STATE OF FLORIDA

Development of Dynamic Modulus Testing and Data Interpretation Capability

Research Report
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STATE MATERIALS OFFICE

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ABSTRACT

A Mechanical-Empirical (M-E) Design Guide developed through National Cooperative Highway Research Program (NCHRP) Project 1-37A has recently been proposed. In the Design Guide, the estimation of damage accumulation over the service life of a pavement is based on empirical rutting and cracking performance equations, which require dynamic modulus as an input parameter. Although the Design Guide is still being calibrated and extended to other distress modes, such as top-down cracking, it is a candidate Design Guide and will be used for the design of flexible pavements in the future. Recognizing the importance of obtaining the dynamic modulus for future implementation of the M-E Design Guide, a research project for developing a dynamic modulus testing system was undertaken at the Florida Department of Transportation.

Cyclic (Dynamic Modulus) tests involve problems associated with accuracy, sensitivity, and stability of instrumentation. Rigorous calibration processes associated with tuning the testing machine and adjusting the testing system were performed. Over the range of five temperatures and six frequencies at each temperature, a series of dynamic modulus tests recommended in AASHTP TP 63-03 was successfully conducted using the testing system developed. From the comparison between measured and predicted dynamic moduli, results appear to be within a reasonable tolerance, compared to similar studies performed on the typical mixtures used in Florida. This indicates that the system was well developed, and provided reliable dynamic moduli comparable with those obtained from other research institutions.

INTRODUCTION

Background

Pavement design procedures have been based on empirical equations derived from the AASHO road test. That test was conducted between 1958 and 1960, with a specific set of asphalt, base, and subgrade materials at one location, Ottawa, Illinois, and with modest traffic levels. It is now well accepted that pavement design should include expected traffic growth, materials, localized seasonal variations in materials and climatic conditions, and soil and moisture conditions. However, pavement designs currently being subjected to traffic loading are far beyond the design conditions that were used in the AASHO Road Test. To meet current demands on the design of pavements, National Cooperative Highway Research Program (NCHRP) sponsored the development of a new design guide for flexible pavements.

A Mechanical-Empirical (M-E) Design Guide developed through National Cooperative Highway Research Program (NCHRP) Project 1-37A has recently been proposed. The primary concept used in this new design guide was to link the mechanical properties, such as modulus, determined from a laboratory or field test, to the regional performance data, such as rutting or cracking. Although the Design Guide is still being calibrated and extended to other distress modes, such as top-down cracking, it is the candidate Design Guide and will be used for the design of flexible pavements in the future.

The estimation of damage accumulation over the service life of a new pavement is based on empirical rutting and cracking performance equations, which require dynamic modulus as an input parameter. The dynamic modulus is dependent upon temperature and loading frequency, and thus allows for a more accurate representation of traffic load effects on pavements.

Recognizing the importance of obtaining the dynamic modulus for future implementation of the M-E Design Guide, a research project for developing a dynamic modulus testing system was undertaken at the Florida Department of Transportation (FDOT). This report presents the dynamic modulus testing system developed and demonstrates specialized analysis software developed for interpretation of the dynamic modulus.

Objectives

The objectives of this research project were to develop dynamic modulus testing and interpretation capabilities. Therefore, the primary objectives of this research are to:

1. Develop dynamic modulus testing capabilities at the FDOT State Materials Office.
2. Develop data acquisition and reduction systems for the dynamic modulus test.
3. Develop analysis software that can facilitate the performance of the dynamic modulus test and efficiently analyze the results of the dynamic modulus test.
4. Optimize the cost of developing the dynamic modulus test.

Scope

The research performed was aimed to optimize the cost of developing a new testing system. The existing testing system that is used for the indirect tensile (IDT) test was utilized to this purpose. Additional testing components used for the dynamic modulus test were designed and produced during the course of this project.

The material selected for dynamic modulus testing is a dense graded asphalt mixture meeting Superpave requirements. A mixture with a nominal aggregate size of 12.5 mm and an unmodified binder graded as PG 67-22, which is the overwhelming mixture type used for FDOT work, was used for the dynamic modulus test performed in this study.

THEORETICAL BACKGROUND

Complex Modulus

The typical asphalt mixtures are said to be a viscoelastic material. Therefore, an accurate determination of the creep compliance or relaxation modulus that represents the rheological behavior of viscoelastic materials is crucial to evaluate the time-, rate-, and temperature-dependent stress and strain responses in flexible pavements or damage evolution in asphalt mixtures. The linear theory of viscoelasticity yields a mathematically tractable solution for stress-strain-time relations of the viscoelastic material. One can be predicted if the other is known. Therefore, the relaxation modulus is generally converted from a more convenient stress-controlled creep compliance test.

Creep compliance can be determined from both time and frequency domains. The former test performed in the time domain is called a creep compliance test, and the later test performed in the frequency domain is called a complex modulus test. In theory, the creep and complex modulus are interchangeable. Therefore, both tests provide the same creep compliance as long as the time and frequency ranges used are wide enough.

Creep compliance of viscoelastic materials in the time domain, which is simply obtained as time-dependent strain $\varepsilon(t)$ divided by a constant stress σ_{0}, has been successfully described as a power function:

$$D(t) = \varepsilon(t) / \sigma_0 = D_0 + D_1 t^m \quad (1)$$

where D_0, D_1 and m are power function parameters.

Complex modulus, which is another way to determine creep compliance in the frequency domain, can be determined from oscillating loading with different frequencies. For a given frequency ω, if the material is viscoelastic and the input is an oscillatory stress $\sigma_0 e^{i\omega t}$, then the strain response $\varepsilon_0 e^{i\omega t}$ will be an oscillation at the same frequency as the stress, but lagging behind by a phase angle δ. From the complex modulus test, complex E^*, dynamic $|E^*|$, storage E', and loss E'' moduli can be determined as follows:

$$E^* = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = \frac{\sigma_0}{\varepsilon_0}(\cos(\delta) + i\sin(\delta)) = \left|E^*\right| \cdot (\cos(\delta) + i\sin(\delta)) = E' + iE'' \qquad (2)$$

Similar to the complex modulus, complex compliance D^*, which can be determined from an oscillatory strain input, can be expressed as follows:

$$D^* = \frac{\varepsilon_0}{\sigma_0} e^{-i\delta} = \frac{\varepsilon_0}{\sigma_0}(\cos(\delta) - i\sin(\delta)) = \left|D^*\right| \cdot (\cos(\delta) - i\sin(\delta)) = D' - iD'' \qquad (3)$$

Since $|D^*|$ and $|E^*|$ are reciprocal, the dynamic $|D^*|$, storage D', and loss D''compliances can be determined from the complex modulus test.

Based on the theory of linear viscoelasticity, the creep and complex compliances are interchangeable. Time and frequency domains are interconnected by the following relationship (Findley et al., 1976):

$$D^*(\omega) = D'(\omega) - iD''(\omega) = i\omega L \mid D(t) \mid_{s=i\omega} \qquad (4)$$

where $L[f(t)] = \int_0^\infty e^{-st} f(t)dt$ denotes the Laplace transform of $f(t)$ and s is the transform parameter.

Time-Temperature Superposition

Since an asphalt mixture is a thermorheologically simple material, the first step to determine the creep compliance or complex modulus that covers a wide time or frequency range is to generate a master curve using the time-temperature superposition principle (Ferry, 1980). Test data collected at different temperatures can be shifted relative to the time t or frequency ω, so that the various curves can be aligned to a single master curve based on a reduced time or frequency ξ. The master curve can be constructed using an arbitrarily selected reference temperature T_0, to which all data are shifted. Once the shift factor, $a(T)$, that defines the required shift at the given temperature is determined, the creep compliance can be obtained at any temperature. The relationship is given by:

$$\xi = \omega \cdot (a(T)) \text{ or } \log(\xi) = \log(\omega) + \log(a(T)) \tag{5}$$

In AASHTO TP 63-03, the dynamic modulus values determined at multiple temperatures were shifted until the shifted data had minimal least-square errors with a Sigmoidal function. The Sigmoidal function is:

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + \exp(\beta - \gamma \log(\xi))} \tag{6}$$

where δ, α, and β, γ are a minimum modulus value, a span of modulus values, and shape parameters, respectively.

Predictive Equation

Creep compliance can be determined from either the creep compliance or complex modulus test. However, performing the rheological tests is difficult and expensive. Therefore, numerous attempts have been made to identify a correlation between the dynamic modulus and conventional volumetric mixture properties.

The predictive equation (Equation 7) developed by Witczak et al. (2002) is one of the most comprehensive models. This predictive equation is based on more than 2,800 different asphalt mixtures tested in the uniaxial compression test. Witczak's prediction equation is presented as follows:

$$\log|E^*| = -1.249937 + 0.029232P_{200} - 0.001767(P_{200})^2$$
$$- 0.002841P_4 - 0.058097V_a - 0.802208\frac{V_{beff}}{(V_{beff} + V_a)}$$
$$+ \frac{[3.871977 - 0.0021P_4 + 0.003958P_{38} - 0.000017(P_{38})^2 + 0.00547P_{34}]}{1 + e^{(-0.603313 - 0.313351\log f - 0.393532\log\eta)}} \qquad (7)$$

where

$|E^*|$ = dynamic modulus, 10^5 psi,

η = bituminous viscosity, 10^6 poise,

f = load frequency, Hz,

V_a = percent air void content,

V_{beff} = percent effective bitumen content, by volume,

P_{34} = cumulative percent retained on 3/4 -in. sieve,

P_{38} = cumulative percent retained on 3/8 -in. sieve,

P_4 = cumulative percent retained on No. 4 sieve,

P_{200} = percent passing on No. 200 sieve.

The M-E Design Guide recommends use of the predictive equation when the complex modulus test (i.e., it is called dynamic modulus because only the absolute value is used for predicting pavement performance) is not available. To estimate the viscosity of the asphalt binder at any given temperature, the regression parameters, A and VTS, must be established for temperature-viscosity relationship. The parameters are found by linear regression of the equation below:

$$\log\log(\eta) = A + VTS\log(T_R) \tag{8}$$

where

η = viscosity, cP,

T_R = temperature, Rankine,

A = regression intercept,

VTS = regression slope.

This is done by first converting the binder stiffness data obtained from the Dynamic Shear Rheometer test (DSR) in accordance with AASHTO T315 to viscosity using the relationship as follows:

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628} \tag{9}$$

where

G^* = binder complex shear modulus, Pa,

δ = binder phase angle, °.

To increase the reliability of the predictive equation, it was recommended to perform a series of DSR tests at multiple temperatures. Use of default A and VTS parameters presented in the Design Guide is allowed, but this may lower the reliability of the predictive equation. The default A and VTS values for PG 67-22 (AC-30) binder recommended in the M-E Design Guide are as follows:

A = 10.6316   VTS = -3.5480

DEVELOPMENT OF DYNAMIC MODULUS TESTING CAPABILITY

The dynamic modulus test system consists of a testing machine, environmental chamber, and measurement system as specified in AASHTO TP 62-03. The same units used for the IDT test are well qualified and fulfill the requirements recommended in the dynamic modulus test (AASHTO TP 62-03). Therefore, its main frame was utilized in development of the dynamic modulus testing system. Additional testing components required for the dynamic modulus test were designed and produced during the course of this project.

