at other temperatures change to negative and positive values accordingly.

- **STEP 4:** Approximate the initial values for the master curve parameters. A symmetrical sigmoid function is expected for the mastercurve fitting and initial value of 1 is used for the parameters $\alpha$, $\beta$, $\gamma$ and $\delta$.

- **STEP 5:** Computation of the coefficient of determination.

$$ R^2 = 1 - \frac{SS_{err}}{SS_{tot}} = \frac{\sum^n_i (y_i - \bar{y})^2}{\sum^n_i (y_i - f_i)^2} $$

- $y_i$ = dataset value
- $f_i$ = modeled value
AASHTO Standard for Developing Dynamic Modulus Mastercurve

- AASHTO PP 62-09: “Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA)

- Same as the sigmoid function stated earlier.

- This specification recommends two shift factor equations

- The final form of the dynamic modulus mastercurve equation is obtained by substituting the selected shift factor relationship into the sigmoid function.

**MEPDG Shift Factor Equation**

\[
\log(f_r) = \log(f) + c (\log(\eta) - \log(\eta_{TR}))
\]

- \( c \) is a fitting coefficient

**Second-Order Polynomial** *(AASHTO PP 62-09)*

\[
\log(f_r) = \log(f) + a_1(T_R - T) + a_2(T_R - T)^2
\]
Fitting the Dynamic Modulus Mastercurve (AASHTO PP 62-09)

- **STEP 1:** Selection of Reference temperature
- **STEP 2:** Perform shift operation
- **STEP 3:** Perform Numerical Optimization

\[
\sum error^2 = \sum_{i=1}^{n} \left( \log |\hat{E}^*|_i - \log |E^*|_i \right)^2
\]

<table>
<thead>
<tr>
<th>Fitting Parameter</th>
<th>Initial Estimate</th>
<th>Fitting Parameter</th>
<th>Initial Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>3.0</td>
<td>( \alpha )</td>
<td>3.0</td>
</tr>
<tr>
<td>( \beta )</td>
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<td>-1.0</td>
</tr>
<tr>
<td>( \delta )</td>
<td>0.5</td>
<td>( \delta )</td>
<td>0.5</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>-0.5</td>
<td>( \gamma )</td>
<td>-0.5</td>
</tr>
<tr>
<td>( c )</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>( a_2 )</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

MEPDG Shift Factors
- \( T_R = 529.67 \degree R \)
- \( |E^*| \) in ksi
- \( f \) in Hz

Polynomial Shift Factors
- \( T_R = 70 \degree F \)
- \( |E^*| \) in ksi
- \( f \) in Hz
Fitting the Dynamic Modulus Mastercurve (AASHTO PP 62-09)

- **STEP 4: Compute “Goodness of Fit” Statistics**

  Standard deviation
  \[ S_y = \sqrt{\frac{\sum_{i=1}^{n}(\log|E^*|_i - \bar{\log}|E^*|)^2}{n - 1}} \]

  Standard error of estimate
  \[ S_e = \left[ \frac{1}{(n - p - 1)} \sum_{i=1}^{n} \left( \log|\hat{E}^*|_i - \log|E^*|_i \right)^2 \right]^{0.5} \]

  Explained variance
  \[ R^2 = 1 - \frac{(n - p - 1)S_e^2}{(1 - n)S_y^2} \]

- **STEP 5: Evaluate Mastercurve**

  The ratio of \( S_e \) to \( S_y \) should be less than 0.05.  
The explained variance should exceed 0.99.
AASHTO PP 62-09 Recommended Data Quality Assessment

Coefficient of Variation for the Mean of Dynamic Modulus Test on Replicate Specimens

<table>
<thead>
<tr>
<th>Number of Specimens</th>
<th>Coefficient of Variation for Mean (CV, %)</th>
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<tbody>
<tr>
<td>2</td>
<td>9.2</td>
</tr>
<tr>
<td>3</td>
<td>7.5</td>
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<tr>
<td>4</td>
<td>6.5</td>
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<td>6</td>
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<td>7</td>
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<td>8</td>
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<tr>
<td>9</td>
<td>4.3</td>
</tr>
<tr>
<td>10</td>
<td>4.1</td>
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Data Quality Statistics Requirements

<table>
<thead>
<tr>
<th>Data Quality Statistic</th>
<th>Recommended Limit</th>
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<tbody>
<tr>
<td>Load standard error</td>
<td>10%</td>
</tr>
<tr>
<td>Deformation standard error</td>
<td>10%</td>
</tr>
<tr>
<td>Deformation Uniformity</td>
<td>30%</td>
</tr>
<tr>
<td>Phase Uniformity</td>
<td>3 degrees</td>
</tr>
</tbody>
</table>
All linear viscoelastic material functions are mathematically equivalent for each mode of loading such as uniaxial load or shear. The interrelationships between linear viscoelastic material functions have a basis in the theory of linear differential and integral equations. Thus, a given (or source) material function can be converted into other (or target) material functions as long as the given function is known over a wide-enough range of time or frequency (Park and Schapery, 1999).
Why Interconversion?

- Required for various reasons.

- The response of a material under a certain excitation condition inaccessible to direct experiment may be predicted from measurements under other readily realizable conditions.

- For example, the response of a very stiff material subjected to a specified deformation is usually difficult to obtain from a constant-strain, relaxation test because of the requirement of a robust testing device.

- However, the required response may be obtained from an easily-realizable, constant-stress, creep test and through an interconversion between the relaxation modulus and creep compliance.