Testing Machine

The loading frame used for the dynamic modulus test was a MTS servo-hydraulic testing machine with a 22-kips load cell. The testing machine was tuned to have a capability over the range of frequencies from 0.1 to 25 Hz at room temperature. The standard error of the applied load was less than 5% over the frequency range. This error was a measure of the difference between the measured load data and the best fit sinusoid.

Environmental Chamber

A chamber for controlling the test specimen is capable of controlling the temperature range from -20 to 60°C to an accuracy of ±0.2°C (Figure 1).

Figure 1. Environmental Chamber

Measurement System

Four extensometers (Figure 2) used for the IDT test were extended by replacing the gage length adapters (Figure 3). Four gage length adapters were designed to have a gage length of 4 in.

The mounting technique currently used is that the magnets at the end of the extensometer snaps in place on the steel gage points glued to the test specimen. A gage-point mounting system, as shown in Figure 4, was designed and made to mount the gage points at the precise positions.

Loading Units

Two loading platens with 4 in. diameter were made and placed on the top and bottom of the test specimen. A loading head that applies loading to the center of the loading platen was also designed and made. A free-universal joint between the loading platen and the loading head was made to retrieve restrain forces and to apply loading to a precise loading point (Figure 5).

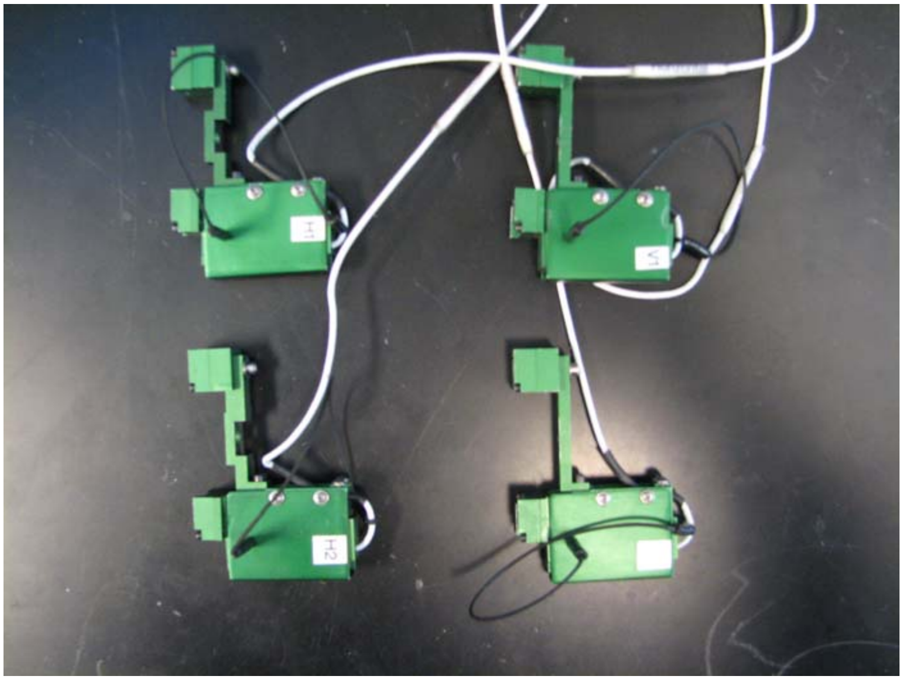


Figure 2. Strain Gauges

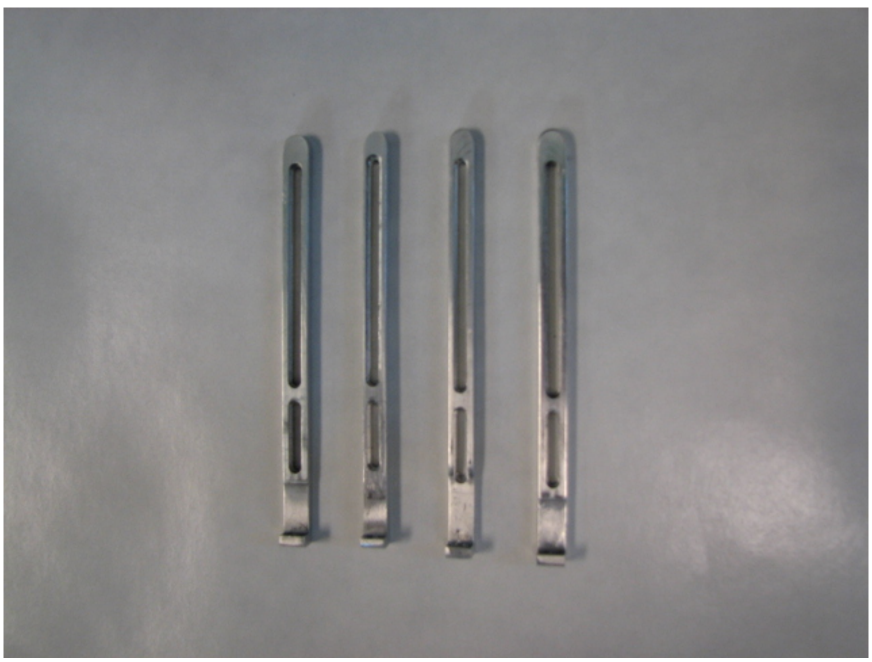


Figure 3. Extended Adapters

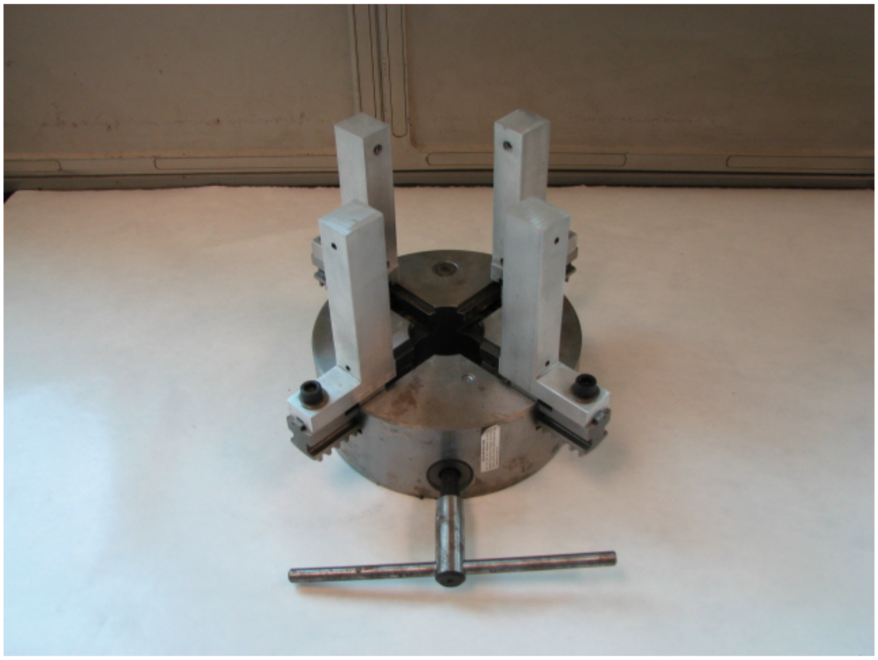


Figure 4. Gage-Point Mounting Unit

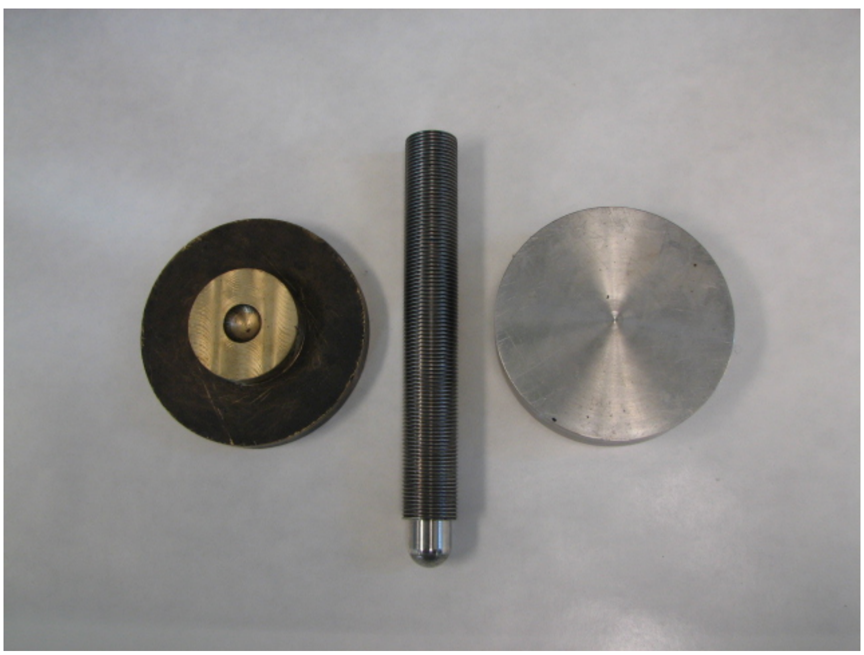


Figure 5. Loading Units

End Treatment

Friction-reducing end treatments made of TEFLON, were placed between the specimen ends and the loading platens, as shown in Figure 6.

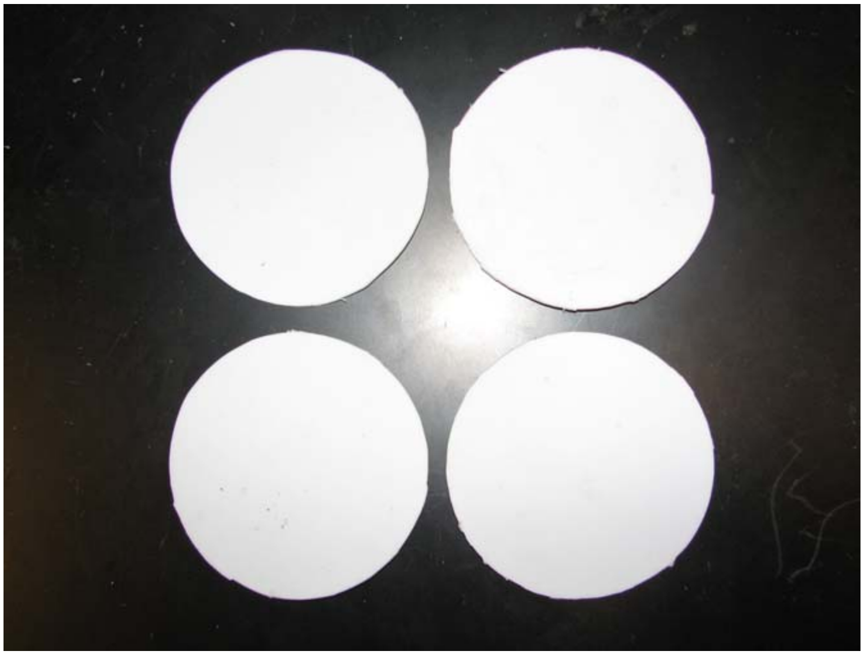


Figure 6. End Treatment

Coring and Cutting Units

AASHTO TP 62-03 recommends higher requirements for the sample preparation than any other mixture tests. Accordingly, coring and cutting test specimens can not be simply performed using the typical coring and cutting machines. Special coring and cutting units with the required precision, which the University of Florida has, were used for coring and cutting test specimens (Figures 7 and 8). With this equipment, four specimens with 4 in. diameter (tolerance of ± 0.04 in.) and a cut surface waviness within a tolerance of ± 0.002 across any diameter were prepared. A completed setup of the dynamic test is presented in Figure 9.

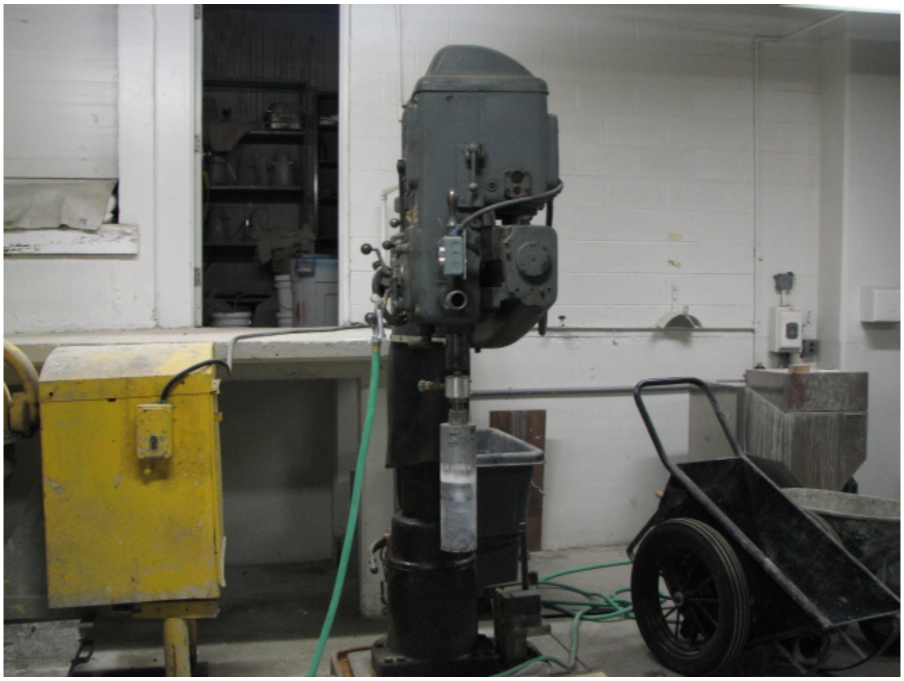


Figure 7. Coring Machine

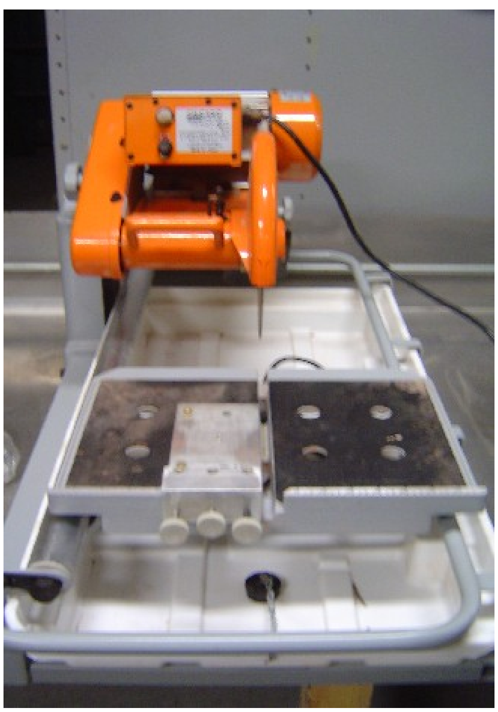


Figure 8. Cutting Machine

Figure 9. Dynamic Modulus Test

Experimental Programs

AASHTO TP 62-03 requires specific frequencies and numbers of cycles for each frequency (Table 1). For this, six testing programs were made. Each program for each frequency test has the same number of cycles as shown in Table 1. Figure 10 shows an example form of this program developed for a frequency test.

Table 1. Number of Cycles for the Test Sequence

Frequency (Hz)	Number of Cycles
25	200
10	200
5	100
1	20
0.5	15
0.1	15

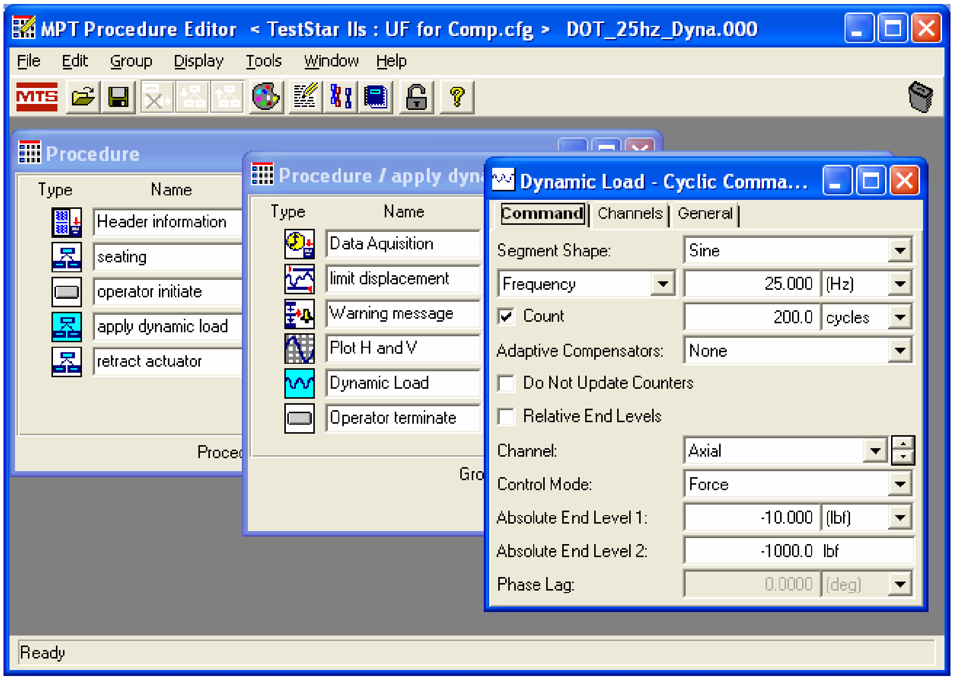


Figure 10. Testing Program

DYNAMIC MODULUS TESTING AND DATA ANALYSIS

The recommended test series for the dynamic modulus tests consists of testing at -10, 4.4, 21.1, 37.8, and 54.4°C for each of the frequencies used in Table 1. Each test specimen should be tested for the 30 combinations of temperatures and frequencies, starting with the lowest temperature and proceeding to the highest. Testing at a given temperature should begin with the highest frequency of loading and proceed to the lowest. General descriptions for testing and analysis procedures are explained below.

Testing Procedure

1. Place the test specimen in the environmental chamber and allow it to equilibrate with the specified testing temperature. The minimum times to reach recommended temperatures are shown in Table 2.
2. Place the friction reducing end treatments (Figure 6) on the top and bottom of the test specimen.
3. Apply a contact load of 10 lb.
4. Apply sinusoidal loading to the specimen. The dynamic load should be adjusted to obtain axial strains between 50 and 150 microstrain.

Table 2. Recommended Equilibrium Times

Specimen Temperature,°C (°F)	Time from Room Temperature, hr 25°C	Time from Previous Test Temperature, hr
-10 (14)	Overnight	Overnight
4 (40)	Overnight	4 hours or overnight
21 (70)	1	3
37 (100)	2	2
54 (130)	3	1

Calculations

1. Over the last five loading cycles, determine the average amplitude of the sinusoidal load from the load cell and deformations measured from the strain gauges for each testing condition.

2. Over the last five loading cycles, determine the average lag time between the peak load and the peak deformation from each strain gauge for each testing condition.

3. Over the last five loading cycles and for each testing condition, calculate the loading stress σ_0 as follows:

$$\sigma_0 = \frac{\overline{P}}{A} \tag{10}$$

where

$\overline{P}$ = average peak load,

A = area of specimen,

σ_0 = average peak stress.

4. Over the last five loading cycles and for each test condition, calculate the recoverable axial strain ε_0 as follows:

$$\varepsilon_0 = \frac{\overline{\Delta}}{GL} \tag{11}$$

where

$\overline{\Delta}$ = average peak deformation,

GL = gage length,

ε_0 = average peak strain.

5. Over the five loading cycles and for each testing condition, calculate the dynamic modulus, $|E^*|$ as follows:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{12}$$

6. Over the last five loading cycles and for each testing condition, calculate the phase angles as follows:

$$\phi = \frac{t_i}{t_p} \cdot 360 \quad (13)$$

where

t_i = average lag time between a cycle of stress and strain, sec,

t_p = average time for a stress cycle, sec,

ϕ = phase angle, °.

7. Calculate average dynamic modulus and phase angle from the results of each individual strain gauge.

Master Curve Development

1. The shift factor *a(T)* defines the required shift at a given reference temperature, T_0:

$$\xi = f \cdot a(T) \quad (14)$$

where

ξ = reduced frequency,

f = frequency of loading,

$a(T)$ = shift factor as a function of temperature,

T = Temperature.

2. Using the shift factors, the master curve can be constructed based on the selected reference temperature to which all data are shifted.

3. Different functions can be used to generate the master curve. As mentioned before, in AASHTO TP 63-03, the Sigmoidal function is recommended for generating the master curve to mathematically model the material response.

COMPUTATION ALGORITHMS

In September 2003, the Superpave Expert Task Group requested that a small group be formed to review AASHTO TP 62-03. The review was completed and the comments were incorporated in track-changes mode to the electronic version of the test protocol. However, there were several important review comments, especially for the computation algorithms, that did not fit directly into a revision of the test protocol. The computation algorithms used to obtain the dynamic moduli and phase angles directly follows the proposed approach.

The data produced from the dynamic modulus test at frequency ω will be in the form of several arrays, one for time $[t_i]$, one for each of the $j = 1,\ 2,\ \ldots m$ transducers used $[y_j]$. In this project, there are $m = 5$ transducers: the first transducer will be a load cell, and transducers 2 through 5 will be specimen deformation transducers. The number of $i = 1,\ 2,\ \ldots n$ points in each array will be based on the number of cycles and acquisition rate. For each sample at a given temperature and frequency, 5 cycles consisting of 250 points were analyzed to obtain the dynamic modulus and phase angle.

The general approach used here is based upon the least squares fit of sinusoid, as described by Chapra and Canale in Numerical Methods for Engineers (McGraw-Hill, 1985). The regression approach used also lends itself to calculating standard errors and other indicators of data quality.

1. The calculation proceeds as follows. First, the data for each transducer are centered by subtracting from the measured data the average for that transducer:

$$Y_{ji}' = Y_{ji} - \overline{Y_j} \tag{15}$$

where

Y_{ji}' = centered data for transducer *j* at point *i* in data array,

Y_{ji} = raw data for transducer *j* at point *i* in data array,

$\overline{Y}_j$ = average for transducer *j*.