- Also, cost of testing a material for all the functions may be significantly reduced by implementing an interconversion of the material functions.
The stress-strain equation for a linear viscoelastic material can be represented by

\[ \sigma(t) = \int_0^t E(t - \tau) \frac{d\varepsilon(t)}{d\tau} d\tau \]  

(1)

From which one can obtain –

\[ \int_0^t E(t - \tau) \frac{dD(\tau)}{d\tau} d\tau = 1 \quad (t > 0) \]  

(2)

The \( s \)-multiplied Laplace transformation (also called Carson transform) of \( E(t) \) and \( D(t) \), termed as operational modulus and compliance can be defined by -

\[ \tilde{E}(s) \equiv s \int_0^\infty E(t) e^{-st} dt \]

\[ \tilde{D}(s) \equiv s \int_0^\infty D(t) e^{-st} dt \]  

(3)

From (2) and (3) one can find –

\[ \tilde{E}(s) \tilde{D}(s) = 1. \]

Similarly, also one can find -

\[ E^*(\omega) D^*(\omega) = 1 \]
Again, the generalized Maxwell model (or Wiechert model) consists of a spring and \( m \) Maxwell elements connected in parallel. The relaxation modulus derived from this model is given by -

\[
E(t) = E_e + \sum_{i=1}^{m} E_i e^{-t/\rho_i}
\]

This series expression often referred to as a Prony or Dirichlet series.

The creep compliance can be characterized more easily using the generalized Voigt model (or Kelvin model) which consists of a spring and a dashpot and \( n \) Voigt elements connected in series, and is given by -

\[
D(t) = D_g + \frac{1}{\eta_0} + \sum_{j=1}^{n} D_j (1 - e^{-t/\tau_j})
\]

for viscoelastic solids \( \eta_0 \to \infty \) and \( E_e > 0 \)

The constants in the generalized Maxwell and generalized Voigt models can be chosen so that the models are mathematically equivalent, and thus a viscoelastic material depicted by one model also can be depicted by the other.

The constants can be obtained by fitting these expressions to the available experimental data.
Using these forgoing relationships Park and Schapery (1999) found the following expressions:

\[
\tilde{E}(s) = E_e + \sum_{i=1}^{m} \frac{s \rho_i E_i}{s \rho_i + 1}
\]

\[
\tilde{D}(s) = D_g + \frac{1}{\eta_0 s} + \sum_{j=1}^{n} \frac{D_j}{s \tau_j + 1}
\]

\[
E'(\omega) = E_e + \sum_{i=1}^{m} \frac{\omega^2 \rho_i^2 E_i}{\omega^2 \rho_i^2 + 1}
\]

\[
E''(\omega) = \sum_{i=1}^{m} \frac{\omega \rho_i E_i}{\omega^2 \rho_i^2 + 1}
\]

\[
D'(\omega) = D_g + \sum_{j=1}^{n} \frac{D_j}{\omega^2 \tau_j^2 + 1}
\]

\[
D''(\omega) = \frac{1}{\eta_0 \omega} + \sum_{j=1}^{n} \frac{\omega \tau_j D_j}{\omega^2 \tau_j^2 + 1}
\]

The only problem is to find out the Prony Series coefficients from experimental data.
From the dynamic modulus test (or complex modulus test) we can have the storage modulus or loss modulus.

So at presence, fitting the storage or loss modulus data to the given Prony series expression is important to find material functions such as relaxation modulus or creep compliance.

A pre-smoothened storage modulus data by sigmoidal function can give an acceptable form of Prony Series representation.

The details of how to find the Prony series coefficients are given in the published journal paper of Park and Schapery (1999).

A set of MATLAB code are developed mimicking this interconversion method proposed by Park and Schapery (1999).

The fundamental steps for the interconversion of storage modulus data to relaxation modulus and thus creep compliance can be shown by the following schematic:
Storage modulus Data extraction

Specify the number of terms in Prony series & relaxation times (generally one decade apart in log scale)

Prony Series Fit to find the relaxation strengths

$E'(\omega) = E_s + \sum_{i=1}^{\infty} \frac{\omega^2 \rho^2_i E_i}{\omega^2 \rho^2_i + 1}$

Develop relaxation modulus data

$E(t) = E_s + \sum_{i=1}^{m} E_i e^{-t/\rho_i}$

Calculate creep compliance

$D(t) = D_0 + \frac{1}{\eta_0} + \sum_{j=1}^{n} D_j (1 - e^{-\omega t})$

Find retardation strengths by solving the system of equations

$[A][D] = [B]$

Find the corresponding retardation time as method recommended by Park & Schapery (1999)

$\tilde{E}(s) = E_s + \sum_{i=1}^{m} \frac{s \rho_i E_i}{s \rho_i + 1}$
Dynamic modulus test data of District 1 SPIV PG76-22 was used for the primary development of the interconversion code set.

The average test data from 3 cylindrical specimens worked as the input for the program.

The code set consists of three program units:
- Data Processing and Mastercurve fitting Unit
- Prony Series fitting Unit, and
- Interconversion to Other Material Functions Unit

The data processing and mastercurve fitting unit is primarily process the raw test data to a more representable form. After that it fits dynamic modulus mastercurve by shifting the test data of different temperatures.

It also generates the storage modulus and loss modulus sigmoid mastercurve fit. Pre-smoothened storage modulus data was necessary to have coherent Prony series fit.

At the end it generates input file for the Prony Series fitting Unit. Basically this input files contains the smoothened storage modulus data.
Numerical Method of Interconversion (Park and Schapery, 1999)

Unit 1 Output
The Prony Series fitting Unit fits the smoothened storage modulus data to Prony Series given as:

\[ E'(\omega) = E_e + \sum_{i=1}^{m} \frac{\omega^2 \rho_i^2 E_i}{\omega^2 \rho_i^2 + 1} \]

Output:

- **Prony Series Fit**
- **Prony Series Coefficients**
- **Equilibrium Modulus**
The interconversion unit generates the retardation times corresponding to the specified relaxation times and develops relaxation modulus and creep compliance data.
Schapery and Park proposed a fairly accurate approximate method of material function interconversion.