2. In the second step in the procedure, the $[X]$ matrix is constructed as follows:

$$[X] = \begin{bmatrix} n & \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} \cos(\omega \cdot t_i) & \sum_{i=1}^{n} \sin(\omega \cdot t_i) \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 & \sum_{i=1}^{n} t_i \cdot \cos(\omega \cdot t_i) & \sum_{i=1}^{n} t_i \cdot \sin(\omega \cdot t_i) \\ \sum_{i=1}^{n} \cos(\omega \cdot t_i) & \sum_{i=1}^{n} t_i \cdot \cos(\omega \cdot t_i) & \sum_{i=1}^{n} \cos^2(\omega \cdot t_i) & \sum_{i=1}^{n} \sin(\omega \cdot t_i) \cdot \cos(\omega \cdot t_i) \\ \sum_{i=1}^{n} \sin(\omega \cdot t_i) & \sum_{i=1}^{n} t_i \cdot \sin(\omega \cdot t_i) & \sum_{i=1}^{n} \sin(\omega \cdot t_i) \cdot \cos(\omega \cdot t_i) & \sum_{i=1}^{n} \sin^2(\omega \cdot t_i) \end{bmatrix} \tag{16}$$

where *n* is the total number of data points, ω is the frequency of the data, and *t* is the time, starting from the data array.

3. Then for each transducer, the $[X_j']$ array is constructed:

$$[X_j'] = \begin{bmatrix} \sum_{i=1}^{n} Y_{ji}' \\ \sum_{i=1}^{n} Y_{ji}' \cdot t \\ \sum_{i=1}^{n} Y_{ji}' \cdot \cos(\omega \cdot t) \\ \sum_{i=1}^{n} Y_{ji}' \cdot \sin(\omega \cdot t) \end{bmatrix} \tag{17}$$

4. The array representing the regression coefficients for each transducer is then calculated by multiplying the $[X]^{-1}$ matrix by the $[X_j']$ matrix:

$$\begin{bmatrix} A_{j0} \\ A_{j1} \\ A_{j2} \\ B_{j2} \end{bmatrix} = [X]^{-1}[X_j'] \tag{18}$$

where the regression coefficients *A*s can be used to calculate predicted values for each of the *j* transducers using the regression function:

$$\hat{Y}_{ji} = A_{j0} + A_{j1} \cdot t_i + A_{j2} \cdot \cos(\omega_0 \cdot t_i) + B_{j2} \cdot \sin(\omega_0 \cdot t_i) + \varepsilon_{ji} \tag{19}$$

where $\hat{Y}_{ji}$ is the predicted value for the i^{th} point of data for the j^{th} transducer, and ε_{ji} represents the error term in the regression function.

5. From the regression coefficients, several other functions are then calculated as follows:

$$\theta_j = \arctan(-\frac{B_{j2}}{A_{j2}})$$

$$|Y_j^*| = \sqrt{A_{j2}^2 + B_{j2}^2}$$

$$\Delta Y_j = \frac{A_{j1} t_N}{|Y_j^*|} \times 100\%$$

$$se(Y_j) = \sqrt{\frac{\sum_{i=1}^{n} (\hat{Y}'_{ji} - Y'_{ji})^2}{n-4}} \cdot \left(\frac{100\%}{|Y_j^*|} \right) \tag{20}$$

where

θ_j = phase angle for transducer j, degrees,

$|Y_j^*|$ = amplitude for transducer j,

ΔY_j = drift for transducer j, as percent of amplitude,

t_N = total time covered by data,

$\hat{Y}'_{ji}$ = predicted centered response for transducer j at point i,

$se(Y_j)$ = standard error for transducer j, %.

The phase angles given by Equation (20) represent absolute phase angles, that is, θ_j is an arbitrary value indicating the angle at which data collection started.

6. The phase angle of the deformation (response) relative to the load (excitation) is the important mechanical property. To calculate this phase angle, the average phase angle for the deformation must first be calculated:

$$\bar{\theta}_D = \frac{\sum_{j=2}^{m} \theta_j}{m-1} \tag{21}$$

where $\bar{\theta}_D$ is the average absolute phase angle for the deformation transducers.

7. The relative phase angle at frequency ω between the deformation and the load, $\theta(\omega)$, is then calculated as follows:

$$\theta(\omega) = \bar{\theta}_D - \theta_P \tag{22}$$

where θ_P is the absolute phase angle calculated for the load.

8. A similar set of calculations is needed to calculate the overall modulus for the material. First, the average amplitude for the deformation $|\bar{Y}_D^*|$ must be calculated:

$$|\bar{Y}_D^*| = \frac{\sum_{j=2}^{m} |Y_j^*|}{m-1} \tag{23}$$

9. Then, the dynamic modulus $|E^*|$ at frequency ω is calculated using the following equation:

$$|E^*(\omega)| = \frac{|Y_P^*| \cdot L_g}{|\bar{Y}_D^*| \cdot A} \tag{24}$$

where L_g is the average gage length for the deformation transducers, and A is the loaded cross-sectional area.

10. The final part of the analysis involves calculation of several factors indicative of data quality, including the average drift for the deformations, the average standard error for the deformations, and uniformity coefficients for deformation amplitude and phase:

$$\Delta\overline{Y}_D = \frac{\sum_{j=2}^{m} A_{j1} t_N}{\sum_{j=2}^{m} |Y_j^*|} \times 100\%$$

$$se(Y_D) = \frac{\sum_{j=2}^{m} se(Y_j)}{m-1}$$

$$U_A = \sqrt{\frac{\sum_{j=2}^{m} (|Y_j^*| - |\overline{Y}_D^*|)^2}{m-1}} \cdot \left(\frac{100\%}{|\overline{Y}_D^*|}\right)$$

$$U_\theta = \sqrt{\frac{\sum_{j=2}^{m} (\theta_j - \overline{\theta}_D)^2}{m-1}} \tag{25}$$

where

$\Delta\overline{Y}_D$	= average deformation drift as percent of average deformation amplitude,
$se(Y_D)$	= average standard error for all deformation transducers %,
U_A	= uniformity coefficient for deformation amplitude %,
U_θ	= uniformity coefficient for deformation phase degrees.

The following limits on these data quality indicators were recommended based on an analysis of the data collected. If these limits are exceeded, the test should be repeated.

- Load and deformation standard error: 10%
- Load drift (absolute value): 3%

- Deformation uniformity: 20%
- Phase uniformity: 3%

DEVELOPMENT OF DYNAMIC TESTING ANALYZER (DTA)

The computations for processing raw data of dynamic modulus testing described above were used to analyze sinusoidal data. It appears easy for engineers and systemizes the computation algorithm of the dynamic modulus test data. Based on the detailed computation algorithms, robust and automatic data analysis software, which is named Dynamic Testing Analyzer (DTA), was developed in this project. The DTA was programmed in Visual Basic, as an Excel Macro. Therefore, in order to use this program, the Excel program is required to be installed. The demonstrations for how to install and use the DTA will be described.

Software Installation

1. Copy the DTA folder to any directory where the DTA is installed (Figure 11).
2. Open and close Dynamic Modulus Test Data Analyzer.xls (Figure 11).

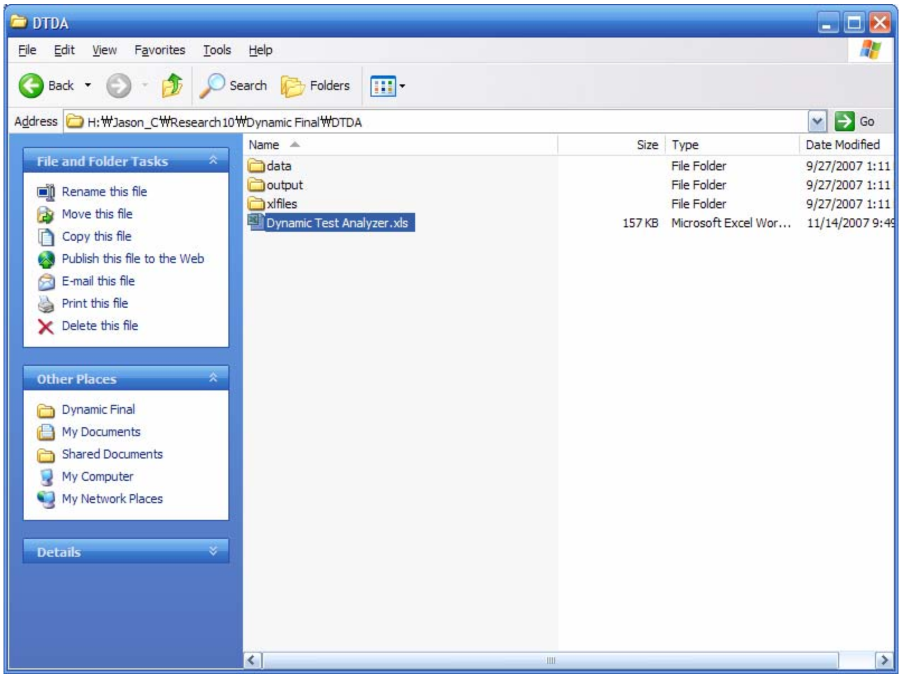


Figure 11. Installation of DTA Software

Use of the DTA for a single frequency test

1. Open the data file with the Excel program after completing any frequency test (Figure 12).
2. Click the “Dynamic Modulus Data Analysis” button shown in the tool bars (Figure 12).
3. Input the temperature and frequency values used (Figure 13).
4. Check the average of strains and repeat the dynamic test with a different load level at the frequency unless the average strains are in the range between 50 and 150 microstrains (Figure 14).

Note: The DTA automatically saves the last data performed and analyzed at the frequency test.

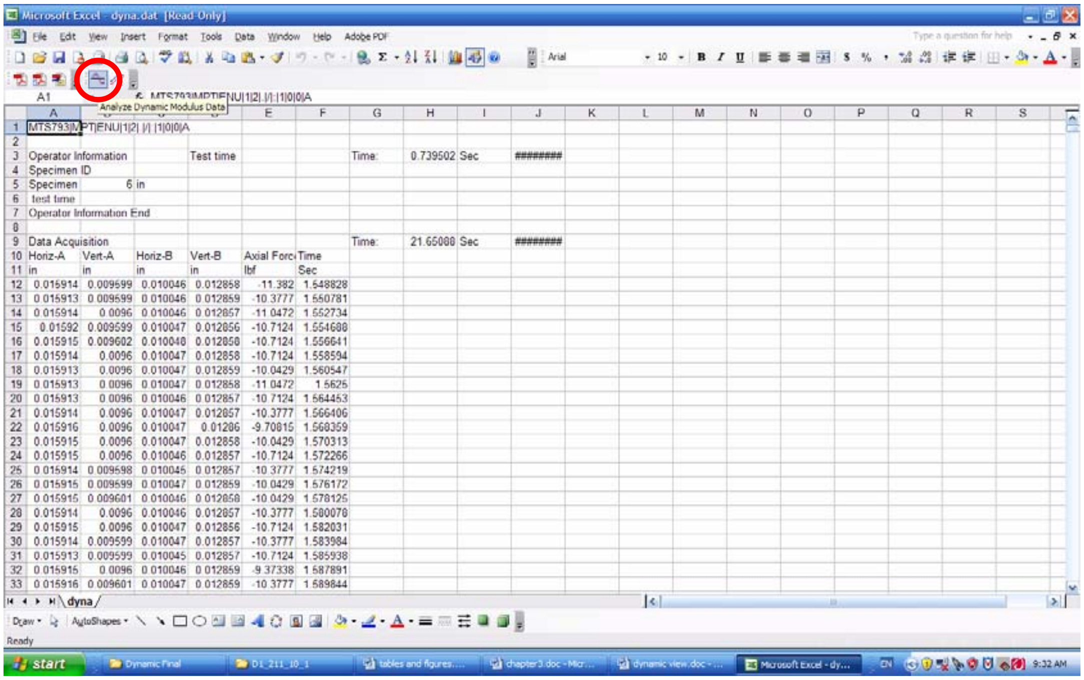


Figure 12. Use of DTA for Frequency Test: Step 1

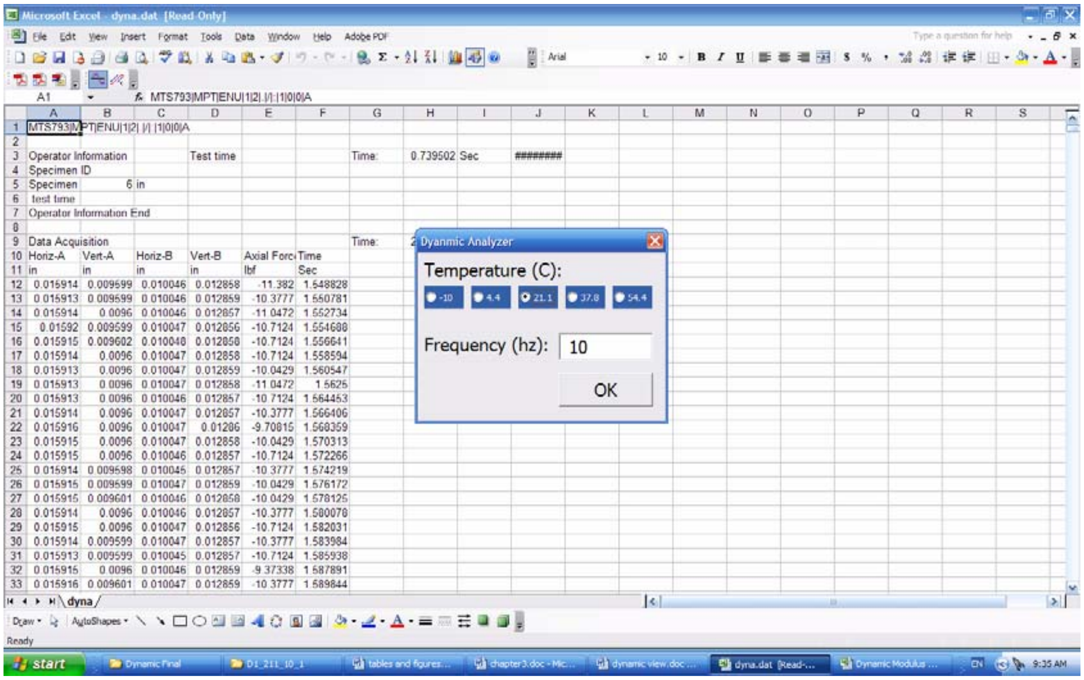


Figure 13. Use of DTA for Frequency Test: Step 2

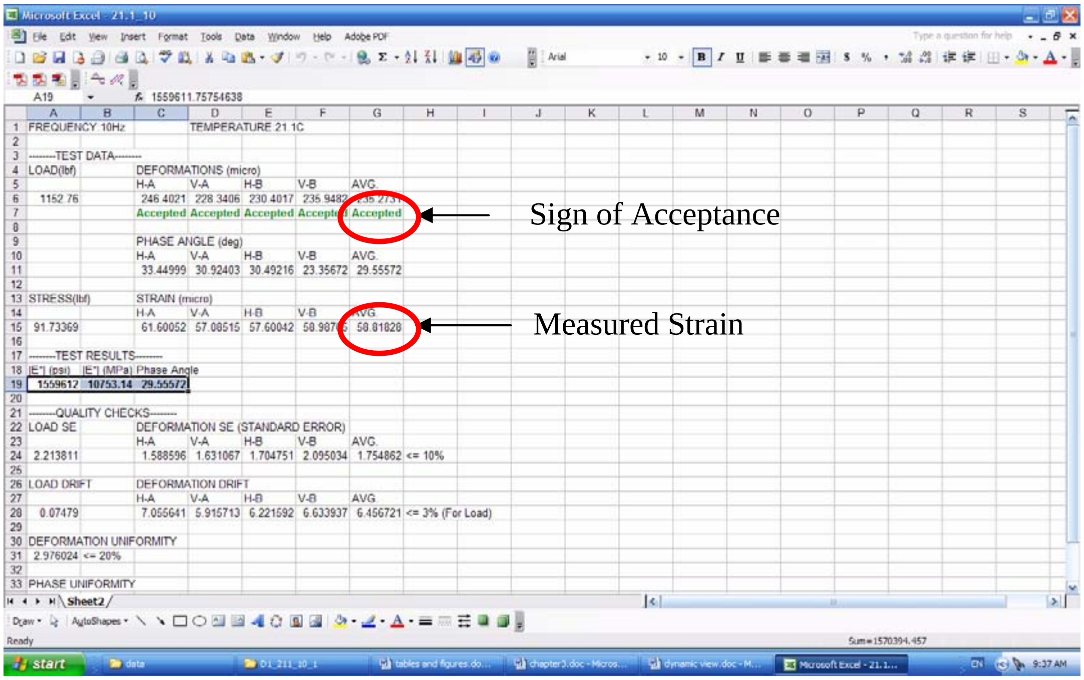


Figure 14. Results of DTA for Frequency Test

Generating a Master Curve Using DTA

After successfully completing the 30 combinations of temperature and frequency tests, the master curve can be generated using the DTA. The numerical optimization (Solver) provided in the Excel program was used to determine the best fit of measured dynamic moduli with the Sigmoidal function. This process used is also recommended in AASHTO TP 62-03.

1. Open Dynamic Modulus Test Data Analyzer.xls. If this file is already opened, skip this part.
2. Click the “Master Curve and Advanced Analysis” button (Figure 15).
3. Select the reference temperature (Figure 16).
4. Store the data and output folders in the DTA folder (Figure 11).

Note: The reference temperature is not specified in AASHTO TP 63-03. However, the M-E Design Guide uses a temperature of 21.1 °C as a reference temperature.