<table>
<thead>
<tr>
<th>Ratios</th>
<th>Adjustment Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\lambda} = \tilde{E}(s) / E(t)$</td>
<td>$\tilde{\lambda} = \Gamma(1 - n)$</td>
</tr>
<tr>
<td>$\lambda' = E'(\omega) / E(t)$</td>
<td>$\lambda' = \Gamma(1 - n) \cos(n\pi / 2)$</td>
</tr>
<tr>
<td>$\lambda'' = E''(\omega) / E(t)$</td>
<td>$\lambda'' = \Gamma(1 - n) \sin(n\pi / 2)$</td>
</tr>
<tr>
<td>$\tilde{\lambda} = E'(\omega) / \tilde{E}(s)$</td>
<td>$\tilde{\lambda} = \cos(n\pi / 2)$</td>
</tr>
<tr>
<td>$\bar{\lambda} = E''(\omega) / \tilde{E}(s)$</td>
<td>$\bar{\lambda} = \sin(n\pi / 2)$</td>
</tr>
<tr>
<td>$\lambda^* = E''(\omega) / E'(\omega)$</td>
<td>$\lambda^* = \tan(n\pi / 2)$</td>
</tr>
</tbody>
</table>

\[ n = -\frac{d \log E(t)}{d \log t} \quad \text{at} \quad t = 1/s \]

\[ n = \frac{d \log \tilde{E}(s)}{d \log s} \quad \text{at} \quad s = 1/t \]
**The Dynamic Shear Rheometer (DSR)**

- DSR measures the complex shear modulus ($G^*$) and phase angle ($\delta$) of a binder specimen.

- Complex shear modulus ($G^*$) is the total resistance to deformation of the binder specimen when repeatedly sheared.

- The phase angle ($\delta$) is the time-lag between the applied shear stress and the resulting shear strain.

- DSR test is used to characterize the elastic and viscous behavior of asphalt binder at medium to high temperatures.

- Test temperature is determined by the actual anticipated temperature of the region where the binder will be used.
The Dynamic Shear Rheometer (DSR) - continued

- DSR test uses a thin asphalt binder sample sandwiched between two circular plates.
- The lower plate is fixed.
- The upper plate oscillates back and forth across the sample at a specified frequency to create a shearing action.
- As a standard practice, the specified loading rate of 10 rad/second (1.59 Hz) is used to simulate the shearing action corresponding to a traffic speed of 55 mph (90 km/hr).
AASHTO T 315 suitable for use when the dynamic shear modulus varies between 100 Pa and 10 MPa. This range in modulus is typically obtained between 6 and 88°C at an angular frequency of 10 rad/s, dependent upon:

- The grade,
- Test temperature, and
- Conditioning (aging) of the asphalt binder.

The test temperature, specimen size and plate diameter depend upon the type of asphalt binder being tested.

Unaged asphalt binder and rolling thin-film oven (RTFO) residue are tested at the high temperature using a specimen of 1 mm thick and 25 mm in diameter.

PAV residue is tested at lower temperatures. These lower temperatures make the specimen quite stiff, which results in small measured phase angles (δ). Therefore, a thicker sample, 2 mm in thickness with a smaller diameter of 8 mm is used so that a measurable phase angle (δ) can be determined.

Again, test temperatures greater than 115°F (46°C) use a sample 1 mm thick and 25 mm in diameter. On the other hand, while the test temperatures are in between 39°F and 104°F (4°C and 40°C), a specimen with 2 mm in thickness and 8 mm in diameter is used.
The required stress or strain amplitude depends upon the value of the complex shear modulus of the asphalt binder being tested.

Stress amplitudes have been selected to ensure that the measurements are within the region of linear viscoelastic behavior.

The test specimen is maintained at the test temperature to within ±0.1°C.

When operating in strain controlled mode, the strain value needed to be determined according to the value of $G^*$. The strain should be controlled within 20 percent of the target value:

$$\gamma, \text{ percent} = 12.0 \div (G^*)^{0.29}$$

When operating in a stress controlled mode, the stress level needed to be determined according to the value of the $G^*$. The stress should be controlled within 20 percent of the target value:

$$\tau = 12.0 \times (G^*)^{0.71}$$
### Precision Estimates of DSR test (AASHTO T 315)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Coefficients of Variation (%)</th>
<th>Acceptable range of two test results (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single-operator precision:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original Binder: $G^*/\sin \delta$ (kPa)</td>
<td>2.3</td>
<td>6.4</td>
</tr>
<tr>
<td>RTFO Residue: $G^*/\sin \delta$ (kPa)</td>
<td>3.2</td>
<td>9.0</td>
</tr>
<tr>
<td>PAV Residue: $G^*\cdot\sin \delta$ (kPa)</td>
<td>4.9</td>
<td>13.8</td>
</tr>
<tr>
<td><strong>Multi-laboratory precision:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original Binder: $G^*/\sin \delta$ (kPa)</td>
<td>6.0</td>
<td>17.0</td>
</tr>
<tr>
<td>RTFO Residue: $G^*/\sin \delta$ (kPa)</td>
<td>7.8</td>
<td>22.2</td>
</tr>
<tr>
<td>PAV Residue: $G^*\cdot\sin \delta$ (kPa)</td>
<td>14.2</td>
<td>40.2</td>
</tr>
</tbody>
</table>
The Dynamic Shear Modulus Mastercurve

- The frequency sweep dynamic shear tests for determining shear modulus (|G*|) and phase angle (δ) of asphalt binder involves conducting dynamic shear tests at different temperatures for a range of angular frequencies to develop |G*| mastercurve and shift factor equation.
- AASHTO T 315: “Determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)” as a guideline for conducting frequency sweep dynamic shear test.
- The seven test temperatures which can be used to develop |G*| Mastercurve are:
  130, 115, 100, 85, 70, 55, and 40 °F or,
  54.4, 46.1, 37.7, 29.4, 21.1, 12.8, 4.4 °C
- The 16 frequencies ranging from 0.5 to 500 rad/sec for each temperature also can be used.
- 25 mm diameter plate, and 1 mm thick samples to test in temperatures of 130 and 115 °F (54.4 and 46.1 °C).
- 8 mm diameter plate, and 2 mm thick samples to test in other temperatures.
The Dynamic Shear Modulus Mastercurve

- $|G*|$ test is conducted in a **strain controlled mechanism**.
- The shear stress is measured by applying a **preselected strain level**.
- The **applied strain level used was 1.0%**.
- This was selected so that the **strain level must be measurable** to the DSR compliance while **taking in to consideration the maximum stress that can be applied by the DSR equipment**.

The Dynamic Shear Modulus MC Fitting Equation

$$\log(|G*|) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log(f_r)}}$$

- $\alpha$, $\beta$, $\gamma$, and $\delta$ are the fitting parameters, and $f_r$ is the reduced frequency.

Shift Factor Fitting Equation for $|G*|$ MC

- Williams-Landel-Ferry equation (WLF) equation is an empirical equation associated with time-temperature superposition of the $|G*|$ data.
  $$\log a_T = - \frac{C_1(T - T_r)}{C_2 + (T - T_r)}$$

- $T_r$ is the reference temperature, $C_1$ and $C_2$ are positive constants that depend on the material and the reference temperature.
## Summary of Sample Collection

### District 1

<table>
<thead>
<tr>
<th>#</th>
<th>Mix Type</th>
<th># Grav.</th>
<th>Spec. Binder PG</th>
<th>Used Binder PG</th>
<th>% RAP</th>
<th>Project No.</th>
<th>Project Location</th>
<th>County</th>
<th>Contractor</th>
<th>Agg. Source</th>
<th>Agg. Source Location</th>
<th>WMA Type</th>
<th>WMA Additive</th>
<th>SML Mix Design No.</th>
<th>Asphalt Source</th>
<th>Binder Collected?</th>
<th>Mix y., lb/yd</th>
<th>Mix Gmm</th>
<th>Status</th>
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<td>MSC</td>
<td>Abo Arroyo Pit</td>
<td>Bernardo, NM</td>
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<td>35</td>
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<td>151.1</td>
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6

7

8

9
# Summary of Sample Collection

## District 6

<table>
<thead>
<tr>
<th>#</th>
<th>Mix Type</th>
<th>Superpave Gradation</th>
<th>Specified Binder PG</th>
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<th>% RAP</th>
<th>Project No.</th>
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<th>County</th>
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<th>Agg Source</th>
<th>Agg Source Location</th>
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### Summary of Sample Collection: Asphalt Binder

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<th>PG grade</th>
<th>Holly Asphalt</th>
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<tr>
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<td>District ID</td>
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<td>Binder PG grade (Specified/Used)</td>
<td>Mix Type</td>
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<tr>
<td>-------------</td>
<td>----------------------</td>
<td>----------------------------------</td>
<td>----------</td>
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<tr>
<td>D-1</td>
<td>SP – IV</td>
<td>76-22/70-22</td>
<td>WMA</td>
</tr>
<tr>
<td>D-4</td>
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<td>HMA</td>
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<td>70-22/58-28</td>
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<td>D-3</td>
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<td>76-22/70-28</td>
<td>WMA</td>
</tr>
<tr>
<td>D-1</td>
<td>SP – III</td>
<td>76-22/58-28</td>
<td>WMA</td>
</tr>
</tbody>
</table>
| D-4 | SP – III | 76-22/70-28 | HMA | 20 | 3 | 1 | 2.473 | 2.337 | 5.5 | 4.6 | Project # 4100600  
Mix Design #2014-HMA-D4-04-44-TS-1  
Contractor: FSG |
|-----|----------|-------------|-----|----|----|----|-------|-------|-----|-----|----------------|
| D-4 | SP – III | 76-22/70-28 | WMA | 20 | 3 | 4 | 2.474 | 2.351 | 5.0 | 4.6 | Project # 4100600  
Mix Design #2014-WMA-D4-05-45-TS2  
Contractor: FSG |
| D-4 | SP – III | 76-22/70-28 | WMA | 20 | 3 | 1 | 2.479 | 2.352 | 5.1 | 4.6 | Project # 4100600  
Mix Design #2014-WMA-D4-07-47-TS3  
Contractor: FSG |
| D-4 | SP – III | 76-22/70-28+ | WMA | 20 | 3 | 4 | 2.475 | 2.331 | 5.8 | 4.6 | Project # 4100600  
Mix Design #2014-WMA-D4-09-49-TS5  
Contractor: FSG |
| D-5 | SP – III | 64-28/58-28 | HMA | 35 | 3 | 1 | 2.522 | 2.372 | 6.0 | 4.7 | Project # 5100411  
Mix Design #2014-HMA-D5-10-60  
Contractor: MSCI |
The Dynamic Modulus Mastercurves

HMA Sample: D-1 SP IV 76-22

Witczak and Sotil Procedure
The Dynamic Modulus Mastercurves

HMA Sample: D-1 SP IV 76-22

\[ y = 0.0001x^2 - 0.1385x + 3.1 \]
\[ R^2 = 0.9955 \]

Witczak and Sotil Procedure

Mastercurve fitting parameters

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \delta )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
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</table>
The Dynamic Modulus Mastercurves