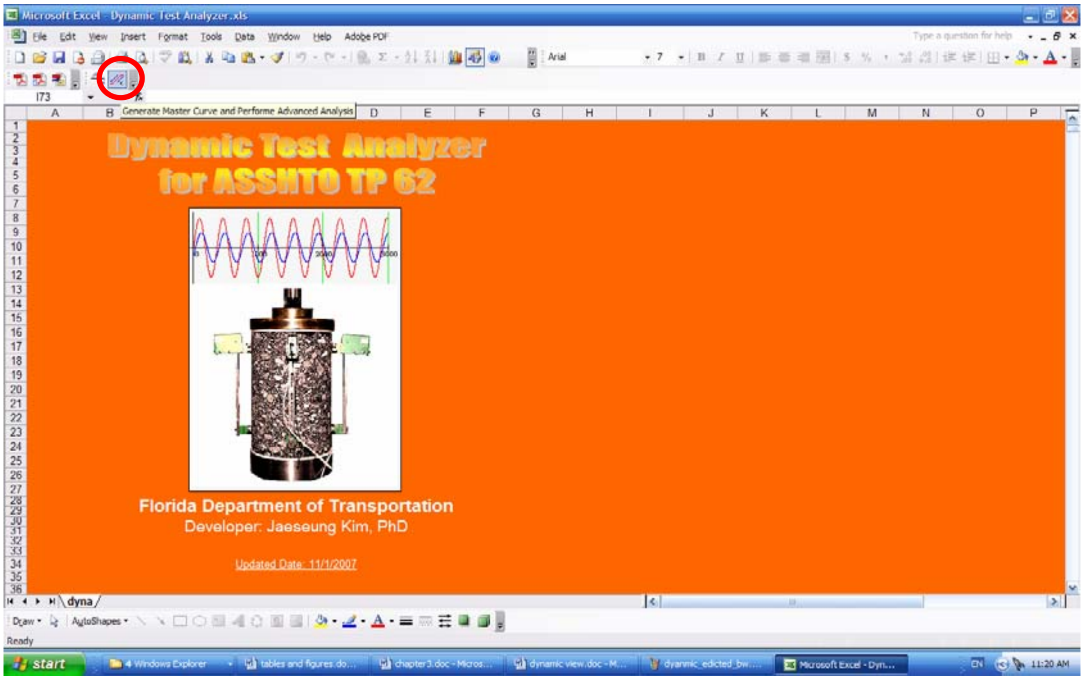


Figure 15. Use of DTA for Master Curve Generation: Step 1

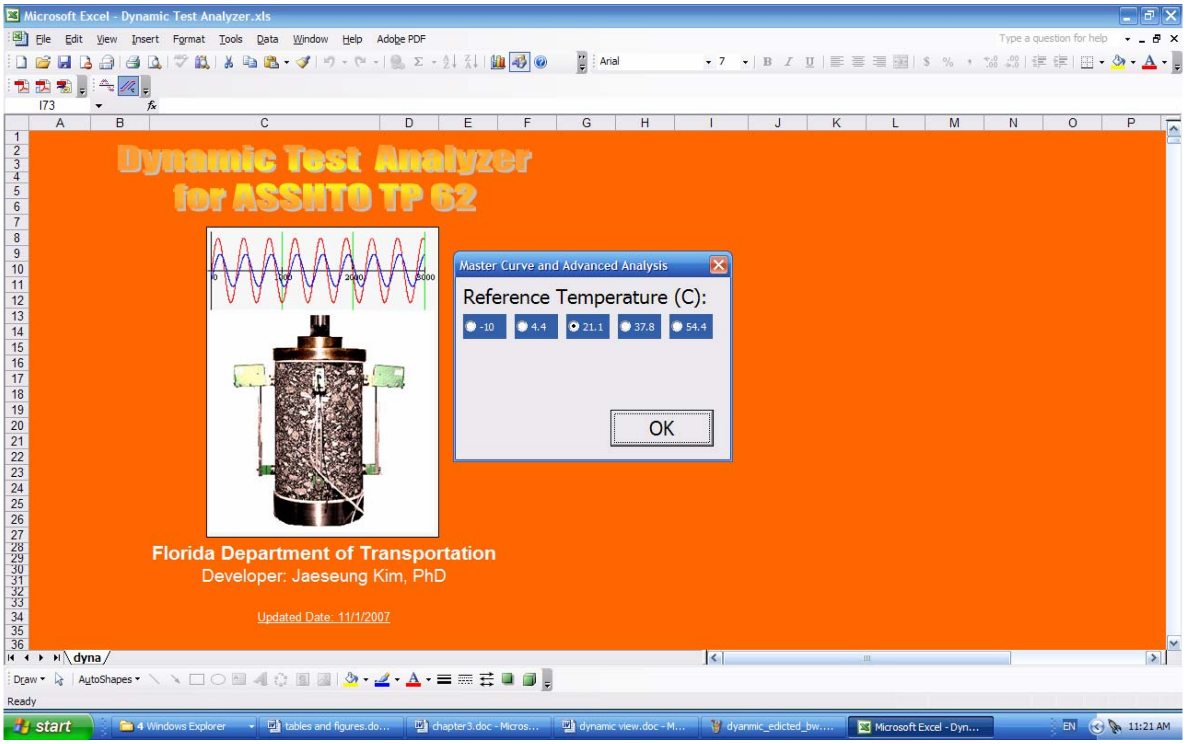
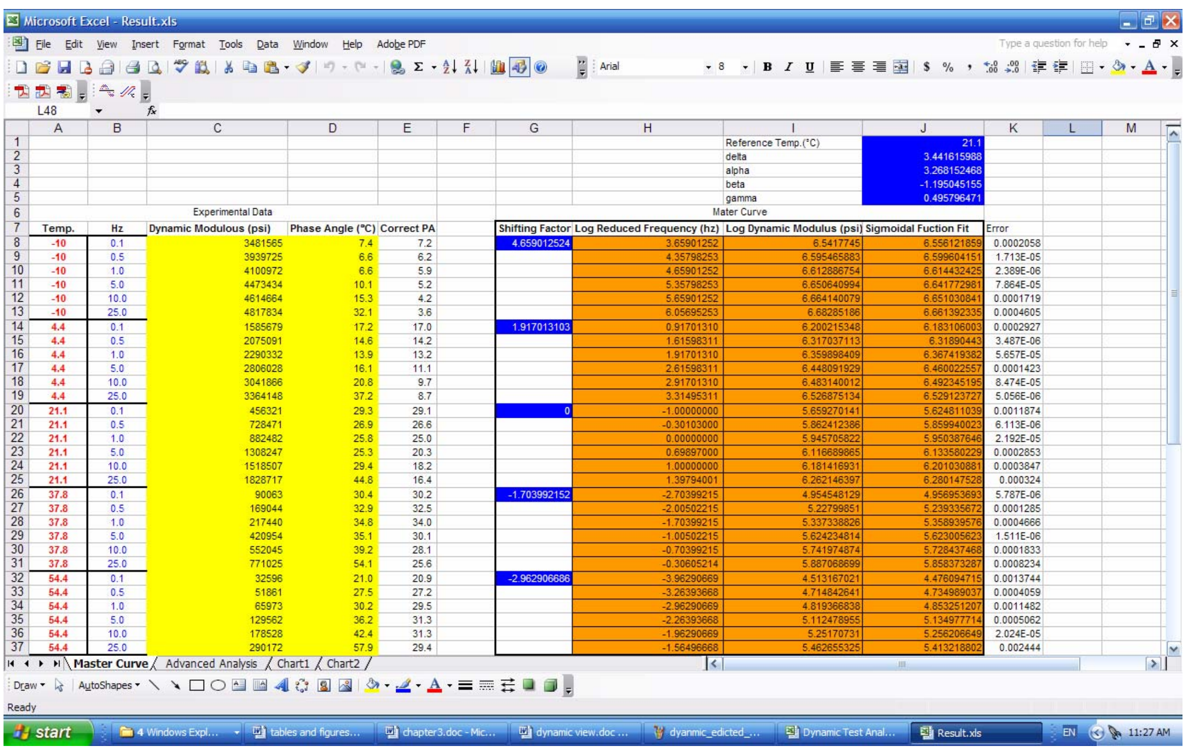


Figure 16. Use of DTA for Master Curve Generation: Step 2

Data Files

As shown above, the DTA program consists of two parts: one for analyzing a frequency test and the other for generating a master curve. For a given frequency test, the results shown in the upper part of the Excel spreadsheet present deformation, force, stress, strain, phase angle, and dynamic modulus values measured, and the results shown in the lower part of the Excel spreadsheet present information related to the quality of data (Figure 14).

Running the second analysis creates the result.xls file which can be obtained from the output folder, and includes all dynamic and phase angle values measured from all the frequency and temperature tests. The purpose of this analysis is to generate a master curve. The Excel spreadsheet presents the shifted dynamic moduli, shift factors, and coefficients of the Sigmoidal function (Figure 17). The accuracy of this analysis can be visually checked from the chart (Figure 18).



Reference Temp.(°C)	21.1
delta	3.441615988
alpha	3.268152468
beta	-1.195045155
gamma	0.495796471

Experimental Data					Mater Curve				
Temp.	Hz	Dynamic Modulous (psi)	Phase Angle (°C)	Correct PA	Shifting Factor	Log Reduced Frequency (hz)	Log Dynamic Modulus (psi)	Sigmoidal Fuction Fit	Error
-10	0.1	3481565	7.4	7.2	4.659012524	3.65901252	6.5417745	6.556121859	0.0002058
-10	0.5	3939725	6.6	6.2		4.35798253	6.595465883	6.599604151	1.713E-05
-10	1.0	4100972	6.6	5.9		4.65901252	6.612886754	6.614432425	2.389E-06
-10	5.0	4473434	10.1	5.2		5.35798253	6.650640994	6.641772981	7.864E-05
-10	10.0	4614664	15.3	4.2		5.65901252	6.664140079	6.651030841	0.0001719
-10	25.0	4817834	32.1	3.6		6.05695253	6.68285186	6.661392335	0.0004605
4.4	0.1	1585679	17.2	17.0	1.917013103	0.91701310	6.200215348	6.183106003	0.0002927
4.4	0.5	2075091	14.6	14.2		1.61598311	6.317037113	6.31890443	3.487E-06
4.4	1.0	2290332	13.9	13.2		1.91701310	6.359898409	6.367419382	5.657E-05
4.4	5.0	2806028	16.1	11.1		2.61598311	6.448091929	6.460022557	0.0001423
4.4	10.0	3041866	20.8	9.7		2.91701310	6.483140012	6.492345195	8.474E-05
4.4	25.0	3364148	37.2	8.7		3.31495311	6.526875134	6.529123727	5.056E-06
21.1	0.1	456321	29.3	29.1	0	-1.00000000	5.659270141	5.624811039	0.0011874
21.1	0.5	728471	26.9	26.6		-0.30103000	5.862412386	5.859940023	6.113E-06
21.1	1.0	882482	25.8	25.0		0.00000000	5.945705822	5.950387646	2.192E-05
21.1	5.0	1308247	25.3	20.3		0.69897000	6.116689865	6.133580229	0.0002853
21.1	10.0	1518507	29.4	18.2		1.00000000	6.181416931	6.201030881	0.0003847
21.1	25.0	1828717	44.8	16.4		1.39794001	6.262146397	6.280147528	0.000324
37.8	0.1	90063	30.4	30.2	-1.703992152	-2.70399215	4.954548129	4.956953693	5.787E-06
37.8	0.5	169044	32.9	32.5		-2.00502215	5.22799851	5.239335672	0.0001285
37.8	1.0	217440	34.8	34.0		-1.70399215	5.337338826	5.358939576	0.0004666
37.8	5.0	420954	35.1	30.1		-1.00502215	5.624234814	5.623005623	1.511E-06
37.8	10.0	552045	39.2	28.1		-0.70399215	5.741974874	5.728437468	0.0001833
37.8	25.0	771025	54.1	25.6		-0.30605214	5.887068699	5.858373287	0.0008234
54.4	0.1	32596	21.0	20.9	-2.962906686	-3.96290669	4.513167021	4.476094715	0.0013744
54.4	0.5	51861	27.5	27.2		-3.26393668	4.714842641	4.734989037	0.0004059
54.4	1.0	65973	30.2	29.5		-2.96290669	4.819366838	4.853251207	0.0011482
54.4	5.0	129562	36.2	31.3		-2.26393668	5.112478955	5.134977714	0.0005062
54.4	10.0	178528	42.4	31.3		-1.96290669	5.25170731	5.256206649	2.024E-05
54.4	25.0	290172	57.9	29.4		-1.56496668	5.462655325	5.413218802	0.002444

Figure 17. Combined Results of DTA

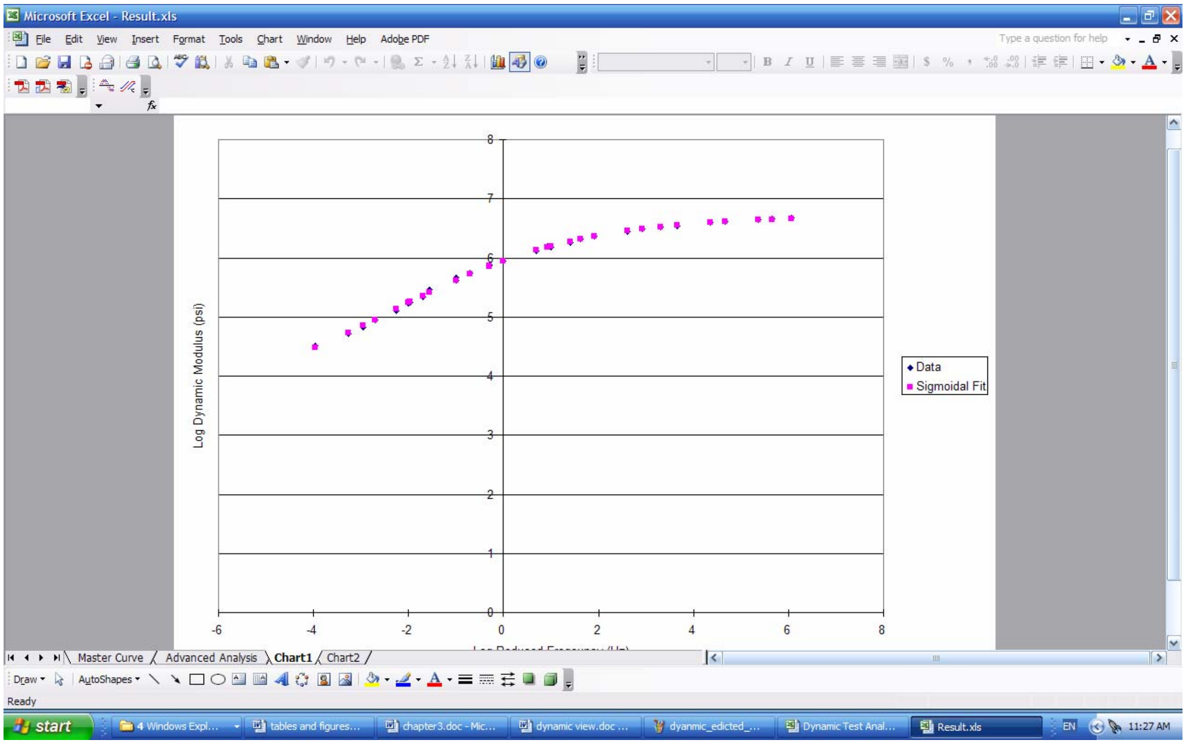


Figure 18. Generated Master Curve

RESULTS OF CALIBRATION TESTS

Calibration Testing

Dynamic modulus testing projects performed at several institutions emphasized performing a calibration test to check the quality of the dynamic modulus test. The calibration test may be a unique way to verify and calibrate the system developed for the dynamic modulus test. The calibration test is normally performed using a linear elastic material with relatively lower stiffness than the materials of the testing system. A specimen with 4 in. diameter by 6 in. tall was made of 6061-T6511 aluminum and was tested over the same frequency range at room temperature.

Figures 19 and 20 show the results of the calibration test. Consistent modulus values over the frequency range were obtained, and the values were close to the known modulus value of the material (approximately 10000 ksi). Therefore, it is concluded that dynamic modulus values obtained from the testing system developed are accurate and reliable. However, the phase angles measured from the same tests increased as the testing frequency increased. It appears that the effect of machine damping, including electronic or dynamic damping occurring in the testing system, becomes significant as the frequency increases. Similar results were reported by Zhao and Kim (2003) and Kim et al. (2005).