HMA Sample: D-1 SP IV 76-22

AASHTO PP 62-09 Procedure
The Dynamic Modulus Mastercurves

HMA Sample: D-1 SP IV 76-22

AASHTO PP 62-09 Procedure

Mastercurve fitting parameters

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
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<tbody>
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The Dynamic Modulus Mastercurves

HMA Sample: D-3 SP III 76-22

Witczak and Sotil Procedure
The Dynamic Modulus Mastercurves

HMA Sample: D-3 SP III 76-22

Witczak and Sotil Procedure

Mastercurve fitting parameters

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<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
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</thead>
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The Dynamic Modulus Mastercurves

HMA Sample: D-3 SP III 76-22

AASHTO PP 62-09 Procedure
The Dynamic Modulus Mastercurves

HMA Sample: D-3 SP III 76-22

AASHTO PP 62-09 Procedure

Mastercurve fitting parameters

<table>
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<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
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The Dynamic Modulus Mastercurves

HMA Sample: D-4 SP III 70-22

Witczak and Sotil Procedure
The Dynamic Modulus Mastercurves

HMA Sample: D-4 SP III 70-22

\[ y = 0.0008x^2 - 0.1609x + 3.1895 \]
\[ R^2 = 0.9986 \]

Witczak and Sotil Procedure

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
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</thead>
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The Dynamic Modulus Mastercurves

HMA Sample: D-4 SP III 70-22

AASHTO PP 62-09 Procedure
The Dynamic Modulus Mastercurves

HMA Sample: D-4 SP III 70-22

AASHTO PP 62-09 Procedure

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<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
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</table>
**Mastercurves**

![Graph](image)

- **Log E* (Mpa)** vs **Log Frequency (Hz)**
- **Witeczak and Sotil Procedure**

Legend:
- Mastercurve Fit
- -10 deg. C
- 4.4 deg. C
- 21.1 deg. C
- 37.8 deg. C
- 54 deg. C
- -10 deg. C Shifted
- 4.4 deg. C Shifted
- 21.1 deg. C Shifted
- 37.8 deg. C Shifted
- 54 deg. C Shifted
**Witczak and Sotil Procedure**
AASHTO PP 62-09 Procedure
Dynamic Modulus ($E^o$, Mpa)

<table>
<thead>
<tr>
<th>Reduced Frequency (fr, Hz)</th>
</tr>
</thead>
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<tr>
<td>0.0001</td>
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<tr>
<td>10</td>
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</table>

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
<th>$a_1$</th>
<th>$a_2$</th>
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<tbody>
<tr>
<td>Values</td>
<td>21.1</td>
<td>2.77</td>
<td>-0.60</td>
<td>2.05</td>
<td>-0.40</td>
<td>0.123</td>
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</table>

**AASHTO PP 62-09 Procedure**
Witczak and Sotil Procedure
**Witczak and Sotil Procedure**

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
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<tr>
<td>Values</td>
<td>21.1</td>
<td>1.74</td>
<td>-0.55</td>
<td>2.80</td>
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</table>

**Equation**

\[ y = 0.0006x^2 - 0.1579x + 2.9846 \]

\[ R^2 = 0.9992 \]


**AASHTO PP 62-09 Procedure**

![Diagram](image-url)
The graph shows the dynamic modulus ($E'$, Mpa) as a function of the reduced frequency ($fr$, Hz). Below the graph, there is a table listing the values for the parameters $\alpha$, $\beta$, $\delta$, $\gamma$, $a_1$, and $a_2$. The values are as follows:

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
<th>$a_1$</th>
<th>$a_2$</th>
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</thead>
<tbody>
<tr>
<td>Values</td>
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<td>1.95</td>
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<td>2.60</td>
<td>-0.60</td>
<td>0.129</td>
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**AASHTO PP 62-09 Procedure**
Witczak and Sotil Procedure
**Witczak and Sotil Procedure**

![Graph showing Mastercurves](image)

**Equation:**

\[
y = 0.0006x^2 - 0.1547x + 3.1392
\]

**R^2:** 0.9991

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>(\alpha)</th>
<th>(\beta)</th>
<th>(\delta)</th>
<th>(\gamma)</th>
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</thead>
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<tr>
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<td>21.1</td>
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<td>-0.40</td>
<td>2.55</td>
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</tbody>
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AASHTO PP 62-09 Procedure
**AASHTO PP 62-09 Procedure**

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
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<tbody>
<tr>
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<td>2.12</td>
<td>-0.4</td>
<td>2.53</td>
<td>-0.45</td>
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Witczak and Sotil Procedure
**Mastercurves**

**Witczak and Sotil Procedure**

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
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<tr>
<td>Values</td>
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<td>2.05</td>
<td>-0.40</td>
<td>2.55</td>
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</table>

\[ y = 0.0006x^2 - 0.1547x + 3.1392 \]
\[ R^2 = 0.9991 \]
AASHTO PP 62-09 Procedure
### Dynamic Modulus ($E^*$), Mpa

<table>
<thead>
<tr>
<th>Reduced Frequency ($fr$, Hz)</th>
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<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>10000</td>
</tr>
<tr>
<td>10000</td>
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<tr>
<td>10000</td>
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</tbody>
</table>

### Reference Temperature ($^\circ$C) | $\alpha$ | $\beta$ | $\delta$ | $\gamma$ | $a_1$ | $a_2$
<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Values</td>
<td>21.1</td>
<td>2.12</td>
<td>-0.4</td>
<td>2.53</td>
<td>-0.45</td>
<td>0.128</td>
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</tbody>
</table>

**AASHTO PP 62-09 Procedure**
Witczak and Sotil Procedure
**Witczak and Sotil Procedure**

### E Mastercurves

<table>
<thead>
<tr>
<th>E* (MPa)</th>
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<tbody>
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<tr>
<td>0.0001</td>
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<tr>
<td>1000</td>
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<tr>
<td>10000</td>
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<tr>
<td>100000</td>
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</table>

**Frequency (Hz)**

- 0.00001
- 0.0001
- 0.01
- 1
- 10
- 100
- 1000
- 10000
- 100000

### Graph 1

**Equation:**

\[ y = 0.0004x^2 - 0.1572x + 3.0829 \]

**R^2 = 0.9985**

**Legend:**
- Shift Factor
- Poly. (Shift Factor)

### Table

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>21.1</td>
<td>2.62</td>
<td>-0.45</td>
<td>2.27</td>
</tr>
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AASHTO PP 62-09 Procedure
<table>
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<th>$\delta$</th>
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<th>$a_2$</th>
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<td>-0.45</td>
<td>2.10</td>
<td>-0.36</td>
<td>0.133</td>
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**AASHTO PP 62-09 Procedure**
Analysis of E* Test Results

The Mastercurves

D-1 SP III 76-22

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
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Analysis of E* Test Results

D-1 SP III 76-22

The Mastercurve

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<th>β</th>
<th>δ</th>
<th>γ</th>
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<th>a₂</th>
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Analysis of $E^*$ Test Results

The Mastercurves

D-6 SP III 76-28

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<th>$\delta$</th>
<th>$\gamma$</th>
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<tbody>
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Analysis of E* Test Results

D-6 SP III 76-28

The Mastercurves

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<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
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<td>2.24</td>
<td>-0.15</td>
<td>2.45</td>
<td>-0.55</td>
<td>0.115</td>
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Analysis of E* Test Results

D-6 SP III 76-28

The Mastercurves

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<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>21.1</td>
<td>2.24</td>
<td>-0.15</td>
<td>2.45</td>
<td>-0.55</td>
<td>0.115</td>
</tr>
</tbody>
</table>
Analysis of $E^*$ Test Results

The Mastercurves

D-6 SP III 76-28/76-28 HMA

Figure 4.1 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.998$).

$y = 0.0002x^2 - 0.1034x + 6.1405$

$R^2 = 0.9995$

Witczak and Sotil Procedure
Analysis of E* Test Results

D-6 SP III 76-28/76-28 HMA

Figure 4.4 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points (R² = 0.998, and Se/Sy = 0.0439).

The Mastercurve

<table>
<thead>
<tr>
<th>Reference Temperature (°C)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
<th>a₁</th>
<th>a₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
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<td>2.52</td>
<td>-0.50</td>
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<td>-0.45</td>
<td>0.072</td>
</tr>
</tbody>
</table>
Analysis of $E^*$ Test Results

The Mastercurves

D-4 SP III 64-28/64-28 HMA

Figure 4.6 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.999$).

$y = 0.0003x^2 - 0.1052x + 6.2379$
$R^2 = 0.9989$

<table>
<thead>
<tr>
<th>Reference Temperature (°F)</th>
<th>α</th>
<th>β</th>
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<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>70</td>
<td>2.27</td>
<td>-0.20</td>
<td>1.51</td>
</tr>
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</table>
Analysis of E* Test Results

D-4 SP III 64-28/64-28 HMA

Figure 4.9 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.998$ and $Se/Sy = 0.0474$).
Analysis of E* Test Results

The Mastercurves

D-4 SP III 70-22/70-22 WMA

Figure 4.1 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.999$).

<table>
<thead>
<tr>
<th>Reference Temperature (°F)</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>70</td>
<td>2.62</td>
<td>-0.81</td>
<td>1.25</td>
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</tbody>
</table>
Analysis of E* Test Results

D-4 SP III 70-22/70-22 WMA

Figure 4.4 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.998$, and $Se/Sy = 0.0463$).
Analysis of E* Test Results

The Mastercurves

D-4 SP III 76-22/76-22 WMA

Figure 4.6 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.999$).

$y = 0.0002x^2 - 0.1001x + 6.2066$

$R^2 = 0.998$

Witczak and Sotil Procedure
Analysis of E* Test Results

D-4 SP III 76-22/76-22 WMA

Figure 4.9 Dynamic modulus mastercurve at 70°F (21.1°C) reference temperature with shifted dynamic moduli data points ($R^2 = 0.999$ and $Se/Sy = 0.0419$).

The Mastercurves

<table>
<thead>
<tr>
<th>Reference Temperature (°F)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
<th>$a_1$</th>
<th>$a_2$</th>
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<tbody>
<tr>
<td>Values</td>
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<td>-0.95</td>
<td>0.99</td>
<td>-0.35</td>
<td>0.075</td>
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</tbody>
</table>

AASHTO PP 62-09 Procedure
Analysis of E* Test Results

Witczak and Sotil Procedure

D-6 SP IV 70-22/70-22 HMA

The Mastercurves

Log |E*| (ksi) vs. Log Frequency (Hz)

Mastercurve Fit
- 14 deg. F
- 40 deg. F
- 70 deg. F
- 100 deg. F
- 130 deg. F
- 14 deg. F Shifted
- 40 deg. F Shifted
- 70 deg. F Shifted
- 100 deg. F Shifted
- 130 deg. F Shifted

R² = 0.999
Analysis of E* Test Results

D-6 SP IV 70-22/70-22 HMA

Witczak and Sotil Procedure

The Mastercurves

log-log plot

semi-log plot
Analysis of E* Test Results

**Witczak and Sotil Procedure**

**D-6 SP IV 70-22/70-22 HMA**

Mastercurve fitting parameters

<table>
<thead>
<tr>
<th></th>
<th>Reference Temperature</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI System</td>
<td>21.1 °C</td>
<td>2.22</td>
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<td>2.5</td>
<td>-0.38</td>
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<tr>
<td>English System</td>
<td>70 °F</td>
<td>2.22</td>
<td>0.1</td>
<td>1.67</td>
<td>-0.38</td>
</tr>
</tbody>
</table>
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 76-22/64-22 WMA