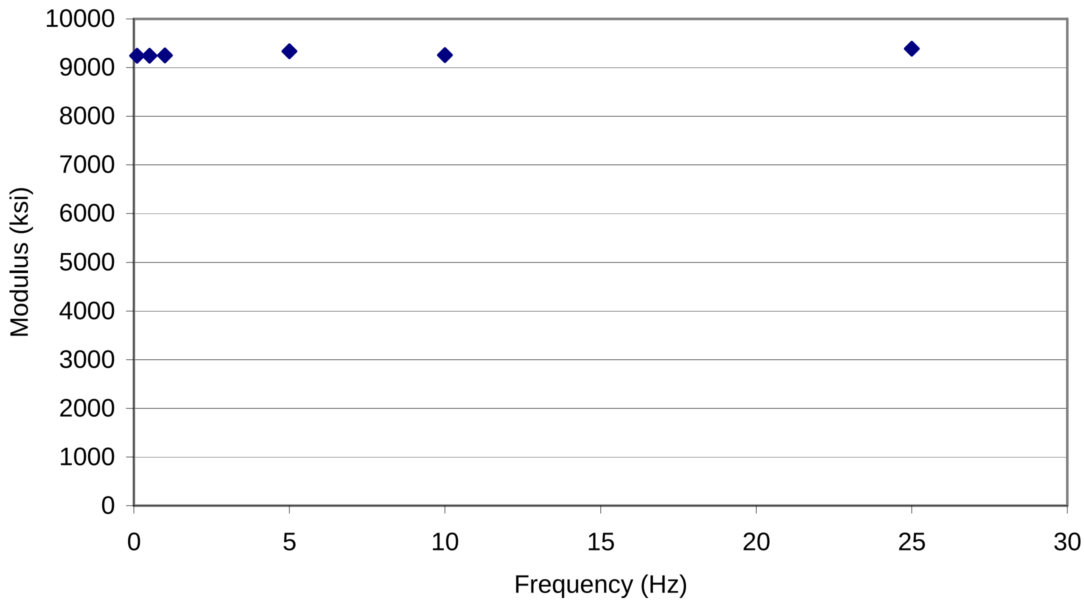


Figure 19. Results of Aluminum Tests: Modulus

It is well known that the phase angles from the aluminum specimen must be zero regardless of frequencies because the phase angle represents viscous response, which is obviously not present in the elastic material. Therefore, corrections must be made by subtracting the phase angle measured from the aluminum specimen, from those obtained from asphalt mixture tests. The DTA makes automatic corrections for phase angles measured from any mixture tests. This consequently provides the true phase angles that represent the pure response of asphalt mixtures.

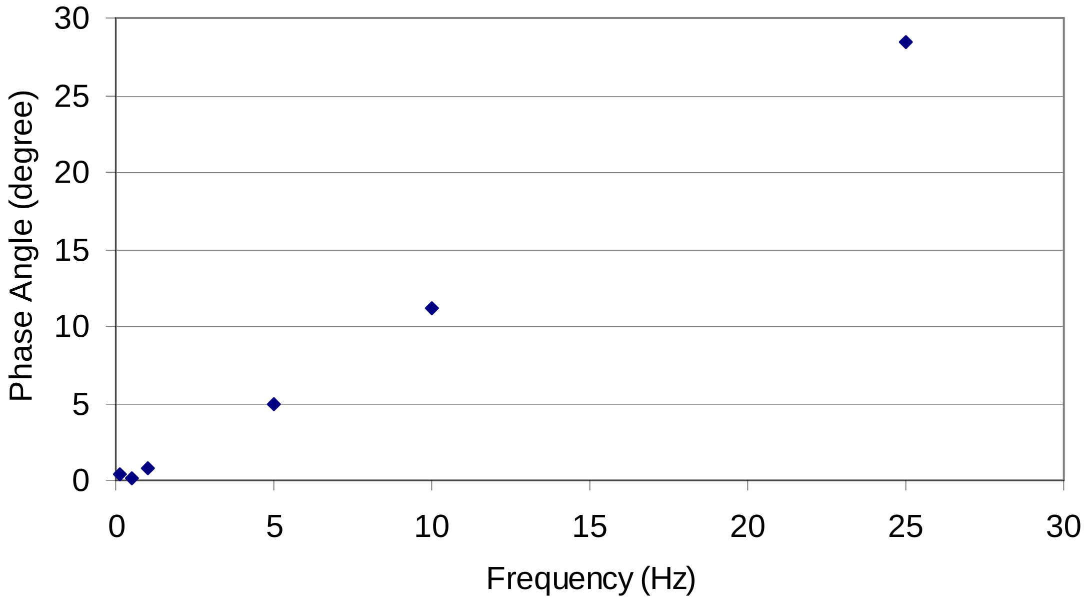


Figure 20. Results of Aluminum Tests: Phase Angle

RESULTS OF DYNAMIC MODULUS TESTS PERFORMED ON AN ASPHALT MIXTURE

Material

A fine-graded mixture with a nominal aggregate size of 12.5 mm and an unmodified binder graded as PG 67-22 was prepared for evaluation of the dynamic modulus test. A detailed gradation of the mixture used is shown in Figure 21.

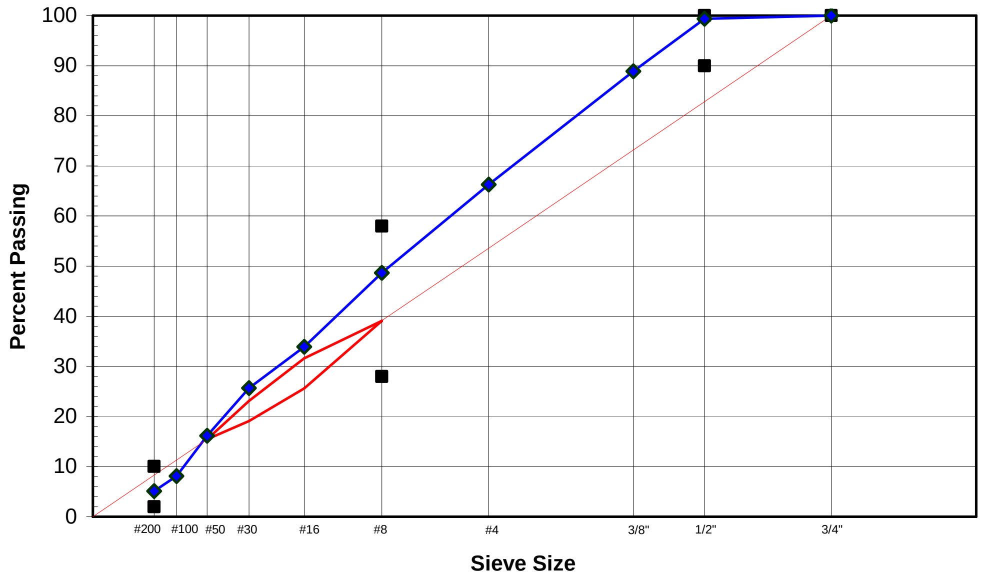


Figure 21. Gradation of Mixture

Data Quality and Test Results

Although the detailed recommendations for checking data quality were proposed above, some of proposed requirements appear to be redundant and may not be fully achieved by the commonly used testing equipment for asphalt mixture tests. The prior work on the dynamic modulus performed at the University of Florida recommended to check the difference between the measured data and the best fit sinusoid. Since calibrations for the load cell, strain gauges, and testing system are periodically conducted in the FDOT laboratory, this single criterion appears to be simple and reliable. A standard error of 10%, which was suggested by the reviewers on AASHTO TP 62-03, was set as a threshold value that determines the quality of data. The results of dynamic modulus tests performed on two specimens are shown in Table 3, and the standard errors, the differences between the measured data and the best fit sinusoid, are shown in Table 4.

Table 3. Measured Dynamic Modulus Values

Temperature (°C)	Hz	Dynamic Modulus (psi)		
		Spec. 1	Spec. 2	Avg.
-10	0.1	3481565	3758523	3620044
-10	0.5	3939725	4229948	4084836
-10	1.0	4100972	4424239	4262605
-10	5.0	4473434	4806306	4639870
-10	10.0	4614664	4979709	4797186
-10	25.0	4817834	5187398	5002616
4.4	0.1	1585679	1766240	1675960
4.4	0.5	2075091	2284678	2179884
4.4	1.0	2290332	2509400	2399866
4.4	5.0	2806028	3026805	2916416
4.4	10.0	3041866	3256742	3149304
4.4	25.0	3364148	3585392	3474770
21.1	0.1	456321	459374	457847
21.1	0.5	728471	746191	737331
21.1	1.0	882482	905287	893885
21.1	5.0	1308247	1343887	1326067
21.1	10.0	1518507	1559612	1539060
21.1	25.0	1828717	1894382	1861549
37.8	0.1	90063	83390	86726
37.8	0.5	169044	156772	162908
37.8	1.0	217440	200308	208874
37.8	5.0	420954	392523	406738
37.8	10.0	552046	510105	531075
37.8	25.0	771025	713490	742258
54.4	0.1	32596	30514	31555
54.4	0.5	51861	45784	48823
54.4	1.0	65973	56530	61252
54.4	5.0	129562	106134	117848
54.4	10.0	178528	142662	160595
54.4	25.0	290172	224505	257339

Table 4. Measured Standard Errors

Temp.	Hz	Specimen 1		Specimen 2	
		Load Error (%)	Deformation Error (%)	Load Error (%)	Deformation Error (%)
-10	0.1	0.2	1.7	0.1	1.4
-10	0.5	0.4	1.9	0.3	1.4
-10	1.0	0.6	1.9	0.6	1.4
-10	5.0	2.1	2.5	1.9	2.1
-10	10.0	2.7	3.0	2.4	2.8
-10	25.0	3.4	4.3	3.2	3.7
4.4	0.1	0.4	1.7	0.3	1.7
4.4	0.5	0.6	1.6	0.4	1.4
4.4	1.0	0.7	1.4	0.6	1.4
4.4	5.0	2.9	2.5	2.7	2.8
4.4	10.0	3.5	3.4	3.1	3.1
4.4	25.0	3.6	3.3	3.4	3.9
21.1	0.1	1.1	5.4	1.0	2.3
21.1	0.5	1.1	2.9	0.8	1.8
21.1	1.0	1.2	2.8	1.0	1.6
21.1	5.0	3.2	3.0	2.9	2.5
21.1	10.0	5.1	4.2	4.4	3.5
21.1	25.0	4.8	3.8	4.3	3.9
37.8	0.1	5.0	6.7	4.6	6.8
37.8	0.5	2.5	3.7	2.6	2.8
37.8	1.0	3.4	3.8	3.4	3.5
37.8	5.0	4.3	3.9	3.9	3.1
37.8	10.0	6.6	5.0	5.6	3.8
37.8	25.0	8.3	6.2	8.1	6.1
54.4	0.1	11.8	12.9	14.4	13.9
54.4	0.5	5.9	4.3	6.7	4.3
54.4	1.0	5.2	4.5	5.5	3.7
54.4	5.0	5.3	4.0	5.0	3.5
54.4	10.0	8.3	5.9	5.4	3.9
54.4	25.0	16.9	10.3	15.7	10.2

Two dynamic modulus values measured from two independent specimens show very close values to each other. Also, standard errors measured from the load and displacements, except for two frequency tests performed at the highest temperature, are lower than the threshold value of 10%. This indicates that the testing system developed minimizes the testing variability occurring from sample to sample, and the load and displacements were well controlled and measured in the system.