The Mastercurves

The graph shows the analysis of E* test results for D-2 SP III 76-22/64-22 WMA material. The data is plotted on a log-log scale with Log E* on the y-axis and Log Frequency (Hz) on the x-axis. The Mastercurve Fit is indicated by a red line, and the data points for different temperatures (14 deg. F, 40 deg. F, 70 deg. F, 100 deg. F, 130 deg. F) are represented by various symbols. The coefficient of determination (R²) is given as 0.999.
Analysis of $E^*$ Test Results

The Mastercurves

Witczak and Sotil Procedure

D-2 SP III 76-22/64-22 WMA

log-log plot

semi-log plot
Analysis of E* Test Results

**Witczak and Sotil Procedure**

**D-2 SP III 76-22/64-22 WMA**

\[
y = 0.0002x^2 - 0.1019x + 6.2447 \\
R^2 = 0.9991
\]

### Mastercurve fitting parameters

<table>
<thead>
<tr>
<th>System</th>
<th>Reference Temperature</th>
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<th>β</th>
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<td>English System</td>
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<td>-0.75</td>
<td>1.16</td>
<td>-0.30</td>
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</table>
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-22 WMA

The Mastercurves

![Graph showing mastercurves for different temperatures (14 deg. F, 40 deg. F, 70 deg. F, 100 deg. F, 130 deg. F, and 14 deg. F shifted). The graph plots Log E* (ksi) against Log Frequency (Hz). The correlation coefficient R² = 0.997.]
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-22 WMA

The Mastercurves

log-log plot

semi-log plot
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-22 WMA

Mastercurve fitting parameters

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI System</td>
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<td>2.63</td>
<td>-1.24</td>
<td>2.20</td>
</tr>
<tr>
<td>English System</td>
<td>70 °F</td>
<td>2.63</td>
<td>-1.24</td>
<td>1.36</td>
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</table>
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-22 HMA

The Mastercurves

Log $|E^*|$ (ksi)

Log Frequency (Hz)

-6 -4 -2 0 2 4 6 8

Mastercurve Fit
- 14 deg. F
- 40 deg. F
- 70 deg. F
- 100 deg. F
- 130 deg. F
- 14 deg. F Shifted
- 40 deg. F Shifted
- 70 deg. F Shifted
- 100 deg. F Shifted
- 130 deg. F Shifted

$R^2 = 0.999$
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-22 HMA

The Mastercurves

log-log plot

semi-log plot
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-22 HMA

\[ y = 0.0002x^2 - 0.1048x + 6.4365 \]
\[ R^2 = 0.9977 \]

Mastercurve fitting parameters

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \delta )</th>
<th>( \gamma )</th>
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<tbody>
<tr>
<td>SI System</td>
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<td>-1.05</td>
<td>1.02</td>
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</table>
Analysis of E* Test Results

The Mastercurves

Witczak and Sotil Procedure

D-2 SP III 70-22/64-28 WMA

\[
\text{Log } |E*| \text{ (ksi)}
\]

\[
\text{Log Frequency (Hz)}
\]

Mastercurve Fit

- 14 deg. F
- 40 deg. F
- 70 deg. F
- 100 deg. F
- 130 deg. F
- 14 deg. F Shifted
- 40 deg. F Shifted
- 70 deg. F Shifted
- 100 deg. F Shifted
- 130 deg. F Shifted

\[ R^2 = 0.998 \]
Analysis of E* Test Results

**Witczak and Sotil Procedure**

D-2 SP III 70-22/64-28 WMA

**The Mastercurves**

![log-log plot](image)

![semi-log plot](image)
Analysis of E* Test Results

Witczak and Sotil Procedure

D-2 SP III 70-22/64-28 WMA

Mastercurve fitting parameters

<table>
<thead>
<tr>
<th></th>
<th>Reference Temperature</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
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Analysis of E* Test Results

Witczak and Sotil Procedure

D-3 SP III 76-22/70-28 WMA

The Mastercurves

Log |E*| (ksi) vs Log Frequency (Hz)

- Mastercurve Fit
- 14 deg. F
- 40 deg. F
- 70 deg. F
- 100 deg. F
- 130 deg. F
- 14 deg. F Shifted
- 40 deg. F Shifted
- 70 deg. F Shifted
- 100 deg. F Shifted
- 130 deg. F Shifted

R² = 0.999
Analysis of E* Test Results

Witczak and Sotil Procedure

D-3 SP III 76-22/70-28 WMA

The Mastercurves

log-log plot

semi-log plot
Analysis of E* Test Results

**Witczak and Sotil Procedure**

**D-3 SP III 76-22/70-28 WMA**

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
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<td>-0.53</td>
<td>1.32</td>
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Mastercurve fitting parameters

$y = 0.0002x^2 - 0.0945x + 5.7649$

$R^2 = 0.9994$

- Poly. (Shift Factor)
Analysis of E* Test Results

Witczak and Sotil Procedure

D-1 SP III 76-22/58-28 WMA

The Mastercurves

Mastercurve Fit
- 14 deg. F
- 40 deg. F
- 70 deg. F
- 100 deg. F
- 130 deg. F
- 14 deg. F Shifted
- 40 deg. F Shifted
- 70 deg. F Shifted
- 100 deg. F Shifted
- 130 deg. F Shifted

$R^2 = 0.995$
Analysis of E* Test Results

Witczak and Sotil Procedure

D-1 SP III 76-22/58-28 WMA

Log-log plot

Semi-log plot

The Mastercurves
Analysis of E* Test Results

**Witczak and Sotil Procedure**

D-1 SP III 76-22/58-28 WMA

### Mastercurve fitting parameters

<table>
<thead>
<tr>
<th>System</th>
<th>Reference Temperature</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
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<td>2.62</td>
<td>-1.00</td>
<td>1.29</td>
<td>-0.40</td>
</tr>
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</table>

$y = 0.0002x^2 - 0.1059x + 6.3798$

$R^2 = 0.9992$
Analysis of E* Test Results

D-4 SP III 76-22/70-28 HMA TS -1

TS1 : HMA

The Mastercurves

R² = 0.999

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>
Analysis of E* Test Results

D-4 SP III 76-22/70-28 HMA TS -1

The Mastercurves

TS1 : HMA

log-log plot

semi-log plot

Shift Factor Poly. (Shift Factor)

y = 0.0002x^2 - 0.1025x + 6.022
R² = 0.9992
Analysis of E* Test Results

D-4 SP III 76-22/70-28 WMA TS -2

TS2 : WMA – Foaming

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
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<td>SI System</td>
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<td>English System</td>
<td>70 °F</td>
<td>2.3012</td>
<td>-0.7404</td>
<td>1.4658</td>
</tr>
</tbody>
</table>

R² = 0.999
Analysis of $E^*$ Test Results

The Mastercurves

TS2 : WMA – Foaming

log-log plot

semi-log plot

D-4 SP III 76-22/70-28 WMA TS -2

$y = 0.0002x^2 - 0.0878x + 5.1984$

$R^2 = 0.9986$
Analysis of $E^*$ Test Results

TS3 : WMA – Evothem

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>English System</td>
<td>70 °F</td>
<td>2.5579</td>
<td>-0.7883</td>
<td>1.4315</td>
</tr>
</tbody>
</table>

$R^2 = 0.999$
Analysis of E* Test Results

D-4 SP III 76-22/70-28 WMA TS -3

The Mastercurves

TS3 : WMA – Evotherm

log-log plot

semi-log plot

\[ y = 2 \times 10^{-5} x^2 - 0.0677 x + 4.6857 \]

\[ R^2 = 0.9993 \]
### Analysis of E* Test Results

#### D-4 SP III 76-22/70-28 WMA TS -4

**TS4 : WMA - Cecabase RT**

#### The Mastercurves

![Mastercurve Fit](image)

- **Mastercurve Fit**
- 14 deg. F
- 40 deg. F
- 70 deg. F
- 100 deg. F
- 130 deg. F
- 14 deg. F Shifted
- 40 deg. F Shifted
- 70 deg. F Shifted
- 100 deg. F Shifted
- 130 deg. F Shifted

**R² = 0.998**

<table>
<thead>
<tr>
<th>Reference Temperature</th>
<th>α</th>
<th>β</th>
<th>δ</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
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<td>21.1 °C</td>
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<td>-0.2768</td>
<td>1.9922</td>
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<tr>
<td>English System</td>
<td>70 °F</td>
<td>2.9073</td>
<td>-0.2768</td>
<td>1.1537</td>
</tr>
</tbody>
</table>
Analysis of E* Test Results

The Mastercurves

D-4 SP III 76-22/70-28 WMA TS -4

TS4 : WMA – Cecabase RT

log-log plot

semi-log plot

y = 9E-05x² - 0.0821x + 5.4551
R² = 0.9971

Shift Factor
Poly. (Shift Factor)
Analysis of $E^*$ Test Results

D-4 SP III 76-22/70-28+ WMA TS -5

TS5 : WMA – 70-28+Cecabase RT

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
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</thead>
<tbody>
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$R^2 = 0.999$
Analysis of $E^*$ Test Results

The Mastercurves

TS5 : WMA – 70-28+ Cebase RT

D-4 SP III 76-22/70-28+ WMA TS -5

$y = 0.0001x^2 - 0.0741x + 4.6695$

$R^2 = 1$

log-log plot

semi-log plot

Frequency (Hz)

Temperature (ºF)

Shift Factor

Poly. (Shift Factor)
Analysis of $E^*$ Test Results

D-5 SP III 64-28/58-28 HMA

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<tr>
<th>Reference Temperature</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
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<td>70 °F</td>
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$R^2 = 0.999$
Analysis of E* Test Results

The Mastercurves

D-5 SP III 64-28/58-28 HMA

Log-Log Plot

\[ y = 0.0003x^2 - 0.1122x + 6.2338 \]
\[ R^2 = 0.998 \]
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<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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<td>District 1 Asphalt Mixes</td>
<td>District 2 Asphalt Mixes</td>
<td>District 3 Asphalt Mixes</td>
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**Main Module**
Typical Sub-module
Analysis on Existing E* Predictive Model

For Specified Binder Grade

For Used Binder Grade
Preparation of IA Specimens

# 6-IA Sample Specimens are prepared up to this quarter.

# From Each mix 4 or 5 specimens are prepared.
## DSR Test Summary

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Binder Source</th>
<th>Binder Grade</th>
<th>Original/Unaged</th>
<th>RTFO</th>
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<td>2</td>
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<td>PG 76-28</td>
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<td>5</td>
<td>NuStar</td>
<td>PG 64-28</td>
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<td>6</td>
<td>NuStar</td>
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Study Progress

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<td>Task 7</td>
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Where we are in the project schedule
Original project schedule
Plan for Next Quarter

Collection of mixes and binders.

Update the material and E* database

Testing on mixes

Testing on asphalt binders
Acknowledgement

- Project technical panel for their valuable suggestions
- Valuable service and time of Virgil Valdez, and Jeff Mann
- Hasan Faisal, who had been very helpful while conducting DSR test