In general, a standard error between the measured data and the best fit sinusoid increases as testing frequency increases. The reason appears that increasing frequency increases an inertia force of the loading system, and this effect substantially affects the strain measurements. Therefore, data measured at the higher frequencies include more errors than those measured at the lower frequencies. The same trend was observed though the results of frequency tests performed at the lower temperatures.

However, the highest errors occurred at both of the lowest and highest frequency tests performed at the highest temperature. Also, the standard error generally increased as temperature increased. This error appears not to be the same type of error that was observed before. It appears to be caused by the load cell used in this project. In general, any load cell includes an inherent error. Depending on the maximum value of a load cell, an approximate tolerance of ± 0.03 % exists in the load cell. Since this project used a 22-kips load cell, the tolerance of the load cell was ± 6.6 lb. Considering that the loading level used for the lowest frequency test performed at the highest temperature was 25 lb, the explanation made for the second type of error appears reasonable and is in accordance with the dynamic modulus test results. Consequently, it is strongly recommended that a load cell with suitable loading capability be used when applying the developed dynamic modulus testing system to other mixtures. In AASHTO T 62-03, it is recommended for use of a load cell with a minimum range of 0 to 5600 lb.

Comparison of Predicted Modulus with Measured Dynamic Modulus

One of the strong advantages of the dynamic modulus is that the modulus values can be predicted using the predictive equation. The general approach for determining dynamic modulus values in the Design Guide is a hierarchical system. Level 1 provides the highest level of accuracy of the performance prediction for rutting or cracking. In this stage, comprehensive laboratory or field tests are required. In contrast, Level 3 provides lower reliability because no laboratory or field tests need to be performed. Inputs of Level 2 are estimated through correlation with other material properties that are measured in the laboratory or field.

In this project, the efficiency of Level 3 for predicting the dynamic moduli was investigated. The volumetric properties of the mixture tested and the default binder parameters of PG 67-22 are used as inputs of the predicted equation. Figures 22 and 23 show the correlation between the measured and predicted dynamic moduli. The slope measured from linear regression was 0.83, and an approximate error of 17 % was obtained from the measured and predicted dynamic moduli. These results appear to be within a reasonable tolerance, compared to similar studies performed on the typical mixtures used in Florida (e.g., Birssion et al., 2004 and Ping and Xiao, 2007). This indicates that the modulus values obtained from the system are comparable with those obtained from other research institutions. In addition, Figure 24 shows master curves obtained from the measured and predicted data at the reference temperature of 21.1 °C. The DAT program was used to generate the master curves.

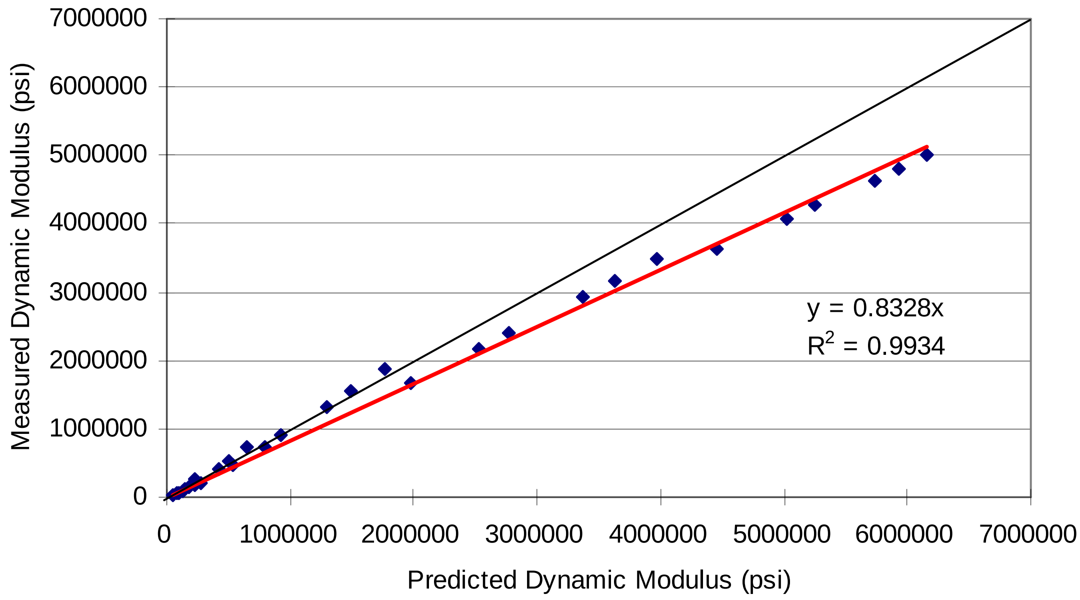


Figure 22. Measured versus Predicted Modulus

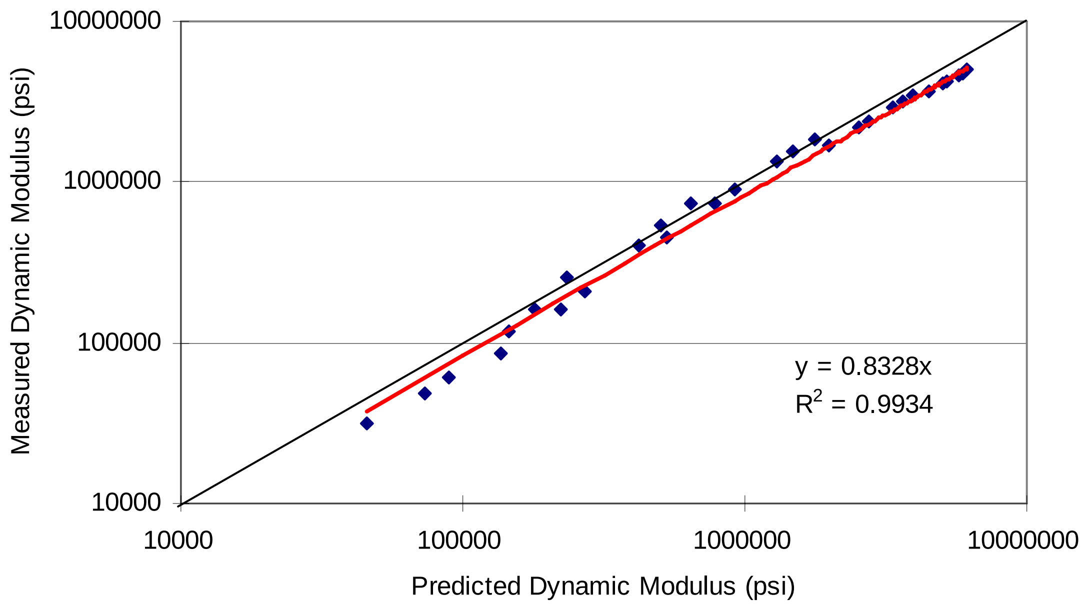


Figure 23. Measured versus Predicted Modulus in Log Scale

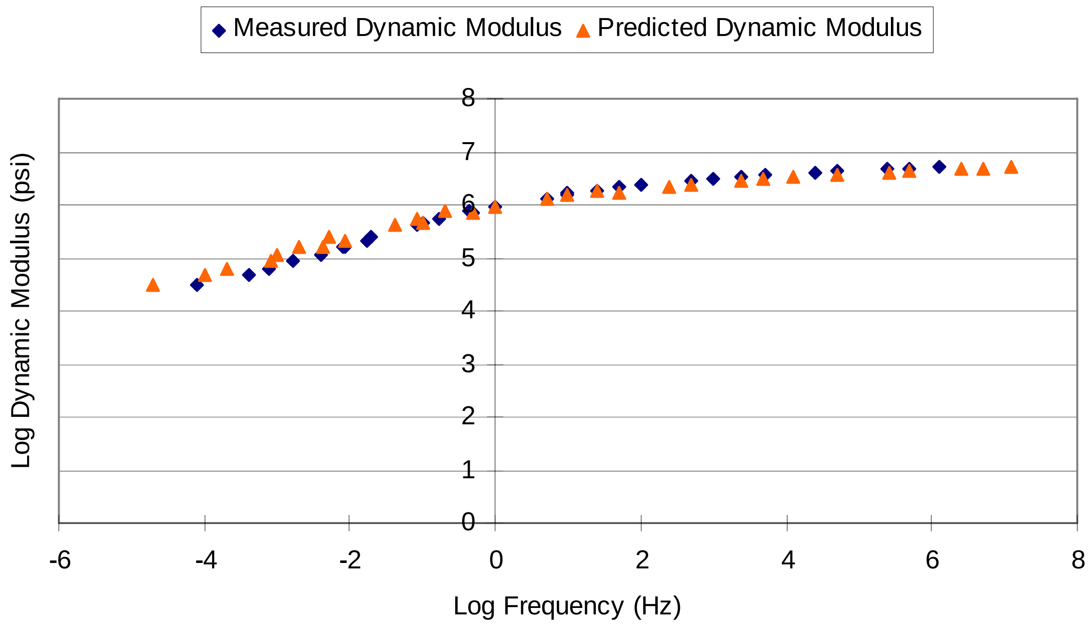


Figure 24. Master Curves from Measured and Predicted Moduli

SUMMARY AND CONCLUSIONS

The objectives of this research project were to develop dynamic modulus testing and interpretation capabilities at the FDOT materials office. Since this research was aimed to optimize the cost of developing a new testing system, the existing testing system that is used for the indirect tensile test was utilized. Additional testing components for the dynamic modulus test were designed and produced during the course of this project. At the same time, robust and automatic data analysis software, which is named Dynamic Testing Analyzer (DTA), was developed for the second purpose of this project.

Since the nature of the cyclic test is somewhat different than that of the static test, problems associated with accuracy, sensitivity, and stability of instrumentation are critical.

Rigorous calibration processes associated with tuning the testing machine and adjusting the testing system were performed, and the resulting data were evaluated by comparing to the known properties of a linear elastic material. The results clearly showed that the dynamic modulus testing system developed was accurate and reliable.

To evaluate the capability of the dynamic modulus testing system on the mixture test, a fine graded asphalt mixture meeting Superpave requirements, which is the overwhelming mixture type used for FDOT work, was evaluated. The recommended test series, as specified in AASHTO TP 62-03, consisting of five temperatures (-10, 4.4, 21.1, 37.8, and 54.4°C) and six loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) was used for the mixture test. The series of dynamic modulus tests using the testing system developed was successfully performed on the mixture. From the comparison between measured and predicted dynamic moduli, the slope was 0.83, and an approximate error of 17 % was obtained. These results appear to be within a reasonable tolerance, compared to similar studies performed on the typical mixtures used in Florida. This indicates that the system was well developed, and provided reliable dynamic moduli, comparable with those obtained from other research institutions.

However, the standard errors estimated for the lowest frequency (0.1 Hz) and the highest frequency (25 Hz) tests performed at the highest temperature (54.4°C) exceeded the limitation of 10 %. This appears to be caused by a load cell with higher than required loading capability used in this project. Therefore, it is strongly recommended to use a load cell with suitable loading capability for further applications of the dynamic modulus testing system with other mixtures.

ACKNOWLEDGEMENT

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